Technical Report of the Arctic Council Task Force on Short-Lived Climate Forcers

An Assessment of Emissions and Mitigation Options for Black Carbon for the Arctic Council

ARCTIC COUNCIL
May 2011

Acknowledgments

An Assessment of Emissions and Mitigation Options for Black Carbon for the Arctic Council is a report of the Arctic Council Task Force on Short-Lived Climate Forcers.

This report and its supplemental material contained in appendices are available at: http://arctic-council.org.

The Task Force's 2011 Progress Report and Recommendations for Ministers is also available at: http://arctic-council.org.

Co-chairs of the Task Force on Short-Lived Climate Forcers:

- Benjamin DeAngelo, U.S. Environmental Protection Agency, editor
- Håvard Toresen, Norwegian Ministry of the Environment

National representatives of the Task Force and contributors to this report:

- Reino Abrahamsson, Swedish Environmental Protection Agency
- Carsten Eskebjerg, Danish Ministry of Climate and Energy
- Mette Frost, Infrastructure Agency, Greenland
- Michael Geller, U.S. Environmental Protection Agency
- Jeanne-Marie Huddleston, Environment Canada
- Jennifer Kerr, Environment Canada
- Kaarle Kupiainen, Finnish Environment Institute/International Institute for Applied Systems Analysis (IIASA)
- Venkatesh Rao, U.S. Environmental Protection Agency
- Seppo Sarkkinen, Finnish Ministry of the Environment
- Marcus Sarofim, U.S. Environmental Protection Agency
- Erika Sasser, U.S. Environmental Protection Agency
- Jesper Stubkjær, Danish Environmental Protection Agency
- Vigdis Vestreng, Climate and Pollution Agency, Norway

The Task Forces wishes to especially thank Zig Klimont of IIASA for making available the GAINS analyses for this report.

The Task Force also thanks those who provided reviews and comments:

Peter Lahm, U.S. Forest Service; Pam Pearson, International Cryosphere Climate Initiative; Elena Kobets, ERC Bellona; Michael Walsh, independent consultant; Ellen Baum, Clean Air Task Force; Brad Kinder, U.S. Forest Service; Brian Muehling, U.S. Environmental Protection Agency

Editing and layout: Katherine Bronstein, RTI International

Photos: All photos contained in this report were taken in Ilulissat, Greenland at the time of the April 2010 Senior Arctic Officials meeting.

Table of Contents

Acknowledgments iii

List of Acronyms xi

Technical Summary TS-1
  Key Findings TS-3

Section 1 – Introduction 1-1

Section 2 – Climate Change and Health Effects: Setting the Context 2-1
  Introduction 2-2
  2.1 Climate Change in the Arctic 2-2
    2.1.1 The Role of Black Carbon in Arctic Climate Change 2-4
    2.1.2 Recent AMAP Analyses 2-8
    2.1.3 The Potential Role of Methane and Tropospheric Ozone in Arctic Climate Change 2-10
  2.2 Brief Overview of Global Health Effects Related to SLCFs 2-10

Section 3 – Current Black Carbon and Organic Carbon Emissions 3-1
  Introduction 3-2
  3.1 Arctic Region Emissions in the Global Context 3-2
  3.2 Comparing Emission Inventories 3-5
    Uncertainties 3-7
  3.3 Total Arctic Council Emission Estimates 3-13
    3.3.1 Bond Emissions Estimates 3-13
    3.3.2 GAINS Emissions Estimates 3-15
    3.3.3 Emissions Data Used by AMAP 3-17
  3.4 National Emission Inventories of Arctic Council Nations 3-18
    3.4.1 Canada 3-18
    3.4.2 Denmark, Greenland, and the Faroe Islands 3-23
    3.4.3 Finland 3-28
    3.4.4 Norway 3-30
    3.4.5 Sweden 3-38
    3.4.6 United States 3-42
  3.5 Synthesis of Emissions Inventories 3-50

Section 4 – Projected Future Emissions 4-1
  Introduction 4-2
  4.1 GAINS Projected Emissions for 2020 and 2030 4-2
  4.2 National Projections 4-11
    4.2.1 Canada 4-11
    4.2.2 Denmark, Greenland, and the Faroe Islands 4-14
    4.2.3 Finland 4-17
    4.2.4 Norway 4-20
    4.2.5 Sweden 4-22
    4.2.6 United States 4-25

Section 5 – Current Regulations, Policies, and Programs Relevant for Emission Control 5-28
  Introduction 5-29
  5.1 Transnational Programs 5-30
    5.1.1 North American Programs 5-30

5.1.2 European Programs 5-30
5.1.3 International Shipping Regulations 5-34
5.2 Arctic Council Nations' Specific Initiatives 5-34
5.2.1 Canada 5-34
5.2.2 Denmark, Greenland, and the Faroe Islands 5-38
5.2.3 Finland 5-41
5.2.4 Norway 5-42
5.2.5 Sweden 5-43
5.2.6 United States 5-45

Section 6 – Additional Mitigation Opportunities 6-1
Introduction 6-2
6.1 Additional Mitigation Potential Estimated by the GAINS Model 6-2
6.2 Sectoral Information Provided By Arctic Council Nations 6-6
6.2.1 Domestic (Residential Heating) 6-6
6.3 Transport 6-10
6.3.1 Off-Road Vehicles and Working Machinery 6-11
6.3.2 International Marine Shipping 6-12
6.3.3 Fishing Vessels 6-13
6.4 Energy and Industrial Production and Waste 6-13
6.4.1 Energy Production 6-13
6.4.2 Industrial Production 6-14
6.5 Agricultural and Open Biomass Burning 6-14
6.5.1 Agricultural Burning 6-16
6.5.2 Prescribed Forest Burning 6-16
6.5.3 Wildfires 6-18
6.6 Gas Flaring 6-18

References R-1

Appendix A – Canada

Appendix B – Kingdom of Denmark, Greenland, and the Faroe Islands

Appendix C – Finland

Appendix D – Norway

Appendix E – Sweden

Appendix F – United States

Appendix G – GAINS Data

Appendix H – Bond Data

List of Figures

TS-1. Total black carbon and organic carbon emissions, excluding open biomass burning, in 2000 and 2005 from the Arctic Council nations, Gigagrams TS-4
TS-2. Total black carbon and organic carbon emissions, including open biomass burning, in 2000 and 2005 from the Arctic Council nations, Gigagrams...TS-5
TS-3. Black carbon emissions projections based on current legislation and a baseline of 2005 (Amman et al., 2010) TS-7
2-1. Average monthly Arctic sea ice extent, September 1979 to 2010 (NSIDC, 2008)................ 2-3
2-2. Arctic September sea ice extent (10^6 km^2) from observations (thick red line) and 13 IPCC AR4 climate models, together with the multi-model ensemble mean (solid black line) and +/- standard deviation (dotted black line). (Stroeve et al., 2007).................. 2-7
3-1. Relative importance of source regions to annual mean Arctic concentrations at the surface and in the upper troposphere (250 hPa) for BC (Shindell et al., 2008) 3-3
3-2. Global BC emissions by latitude for the Arctic region and the rest of the world (Gg/degree latitude). 3-4
3-2. Global BC emissions by source category for 2000 by latitude.. 3-5
3-3. Black carbon emissions by sector and Arctic Council nation for 2000 in Gg (Bond, 2009). 3-14
3-4. Organic carbon emissions by sector and Arctic Council nation for 2000 in Gg (Bond, 2009); open burning included. 3-14
3-5. Organic carbon emissions by sector and Arctic Council nation for 2000 in Gg (Bond, 2009); open burning not included. 3-15
3-6. BC emissions by sector for 2000 and 2005, not including open biomass burning, all Arctic Council nations (Gg/yr). 3-16
3-7. OC emissions by sector for 2000 and 2005, all Arctic Council nations (Gg/yr). 3-17
3-8. BC and OC emissions for 2006 by sector, Canada (Gg/yr). 3-20
3-9. Provincial breakdown of BC emissions in 2006 by sector, Canada (Gg/yr)....................... 3-21
3-10. Provincial breakdown of OC emissions in 2006 by sector, Canada (Gg/yr). 3-21
3-11. BC and OC emissions for 2000 and 2005 by sector, excluding open biomass burning, Canada in Gg/yr. 3-23
3-12. BC and OC emissions by sector for 2000, 2005, and 2010, Denmark and the Faroe Islands (Gg/yr). 3-24
3-13. BC and OC emissions by sector for 2000, 2005, and 2010, Greenland (Gg/yr)................. 3-26
3-14. Comparison of total BC and OC emissions inventories for Denmark, Greenland, and the Faroe Islands to GAINS and Bond (Gg/yr).. 3-27
3-15. BC and OC emissions for 2000 and 2005 by sector, Denmark, Greenland, and the Faroe Islands in Gg/yr... 3-27
3-16. BC and OC emissions by sector for 2000 and 2005, Finland (Gg/yr). 3-29
3-17. BC and OC emissions for 2000 and 2005 by sector, Finland in Gg/yr............................... 3-30
3-18. Historical trends in $PM_{2.5}$ emissions by SNAP category for 1980, 1990, 1995, and 2000–2008, Norway (Gg/yr)... 3-31
3-19. Temperature and snow cover in Oslo, Norway, in autumn 2002....................................... 3-32
3-20. Ratio between flared and produced petroleum in Norway, 1990–2008............................. 3-35
3-21. Comparison of Norwegian and GAINS $PM_{2.5}$ emissions for 1990–2005, aggregated to SNAP categories in Gg/yr.. 3-37
3-22. BC and OC emissions for 2000 and 2005 by sector, Norway (Gg/yr). 3-37
3-23. Total emissions of $PM_{2.5}$ for 1990–2008, Sweden (Gg/yr).. 3-38
3-24. Detailed emissions breakdown of $PM_{2.5}$ emissions in Sweden for 1990–2008, excluding international shipping (Gg/yr)... 3-39
3-25. Emissions of $PM_{2.5}$ in 2007 from combustion sources and the amount derived from different fuels, Sweden (Gg/yr). 3-40
3-26. BC and OC emissions by sector for 2007, Sweden (Gg/yr). 3-41

3-27. BC and OC emissions for 2000 and 2005 by sector, Sweden (Gg/yr). 3-42
3-28. BC and OC emissions by sector for 2005, United States (Gg/yr). 3-45
3-29. Emissions of $PM_{2.5}$, OC, and BC by source category in 2005, United States (Gg/yr). 3-46
3-30. Percent of BC and OC emissions in Gg for 2005, grouped by combustion categories, United States. 3-47
3-31. Detailed breakdown of BC emissions (total of 308 Gg) in the Transport sector, United States 2005 NEI (U.S. EPA, 2011). 3-48
3-32. BC and OC emissions for 2000 and 2005 by sector, United States (Gg/yr). 3-49
3-33. BC and OC emissions for 2000 and 2005 by sector, United States (Gg/yr). 3-50
3-34. BC and OC emissions for 2000 and 2005 by sector, Iceland (Gg/yr). 3-51
3-35. BC and OC emissions for 2000 and 2005 by sector, the Russian Federation (Gg/yr). 3-52
4-1. BC emissions for all Arctic Council nations by aggregated sector (Gg/yr). 4-5
4-2. OC Emissions for Arctic Council nationa by aggregated sector (Gg/yr). 4-6
4-3. GAINS projected BC and OC emissions for Canada (Gg/yr). 4-7
4-4. GAINS projected BC and OC emissions for Denmark, Greenland, and the Faroe Islands (Gg/yr). 4-7
4-5. GAINS projected BC and OC emissions for Finland (Gg/yr). 4-8
4-6. GAINS projected BC and OC emissions for Iceland (Gg/yr). 4-8
4-7. GAINS projected BC and OC emissions for Norway (Gg/yr). 4-9
4-8. GAINS projected BC and OC emissions for the Russian Federation (Gg/yr). 4-9
4-9. GAINS projected BC and OC emissions for Sweden (Gg/yr). 4-10
4-10. GAINS projected BC and OC emissions for the United States (Gg/yr). 4-10
4-11. Total BC emissions trends 2005 through 2030, Canada. 4-12
4-12. BC emissions trends by major sector in Gg, 2005 through 2030, Canada. 4-13
4-13. Comparison of national and GAINS CLE projected 2030 BC emissions estimates, Canada (Gg). 4-14
4-14. BC and OC emissions for 2000–2030, Denmark and the Faroe Islands. 4-15
4-15. BC and OC emissions projections for Greenland in Gg/yr, 2010–2030. 4-16
4-16. Comparison of national and GAINS projected 2030 BC emissions estimates, Denmark, Greenland, and the Faroe Islands (Gg). 4-17
4-17. Comparison of national and GAINS projected 2030 OC emissions estimates, Denmark, Greenland, and the Faroe Islands (Gg). 4-17
4-18. BC and OC Emissions Projections for Finland, 2005 and 2020. 4-19
4-19. Comparison of 2020 Projected BC Emissions, Finland (Gg). 4-19
4-20. Comparison of 2020 Projected OC Emissions, Finland (Gg). 4-20
4-21. Projections of $PM_{2.5}$ emissions for 2000, 2010, and 2020, Norway (SFT, 2006). 4-21
4-22. Comparison of $PM_{2.5}$ emissions from SFT and GAINS for 2000, 2010, and 2020 in Gg, Norway. 4-22
4-23. $PM_{2.5}$ emissions projections in Gg with base year of 2007, Sweden. 4-23
4-24. Projected BC and OC emissions for 2020 compared with base year 2007, Sweden. 4-24
4-25. Comparison of projected 2020 BC emissions to GAINS, Sweden (Gg). 4-24
4-26. Comparison of projected 2020 OC emissions to GAINS, Sweden (Gg). 4-25
4-27. Mobile source direct $PM_{2.5}$ emission trends. 4-27
4-28. Mobile source direct BC emission trends. 4-27
6-1. Cost efficiency of additional measures in the Domestic sector in 2020, Norway. 6-9

List of Tables

2-1. Seasonal impacts of solar radiation, sources, and transport in the Arctic 2-8
3-1. GAINS Meta Categories and Sub-Categories 3-7
3-2. Aggregation Matrix of Country-specific Source Categories and the Broader Sectors Used in this Report 3-9
3-3. Percent of BC and OC Emissions from the Domestic and Transport Sectors in Denmark and the Faroe Islands for 2000, 2005, and 2010 3-24
3-4. BC and OC Emissions from International Navigation and International Civil Aviation in Denmark for 2000, 2005, and 2010, Gg 3-25
3-5. Percent of BC and OC Emissions from the Transport and the Fishery Source Categories in Greenland for 2000, 2005, and 2010 3-26
3-6. Wood Consumption Distributed on Different Technologies and PM_{10} Emission in Norway for 2009 3-33
3-7. Emission Factors Applied in the Norwegian $PM_{2.5}$ Inventory 3-33
3-8. Emission Factors for Flare Operations from U.S. EPA (2002) 3-36
3-9. Assumed Fractions of BC and OC Per Unit $PM_{2.5}$ Emissions for Source-specific Categories in Sweden for 2007 3-41
3-10. 2005 Biomass Burning Emissions from Grouped Subcategories in Gg 3-47
4-1. Summary of GAINS BC Projected Emissions for 2020 and 2030 4-3
4-2. Summary of GAINS OC Projected Emissions for 2020 and 2030 4-4
4-3. Black Carbon Emissions for all AC Countries by Sector (Gg/yr) 4-4
4-4. Organic Carbon Emissions for AC Countries by Sector (Gg/yr) 4-5
5-1. BC-Specific Measures Used by the IIASA GAINS Model Emissions Estimates 5-29
5-2. European Emission Standards for Diesel Passenger Cars and Light Commercial Vehicles ≤1305 Kg 5-30
5-3. European Emission Standards for Diesel Light Commercial Vehicles 1305–3500 kg 5-31
5-4. European Emission Standards for Heavy-duty Diesel Engines 5-32
5-5. European Emission Standards for Off-road Diesel Mobile Machinery and Agricultural/Forestry Tractors 5-33
5-6. Emission Limit Values for Wood Stoves in Norway (NS3059) 5-42
6-1. Total BC Emissions and Further Mitigation Potential (Gg/yr) by Sector (GAINS data) 6-1
6-2. Total OC Emissions and Further Mitigation Potential (Gg/yr) by Sector (GAINS data) 6-1
6-5. Number of various residential heating installations in 2003, Sweden 6-7
6-6. Analysis Results for Various Scenarios, Emission Reductions, and Costs (2020) 6-8
6-7. Scenario Analysis Regarding Abatement Measures for Off-Road Mobile Machinery and Tractors in Sweden (IVL, 2009) 6-12
6-8. Analysis of Two Scenarios for Reducing PM Emissions from Shipping (2020)................. 6-13

List of Acronyms

µg/L	micrograms per litre
AMAP	Arctic Monitoring and Assessment Programme
BAT	Best Available Technologies
BBR	Boverkets Byggregler, Swedish building regulations
BC	black carbon
BEP	Best Environmental Practices
CAAQS	Canadian Ambient Air Quality Standards
CAMS	Comprehensive Air Management System
CCME	Canadian Council of Ministers of the Environment
CEMS	continuous emissions monitoring system
CLE	current legislation
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
CSA	Canada Standards Association
CWS	Canada-wide Standards
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EC	Environment Canada
ECA	Emission Control Areas
EER	Exceptional Event Rule
EGU	electric generating unit
EQS	Environmental Quality Standards
ESC	European steady-state
ESP	electrostatic precipitator
ETC	European transient cycle
EU	European Union
EV	electric vehicle
FRES	Finnish Regional Emission Scenario model
GAINS	Greenhouse Gas – Air Pollution Interactions and Synergies
Gg	Gigagram
GHG	greenhouse gas
GIS	geographic information systems
hPa	hectopascal
IED	Directive on Industrial Emissions
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IVL	Swedish Environmental Research Institute
kW	kiloWatts
L/min	litres/minute
m^3	cubic meters
MACT	Maximum Achievable Control Technology
MW	MegaWatt
NAAQS	National Ambient Air Quality Standards
NAICS	North American Industry Classification System

NEC	National Emissions Ceiling
NEI	National Emissions Inventory
NOAA	National Oceanic and Atmospheric Administration
NOK/ton	Norwegian Krone per metric ton
NO_X	nitrogen oxides
NPD	Norwegian Petroleum Directorate
NPRI	National Pollutant Release Inventory
NSPS	New Source Performance Standard
OC	organic carbon
OLF	Norwegian Oil Industry Association
OM	organic mass
PIRD	Pollutant Inventories and Reporting Division
PJ	Petajoule
PM	particulate matter
$PM_{2.5}$	particulate matter with a diameter of 2.5 microns or less
POP	persistent organic pollutant
ppb	parts per billion
ppm	parts per million
RCP	Representative Concentration Pathways
RPO	Regional Planning Organization
SCC	Source Category Code
SKYE	Finnish Environment Institute
SLCF	short-lived climate forcers
Sm^3	standard cubic meters
SNAP	selected nomenclature for air pollutants
SO_x	Sulphur oxides
TSP	total solid particulates
TWh	TerraWatt-hours
USDA	United States Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency’s
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
Wm^{-2}	watts per square meter

Technical Summary

The term “short-lived climate forcers” (SLCFs) often is used to describe a subset of greenhouse gases (GHGs) and aerosols that alter Earth’s energy balance. Compared to long-lived GHGs such as carbon dioxide (CO_2), SLCFs remain in the atmosphere for much shorter time periods. SLCFs include particulate aerosols such as black carbon (BC), nitrates, and sulphates; gases formed from precursor emissions such as tropospheric ozone; and directly emitted GHGs such as methane.[1] In the Arctic Council context, SLCFs mainly include BC, ozone, and methane.

This report focuses on BC because the Arctic Council Task Force on Short-Lived Climate Forcers (henceforth referred to as the Task Force) decided that, among the SLCFs, BC requires the most additional technical analyses. BC is the carbonaceous component of particulate matter (PM) formed by incomplete combustion of fossil fuels and biomass.[2] BC particles strongly absorb sunlight and give soot its black colour. Sources of BC emit a complex mixture of substances, including organic carbon (OC), nitrates, and sulphates. BC remains in the atmosphere for days to weeks and warms the climate by absorbing both incoming and outgoing solar radiation and by darkening snow and ice after deposition, thereby reducing the surface albedo, or reflectivity. This albedo effect is particularly prevalent in the Arctic region.

Although this report focuses on BC, this focus does not represent a judgment by the Task Force that BC is the most important climate forcer in terms of Arctic climate change. Consistent with the Task Force’s mandate, this report does not produce new scientific findings regarding the role of BC in Arctic climate change; rather, the available science presented herein provides an important context for the report’s emissions and mitigation assessment, namely the following:

- Although CO_2 emissions are the dominant factor contributing to observed and projected rates of Arctic climate change, addressing SLCFs such as BC, methane, and ozone offers unique opportunities to slow Arctic warming in the near term.
- BC emitted both within and outside of the Arctic region contributes to Arctic warming. Per unit of emissions, BC emission sources within Arctic Council nations (i.e., Canada, Denmark [including Greenland and the Faroe Islands], Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States of America) generally have a greater impact on climate change.
- Sources of BC emit a complex mixture of substances, some of which may cool the climate, such as OC or sulphates. However, in the Arctic, the potential for such offsetting effects from non-BC aerosols is weaker. When BC physically deposits on snow and ice (i.e., highly reflective surfaces), its warming impact is magnified; therefore, the same substances that might cool the climate in other regions may cause warming in the Arctic.
- Unlike the case for methane and other well-mixed GHGs (including CO_2, nitrous oxide, and fluorinated gases), the most effective BC control strategies for Arctic climate benefits vary by location and season. For example, BC emissions from

---

[1] Methane has an atmospheric lifetime of roughly a decade, which allows it to become globally well-mixed; however, most other GHGs have much longer atmospheric lifetimes. This is why methane can also be referred to as “short-lived.”

[2] Most source characterization studies measure elemental carbon (EC) rather than BC. However, for the purposes of this report, BC is assumed to be roughly equivalent to EC.

agricultural burning, wildfires, and residential heating tend to be seasonally dependent.

- Regardless of the role that BC and other SLCFs play in Arctic climate change, measures aimed at decreasing these emissions will have positive health effects for communities exposed to PM emissions containing BC.

Key Findings

For this technical report, the Task Force has compiled and compared national and global BC emissions inventories, examined emission trends and projections, synthesized existing policies and programs, and identified additional emission mitigation opportunities for BC. The key findings of this technical report are discussed below.

The largest sources of BC emissions in Arctic Council nations have been identified.

The two independent research emissions inventories referenced in this report are the Bond emissions inventory (2009) and the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS) emissions inventory (Amman et al., 2010). The Bond emissions inventory is global in scale and presents a bottom-up estimate of BC and OC emissions. For the purposes of this report, the Bond inventory was broken out for each of the eight Arctic Council nations (i.e., Canada, Denmark [including Greenland and the Faroe Islands], Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States of America). The Bond emissions estimates used in this report build upon a previously published inventory and are estimated for a base data year of 2000.

Like the Bond inventory, the GAINS (Amman et al., 2010) inventory contains estimates of global BC and OC emissions, but also provides specific estimates by Arctic Council nation and their respective emission source categories. A key difference of the GAINS inventory from the Bond inventory is that the GAINS emissions estimates do not include open forest burning (i.e., wildfires and prescribed forest burning), which is a significant source of both BC and OC emissions globally and for key Arctic Council nations, specifically Canada, the Russian Federation, and the United States.

In addition to these two global emissions inventories, most Arctic Council countries submitted a national BC and OC emissions inventory utilizing country-specific data. To develop these inventories, the nations applied BC and OC fractions to national-scale $PM_{2.5}$ emissions inventories for various country-specific source categories. Nationally developed inventories from Iceland and Russia are not included in this report. Norway provided a $PM_{2.5}$ emissions inventory.

In order to compare country-by-country emissions estimates, each of which involve some variation of methodology and source categories, the national emissions inventory data were aggregated into seven sectors: Domestic; Energy & Industrial Production, Waste; Transport; Agricultural; Open Biomass Burning; Flaring; and Other. These sectors are based on the source categories and meta-categories used in GAINS methodology, and are discussed more in ***Section 3*** of this report. **Figures TS-1 and**

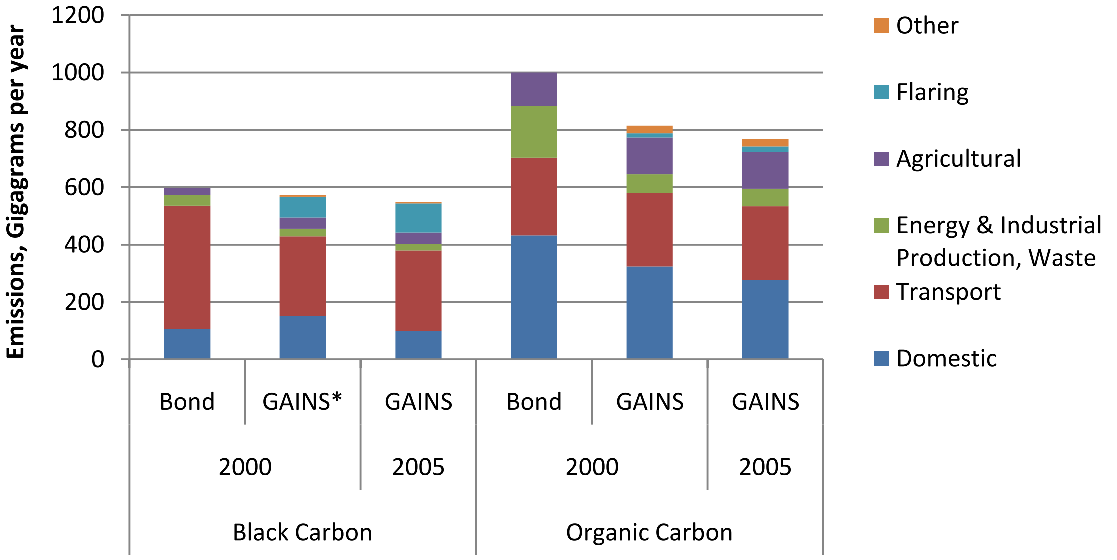
TS-2 provide the BC and OC emissions estimates for each sector used in this report and identify the largest BC emissions sources for the Arctic Council as a whole and for each nation. Figure TS-1 does not present data on emissions from open biomass burning, while Figure TS-2 does include these data. The GAINS model does not model emissions from prescribed forest burning and wildfires, whereas the Bond inventory does model these emissions. As shown in the figures, the three primary sectors are the following:

- **The Transport sector,** primarily due to emissions from on-road transportation, including on-road and off-road diesel vehicles;
- **The Domestic sector** due to emissions from domestic heating, primarily wood but also coal combustion;
- **The Open Biomass Burning sector,** primarily due to emissions from agricultural burning, prescribed burning in forestry, and wildfires.

Marine shipping is a relatively small source of transport-related BC emissions, but is a potentially significant source due to the proximity of Arctic shipping routes to Arctic snow and ice. Regarding domestic heating, many homes in Arctic Council countries have transitioned from using oil to the use of wood over the past decade, a trend that is expected to continue. Many homes that use wood stoves are located in the more near-Arctic regions; therefore, their emissions are more likely to be transported to the Arctic.

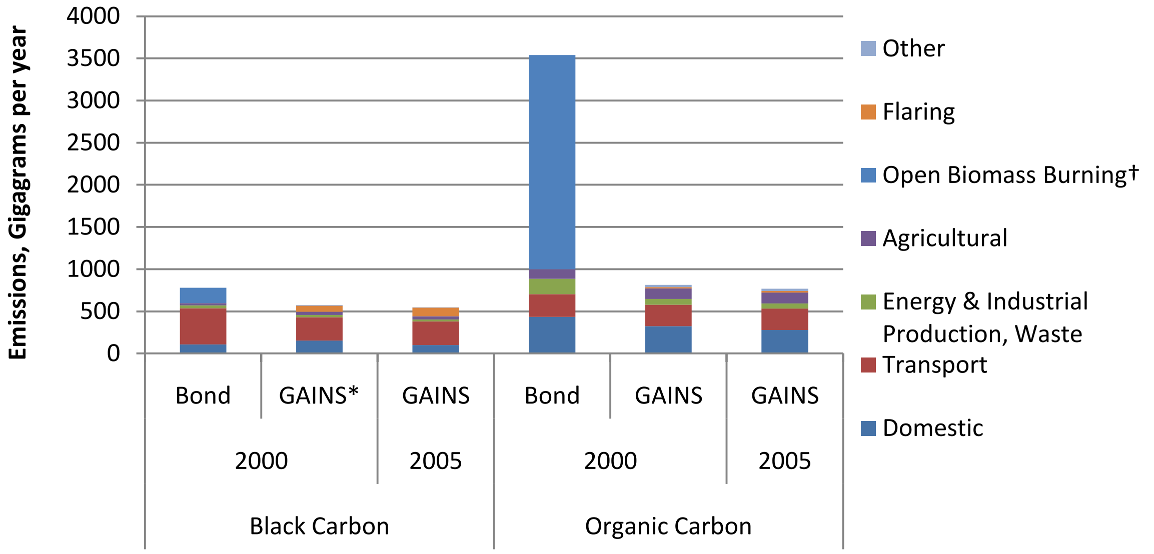
The estimates shown in this report also suggest that gas flaring from fossil fuel production potentially is a significant emission source. However, gas flaring emissions are not well characterized, and more robust emissions inventories are needed.

Figure TS-1. Total black carbon and organic carbon emissions, excluding open biomass burning, in 2000 and 2005 from the Arctic Council nations, Gigagrams



* GAINS data for 2000 and 2005 include agricultural burning emissions, but do not include other open biomass burning (wildfires and prescribed forest burning).

Figure TS-2. Total black carbon and organic carbon emissions, including open biomass burning, in 2000 and 2005 from the Arctic Council nations, Gigagrams



* GAINS data for 2000 and 2005 include agricultural emissions and do not include other open biomass burning (wildfires and prescribed forest burning) in the Open Biomass Burning sector.

† Only the Bond data for 2000 and 2005 include emissions from open biomass burning (wildfires and prescribed forest burning).

There is still considerable uncertainty regarding the quantification of the exact magnitude of BC emissions, particularly from sources such as agricultural burning, open biomass burning (i.e., wildfires and prescribed forest burning), and gas flaring.

Despite general confidence that the largest sources of BC emissions within Arctic Council nations can be identified, there remains considerable uncertainty in the exact magnitude of the emissions inventories. Different methodologies and source categories are used for each national emissions inventory presented in this report. In some cases, certain source categories are not included due to a lack of available data, particularly with respect to wildfires, agricultural burning, prescribed forest burning, and gas flaring. Additionally, some nations were able to provide more detailed source categories than others.

In general, there is good agreement between the national representation within the two independent research emissions inventories (Bond and GAINS) and those submitted by the Arctic Council nations, despite the differences in methodology. In some cases, large differences exist between the global research inventories and the national inventories, mainly due to a difference in or absence of certain source categories and estimation methodologies. Any significant differences in the total magnitude of BC or OC emissions among inventories typically results from the inclusion or exclusion of prescribed forest burning and wildfires.

The size of BC emissions alone does not convey the complete story about the climate impacts of each emission source on the Arctic region. Arctic climate effects are influenced by other factors, including the extent to which BC emissions are transported to the Arctic, whether emissions deposit on snow and ice, and the extent to which the emissions cause climate effects outside of the Arctic, which in turn influence the Arctic climate. Recent analyses by the Arctic Monitoring and Assessment Programme (AMAP), briefly summarized in this report, provide further insights into the Arctic climate effects of BC emission sources within and outside of the Arctic Council nations.

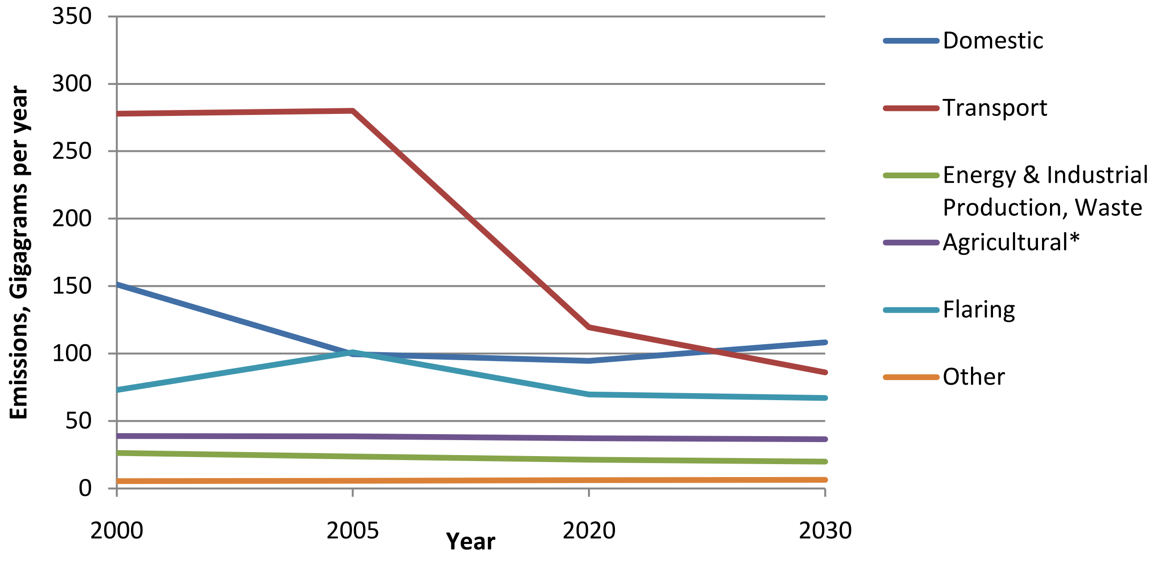
Overall, total BC emissions from Arctic Council nations are projected to decrease in the coming decades, primarily due to the effective implementation of transportation-related PM controls.

Overall, BC emissions from Arctic Council nations are projected to decrease in coming decades, primarily because of stronger $PM_{2.5}$ controls on diesel vehicles and working machinery. These controls are largely motivated by health and other air quality benefits, not by Arctic climate concerns. The overall projected decrease in BC emissions will be highly dependent on the effective implementation of current and future adopted legislation, as well as by how rapidly older vehicles not covered by the new legislation are retired.

Analyses by the IIASA GAINS model, as presented in **Figures TS-3 and TS-4,** show that total BC emissions from Arctic Council nations are projected to decrease by 41% from 2005 to 2030, and total OC emissions are projected to decrease by 25% from 2005 to 2030. Emissions from marine shipping are included in the Transport sector. Emissions from open biomass burning (i.e., wildfires and prescribed forest burning), which are challenging to project into the future and for which there is no compelling reason to expect a significant downward trend, were not modelled by IIASA and are not included in these figures.

Emissions from source categories aside from on- and off-road mobile sources in the GAINS model are not projected to significantly decrease and may even increase in the future. Few existing or planned regulations in Arctic Council nations will lead to decreases in BC and OC emissions from domestic heating, open biomass burning, and marine shipping. Emissions from domestic heating may grow because many nations are increasingly using wood as a fuel. In addition, as marine shipping becomes more prevalent in the Arctic, BC emissions may increase, and their impact may be magnified due to the close proximity to Arctic snow and ice. As a result, there remains much that Arctic Council nations can do to further decrease their individual BC and OC emissions.

Figure TS-3. Black carbon emissions projections based on current legislation and a baseline of 2005 (Amman et al., 2010)



* Emissions in the Agricultural sector do not include wildfires, prescribed burning, and other types of open biomass burning.

To maximize climate benefits, PM control programs must aim to achieve maximum BC reductions.

No Arctic governments currently control BC per se. While PM controls do help to decrease BC emissions, the effect of these controls on BC emissions are not always proportionate. This is because the amount of BC in directly emitted PM varies by source, and also because PM mitigation programs that focus on sulphur and nitrogen oxides (NO_x) may not lead to reductions in BC. Therefore, BC-specific efforts for regional climate purposes can be worthwhile as a complement to existing PM controls for health and environmental purposes.

Several mitigation measures have been identified to further reduce major emission source categories.

On- and Off-Road Mobile Transportation. Measures to reduce BC from transportation sources, especially diesel-powered vehicles, could include more retrofitting of older vehicles and equipment; retirement of old engines, vehicles, and equipment; and enhancement or expansion of current controls to the extent that PM standards are not in place. Most Arctic countries already have regulations for new on- and off-road diesel engines that are either in effect or will become active by 2020 and which require these vehicles to implement technologies that should reduce BC emissions by over 90% compared to pre-regulation engines. Similar retrofit, retirement, or replacement measures could be applied to reduce BC emissions from stationary engines and equipment. Additional measures—all of which have strong health co-benefits—could include the following:

- Accelerated implementation of ultralow sulphur diesel requirements for both on- and off-road diesel fuels (an important prerequisite to BC reductions), accompanied by emissions controls to reduce diesel PM;
- Development and implementation of particulate emission standards that enforce the use of particulate traps for new engines of on- and off-road vehicles, mobile machinery, locomotives, and certain marine vessels, where such standards may not be in place;
- Retrofitting of existing older and high-emitting vehicles and equipment with particle filters through regulation or voluntary subsidy programs;
- Retirement or replacement of the dirtiest existing sources (especially those not easily fitted with filters) through regulation or financial incentives; guidelines for early retirement or scrappage programs should ensure that the original engine is either destroyed or, when possible, returned to the manufacturer to be remanufactured to cleaner emission standards;
- Coordinated campaigns for better enforcement of new standards, more stringent inspection requirements, and encouragement of better maintenance practices;
- Introduction or expansion of "green zones" that ban or require special fees for vehicles with high particle emissions; and
- Reduction of truck and off-road idling through regulation, education, or rest stop electrification; additional vehicle efficiency programs; addition of auxiliary power units on non-road equipment; and use of smart transportation algorithms.

Domestic Heating. Wood stoves and boilers have emerged as a leading target for BC mitigation strategies because they represent a major source of BC emissions in the Arctic. Wood burning also produces emissions of methane and ozone precursors. Although some countries do regulate particle emissions from these stoves and boilers, control measures may not always capture BC emissions. Although planned stove replacement campaigns and particle emissions controls may reduce BC emissions in some areas, without new measures, overall emissions from this sector are projected to remain steady or increase by 2030. New technologies may enable highly effective mitigation measures to improve both health and climate. The following measures offer potential for reductions of BC emissions in the Domestic sector:

- Implementation of stringent BC emission standards or stricter PM standards that maximize BC reductions, regulations, and inspection regimes for stoves and boilers;
- Development of point-of-manufacture certification programs for stoves and boilers meeting emissions and performance standards;
- Voluntary old stove/boiler change-out programs and incentives for newer models that emit less BC;
- Increased combustion efficiency;
- Boiler retrofits, for example, with accumulator tanks; and
- Operator education campaigns (best fuels and burning techniques).

Open Biomass Burning. All forms of open biomass burning release much larger amounts of OC compared to BC. Therefore, the contribution of these emissions to global warming may be unclear; however, the work of AMAP suggests that, because of the reflective Arctic surface, emission reductions of BC and OC from open biomass burning near or within the Arctic are likely to help slow Arctic warming. Controlled burning may be necessary, such as when fire plays a critical and natural ecological role. Options for reducing BC from agricultural burning, prescribed forest burning, and wildfires include the following:

- Technical assistance (seminars, exchanges) and micro-financing assistance to foresters and farmers to encourage the use of no-burn methods, such as either conservation tillage or soil incorporation;
- Demonstration projects and exchange of information to show the efficacy of no-burn methods, both bilaterally and as exchanges between national and sub-national governments of Arctic Council countries or organizations, and through joint Arctic Council projects;
- Development of fire management programs and strategies aimed at preventing accidental wildfires and avoiding unnecessary application of fire in land management (information campaigns aimed at decreasing such fires may represent a relatively low-cost way to decrease BC emissions);
- For controlled burns, where necessary in forestry or agriculture, use of more efficient and controlled burning techniques or measures to control the timing of burns, and mechanical removal of material before the burn for possible use in energy or biochar production; and
- Expansion of resources for fire monitoring, fire management decision support, and fire response.

Marine Shipping. The Arctic Council countries comprise 90% of current shipping activities in the region; therefore, they have a unique ability to influence the development of future BC emissions from this sector by enacting early voluntary measures and engaging in international regulatory regimes, such as the International Maritime Organization (IMO), including

- Voluntary measures by all eight Arctic Council countries to decrease BC emissions, and encouragement of vessels (especially cruise ships) flagged in non-Arctic Council countries and operating in the Arctic to adopt these measures;
- Support by all eight Arctic countries of the current IMO submission on BC by Norway, Sweden, and the United States, which raised the importance of BC emissions from shipping on the Arctic climate and identified a range of technical and operational measures (e.g., speed reduction, improved engine tuning, energy efficiency enhancements, better fuel injection, use of diesel particulate filters);
- Adoption by all eight Arctic Council countries of the proposed amendment of MARPOL Annex VI to establish an Energy Efficiency Design Index for new ships; and
- Ongoing provision of new scientific and technical developments to the IMO by AMAP and other Arctic Council working groups, and vice versa.

Gas Flaring. The significance of BC emissions from gas flaring remains highly uncertain, but is a source of potential concern in the High Arctic, especially as oil and gas activities expand. More effective methods to quantify BC emissions from flaring are currently being developed through, for example, a Canadian research effort involving Carleton University and Natural Resources Canada, and efforts by Norway to engage the oil and gas private sector. Resources should be made available to support such efforts. Oil and gas activities also constitute a very large Arctic source of methane emissions, and such studies could determine methane emissions and leakage in parallel to work on BC:

- Implementing leak-reduction activities, such as replacing high-bleed pneumatic devices and conducing enhanced inspection and maintenance programs;
- Funding immediate work on in-field measurements and scientific and technical analysis, in concert with the private sector, aimed at filling current information gaps;
- Obtaining better BC emissions data, as well as location and other basic information on gas flaring practices;
- Providing information on best practices and regulatory options from the energy industry where there has been progress in reducing flaring (e.g., Canadian provinces such as Alberta); and
- Ensuring coordination with other international efforts addressing venting and flaring, such as the Global Gas Flaring Reduction Partnership and Global Methane Initiative.

Additional measurements, research, and analyses are needed to better identify the specific BC mitigation measures—both inside and outside of the Arctic Council nations—that will lead to the largest Arctic climate benefits.

For BC measures, key areas where knowledge can be improved include the costs of implementing certain measures, the additional emission-reduction potential of some measures, potential Arctic climate benefits, and potential health benefits. Improved understanding of the role that BC and OC emissions from non-Arctic Council nations play in Arctic climate change, and thus in potential mitigation efforts to address Arctic climate change is also important.

Section 1

Introduction

The Arctic Council Ministerial Tromsø Declaration of April 2009 noted the role that short-lived climate forcers (SLCFs) such as black carbon (BC), methane, and tropospheric ozone may play in Arctic climate change and recognized that reductions of emissions of these compounds and their precursors have the potential to slow the rate of Arctic snow, sea ice, and sheet ice melting in the near term. That same Declaration established the Arctic Council Task Force on Short-Lived Climate Forcers (henceforth referred to as the Task Force) to identify existing and new mitigation measures to reduce emissions of these SLCFs, to recommend further immediate actions that can be taken, and to report on progress at the 2011 Arctic Council Ministerial meeting.

The Task Force has developed two products to fulfil its mandate: a Progress Report and Recommendations for (Arctic Council) Ministers, and this underlying technical report. This technical report compiles and compares BC emissions inventories submitted by Arctic Council nations (i.e., Canada, Denmark [including Greenland and the Faroe Islands], Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States of America), as well as global emissions inventories estimated by outside research organizations. Existing regulations, policies, and programs for emission control within the Arctic Council nations and potential future mitigation measures are also presented. Consistent with the mandate of the Task Force, this report does not produce new scientific findings regarding the role of BC in Arctic climate change or the direct health effects from reducing BC emissions; however, it does provide brief summaries of the state of knowledge on these topics and uses this information for important messaging and context setting regarding BC mitigation measures.

The term SLCFs is often used to describe a subset of greenhouse gases (GHGs) and aerosols that alter Earth’s energy balance by absorbing or reflecting radiation. SLCFs remain in the atmosphere for much shorter time periods compared to other, long-lived greenhouse gases (GHGs), such as carbon dioxide (CO_2).[3] SLCFs include particulate aerosols such as BC, methane, ozone, nitrates, and sulphates. Depending on their composition, SLCFs can exert either a cooling or warming effect on the climate. Sulphates, nitrates, and organic carbon (OC) scatter and reflect incoming solar radiation, producing a cooling effect. BC, ozone, and methane exert a warming effect on the climate. Black carbon absorbs both incoming and outgoing solar radiation and darkens snow and ice after deposition, reducing the surface’s albedo, or reflectivity, particularly in the Arctic.

Although CO_2 emissions are the dominant factor contributing to observed and projected rates of Arctic climate change, addressing SLCFs offers unique opportunities to slow Arctic warming in the near term. There has been increased interest in the role that these SLCFs play in climate change, particularly in how emission reductions of the SLCFs may contribute to climate protection. Given the high rates of warming and snow and ice melt being observed in the Arctic region, the idea that reducing emissions of SLCFs

---

[3] In order to be classified as “long-lived,” gases require an atmospheric lifetime of at least 1 year, but can remain in the atmosphere for decades to hundreds of years. Methane has an atmospheric lifetime of roughly a decade, which allows it to become globally well mixed. However, although most other GHGs have much longer atmospheric lifetimes, which is why methane can also be referred to as “short-lived.”

may help slow Arctic climate change over the next few decades has gained particular traction within the Arctic Council.[4]

This technical report is being utilized to inform and support the key findings and recommendations of the Task Force that are being delivered to the Senior Arctic Officials.[5] This technical report represents the collective efforts of the Task Force participants, including both national representatives from the Arctic Council nations and subject matter experts who were invited to participate by the Task Force co-chairs (see the Acknowledgements section of this report for a list of names of the authors and contributors).

The primary emphasis of this technical report is placed on BC emissions, as the Task Force decided that, among the SLCFs, BC represents the area where additional technical work is most needed to improve our understanding of SLCF emissions in order to make well-informed recommendations regarding the emissions inventories and mitigation priorities. BC, or sometimes commonly referred to as “soot,” is the shortest-lived of the warming pollutants and is composed of small, dark particles that remain in the atmosphere for only days to weeks after incomplete combustion of fossil fuels or biomass. BC constitutes a fraction of particulate matter (PM) and is defined as the light-absorbing part of PM. The focus of this report on BC does not represent a judgment by the Task Force that BC is the most important of the SLCFs in terms of Arctic climate change. In some limited cases, this report provides information on methane and other GHGs for background and context.

The goals of this technical report are to (1) identify the key sources of BC emissions among the Arctic Council nations by utilizing both the national emissions inventories submitted by the nations and the global or regional research inventories published in the literature; (2) catalogue the existing policies, regulations, and programs that are relevant in terms of their known or potential effect to reduce BC emissions; (3) characterize the expected BC emissions trends over the next 10 to 20 years among Arctic Council nations in light of existing and forthcoming air quality policies or other key emission drivers; and (4) identify existing and new measures to reduce emissions of BC, including, where feasible, the costs and implementation feasibility factors associated with these mitigation options.

The remainder of this report is structured as follows:

- ***Section 2*** provides a brief context about climate change and health science relevant for BC emissions that may affect the Arctic. Given the mandate of the Task Force to focus on mitigation actions, this section of the report summarizes key findings from the existing literature rather than presents new analyses. More detailed information regarding the role of BC in Arctic climate change is provided in the technical report from the Arctic Monitoring and Assessment Programme (AMAP) Expert Group on

---

[4] The Arctic Council is a high-level intergovernmental forum to provide a means for promoting cooperation, coordination, and interaction among the Arctic nations, with the involvement of the Arctic indigenous communities and other Arctic inhabitants on common Arctic issues, in particular issues of sustainable development and environmental protection in the Arctic. The nations of the Arctic Council are Canada, Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States of America.

[5] Arctic Council Task Force on Short-Lived Climate Forcers Progress Report and Recommendations for Ministers.

Short-Lived Climate Forcers (AMAP, 2011), which emphasizes these new results generated from AMAP's efforts.

- ***Section 3*** provides detailed estimates of current BC and OC emissions at the global scale, for the Arctic Council nations as a whole, and for individual Arctic Council nations based on emissions inventories provided by two research organizations and by the individual Arctic Council nations. The two research emissions inventories referenced in this report are the Bond emissions inventory (Bond, 2009) and the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS) emissions inventory (Amman et al., 2010). This report aggregates the national emissions estimates into seven major sectors to facilitate comparison among the emissions estimates of the Arctic Council nations and the independent research emissions inventories.
- ***Section 4*** provides estimates of projected future trends in BC and OC emissions based on current regulations, policies, and programs for the combined Arctic Council nations, as well as for the individual Arctic Council nations. The timeframe of future projections typically extends to the year 2030.
- ***Section 5*** provides a catalogue of relevant regulations, policies, and programs that are currently in place within the Arctic Council nations that are known to have an effect on current BC emissions and/or a potential effect on future BC emission trends. The primary focus of this section is air quality policy that targets PM emissions or ambient concentrations. These policies also will indirectly target BC and OC emissions since they are fractions of PM.
- ***Section 6*** discusses a broad range of mitigation measures that are either already proven to reduce BC emissions or offer future potential to reduce BC emissions. This section discusses the mitigation opportunities in each of the key source categories across the Arctic Council nations, including residential heating, transportation (both on- and off-road), marine shipping, energy and industrial production, open biomass burning, and gas flaring. The feasibility of implementation and cost information for the potential mitigation measures is provided where available.

Section 2

Climate Change and Health Effects: Setting the Context

Introduction

This section provides a brief context about climate change and health science relevant for BC emissions that may affect the Arctic. Given the mandate of the Task Force to focus on mitigation actions, this section of the report summarizes key findings from the existing literature rather than presenting new analyses. More detailed information specific to the climate change impacts of BC on the Arctic can be found in the AMAP Report *The Impact of Black Carbon on Arctic Climate* (AMAP, 2011).

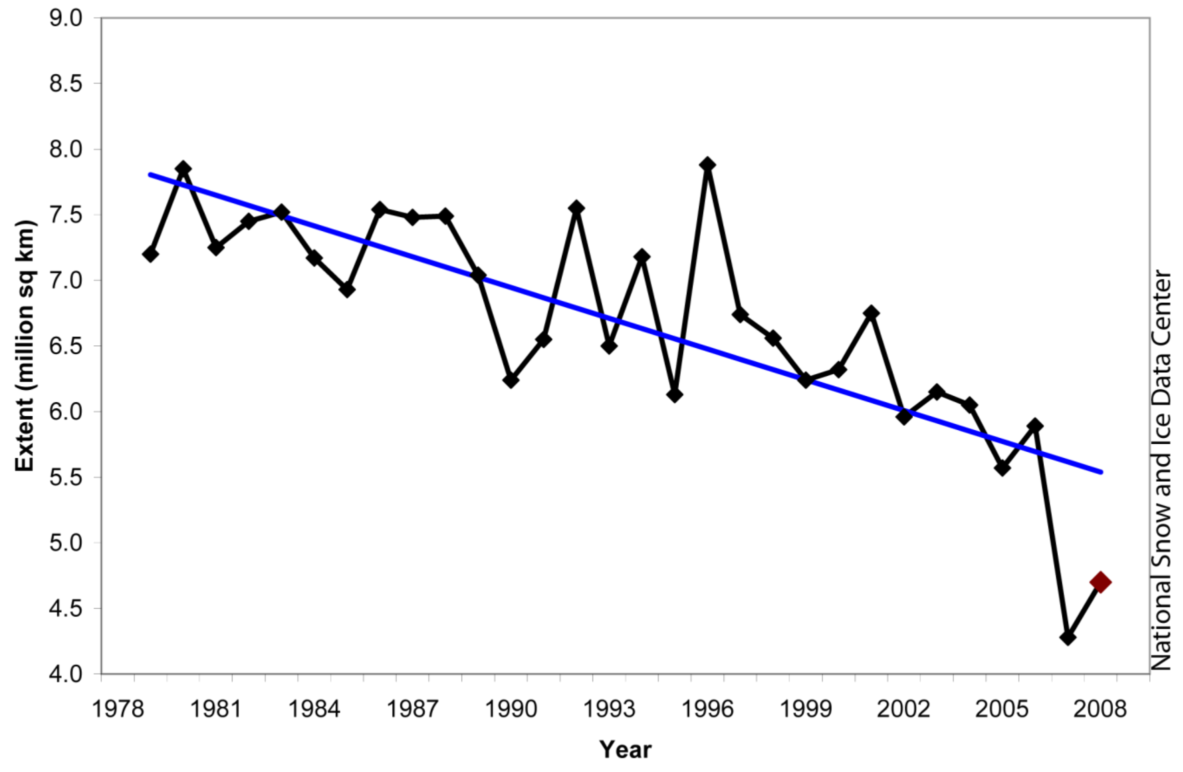
2.1 Climate Change in the Arctic

The temperature in the Arctic region has warmed at twice the global rate over the past 100 years (IPCC, 2007). Annual mean temperatures in virtually all parts of the Arctic increased between 1966 and 2003, with trends exceeding 1 to 2 ºC per decade in northern Eurasia and north-western North America (ACIA, 2004). This warming has been accompanied by an earlier onset of spring ice melt, a lengthening of the melt season, and increasing discharge from the Greenland ice sheet. Summer sea ice extent has decreased by 40% since modern satellite observations began in 1979,[6] and in 2007, it dropped to its lowest level, resulting in the first recorded complete opening of the Northwest Passage (NSIDC, 2007; Perovich et al., 2008) (see **Figure 2-1**). Some climate models have predicted the complete disappearance of summer sea ice as early as 2040 (Perovich and Richter-Menge, 2009; Polyak et al., 2009; Wang and Overland, 2009). **Figure 2-2** (Stroeve et al., 2007) shows that observed sea ice loss has been faster than predicted by any of the modelling scenarios in the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report (AR4)* (IPCC, 2007). Despite strong uncertainties between the models, there is a qualitative agreement between observations and models regarding an overall decline in September sea ice extent in the Arctic (Stroeve et al., 2007).

---

[6] Modern satellite observations of Arctic sea ice and surface temperatures span from 1979 to 2006. Earlier estimates (spanning from 1953 to 1979) are based on a combination of satellite observations and aircraft and ship reports (Stroeve et al., 2007).

Figure 2-1. Average monthly Arctic sea ice extent, September 1979 to 2010 (NSIDC, 2008)



The impacts of ice loss include reduction of the Earth's albedo, or the extent to which the Earth's surface reflects the sun's radiation. Albedo is a dimensionless ratio of reflected radiation from the surface to incident radiation upon it. As global warming causes greater amounts of snow to melt, bare sea ice and eventually dark ocean water are exposed, which absorb more radiation. This positive snow albedo feedback leads to further warming and is one of the reasons that the Arctic is highly sensitive to global warming. The earlier onset of spring melt observed in recent years is of particular concern because this is the season of maximum snow albedo feedback (Hall and Qu, 2006).

Increases in Arctic temperatures will lead to changes in Arctic flora and fauna, including the sea-ice biomes and predators higher in the food chain. These shifts will require changes in the lifestyle of indigenous peoples and may be devastating for polar bears, seals, and other marine mammals dependent on the sea ice, as well as the people who depend on these animals for food (Quinn et al., 2008). Arctic warming and associated impacts also have implications beyond the Arctic, as melting of Arctic land-based glaciers is one of the factors contributing to global sea-level rise (ACIA, 2004).

Arctic warming is primarily a manifestation of global warming, and the most important long-term driver of Arctic climate change is the atmospheric build up of long-lived GHGs such as CO_2. Long-lived GHGs generally refer to gases that remain in the atmosphere long enough to become well-mixed throughout the entire global atmosphere. However, because of the long atmospheric lifetime of CO_2, even large and swift reductions in emissions may not achieve the reductions in atmospheric concentrations needed to delay rapid, and perhaps irreversible, climate change and associated sea-ice loss in the Arctic.

CO_2 is not the only climatically important species contributing to warming in the Arctic. Several shorter-lived pollutants (i.e., SLCFs), including BC, methane, and tropospheric ozone, may be collectively responsible for as much temperature impact in the Arctic as CO_2 (Quinn et al., 2008). SLCFs are emitted both within and outside the Arctic region and do not need to be deposited within the Arctic region boundaries in order for climate impacts to be observed. Addressing emissions of SLCFs, such as BC, has the advantage that emissions reductions will be felt much more quickly than reductions of long-lived GHGs.

2.1.1 The Role of Black Carbon in Arctic Climate Change

Black carbon warms the Arctic in several ways. First, as an aerosol, it absorbs incoming solar radiation, heating the atmosphere and contributing to overall global and Arctic warming. Second, the deposition of BC onto Arctic ice and snow darkens the surface, increasing the absorption of radiation (Flanner et al., 2007; Warren and Wiscombe, 1980). This BC snow albedo effect intensifies warming of the lower atmosphere and the melting of snow and ice.

According to Quinn and colleagues (2008), once BC has been deposited on glaciers, it has lasting impacts. BC deposited directly on glacier ice tends to remain for years before being removed by surface run-off processes. In addition, BC entrained in snow accumulation on large glaciers and ice caps is gradually buried and transported downward via ice flow, eventually transporting the BC out of the melt zone, where it is re-exposed to solar radiation.

BC influences the climate through multiple mechanisms, both directly and indirectly. The best understood mechanism is radiative forcing, which is the change in energy balance between incoming solar radiation and exiting infrared radiation, typically measured in Watts per square meter (Wm^{-2}), over a specific time period. Positive radiative forcing leads to climate warming, while negative radiative forcing leads to climate cooling. The net radiative forcing for BC is the sum of several types of forcing, each briefly described below:

- **Direct Radiative Forcing –** In direct radiative forcing, BC absorbs both incoming and reflected solar radiation. The direct radiative forcing of BC appears to be significant both globally and regionally, although there remains uncertainty in the estimates of the radiative forcing that is caused by BC. In 2007, Forster and colleagues estimated that BC is responsible for 0.34 (± 0.25) Wm^{-2} of globally averaged direct radiative forcing, third to CO_2 and methane (Forster et al., 2007). Other studies have reported higher values globally for direct radiative forcing (Chung and Seinfeld, 2005; Ramanathan, 2010; Bond et al., 2011) and in the Arctic (Quinn et al., 2008). The IPCC (2007) estimates the radiative forcing for elevated concentrations of CO_2 and methane at $+1.66\ Wm^{-2}$ and $+0.48\ Wm^{-2}$. Methane also contributes to warming through effects on tropospheric ozone and stratospheric water vapour concentrations, and the IPCC estimates that historical emissions of methane have contributed $+0.86\ Wm^{-2}$ when including ozone and water vapour impacts.
- **Snow/Ice Albedo Forcing –** As BC deposits on snow and ice, it directly decreases the surface albedo (reflectivity) and increases the extent to which solar radiation is

absorbed. When the albedo of snow, glacier, and sea ice surfaces decreases, melting occurs, and the darker, underlying surfaces such as tundra and ocean are revealed. These melting, retreating, uncovered surfaces absorb more solar radiation, triggering a positive snow/ice albedo feedback. The BC snow albedo effect is estimated to be responsible for an additional +0.10 (± 0.10) Wm^{-2}, bringing the estimated total direct radiative forcing to +0.44 Wm^{-2} (IPCC, 2007). Other studies have reported smaller values globally for the snow albedo effect (Bond et al. 2011).

- **Forcing Due to Cloud Interactions** – All aerosols, including BC, alter the properties of clouds, affecting cloud reflectivity, precipitation, and surface dimming. The net effect of BC interactions with clouds is uncertain, but is thought to be warming when over snow and ice.

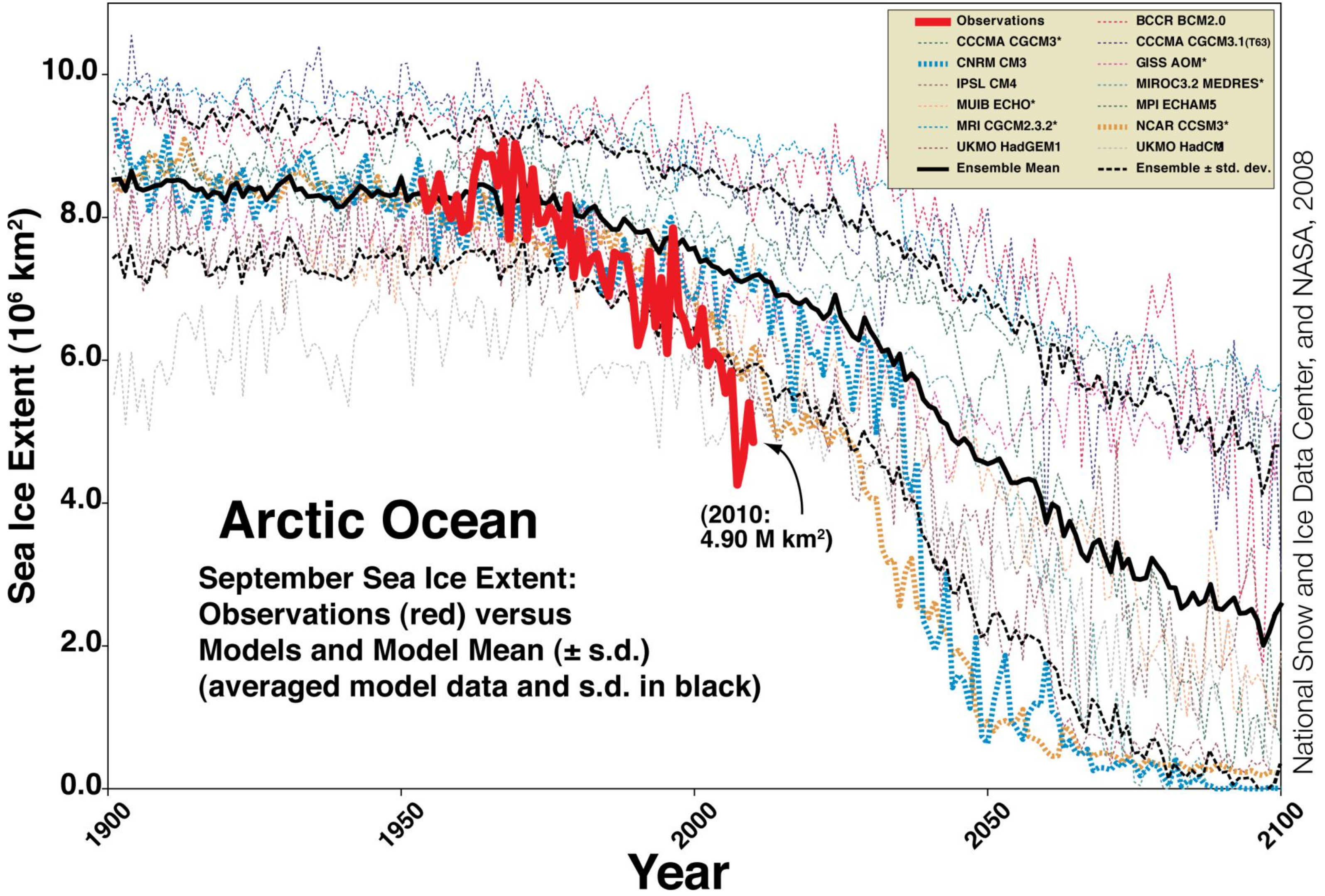
BC and OC have been identified as having potentially significant impacts on climate change, particularly at regional scales. BC emitted both within and outside of the Arctic region contributes to Arctic warming. Per unit of emissions, sources within Arctic Council nations generally have a greater impact because the relatively short atmospheric life span of BC and the nature of the Arctic front limit transport of emissions from distant sources to the Arctic. Currently, the vast majority of Arctic BC originates from below 60 degrees north (°N), specifically from North America, Europe, the Russian Federation, and Asia. For example, BC emissions from biomass burning (e.g., forest fires) in North America and Siberia may contribute up to 30% of Arctic BC in years of exceptionally strong burning (Flanner et al., 2007). BC also has a longer lifetime in the Arctic, which contributes to Arctic haze (Garrett et al., 2004; Quinn et al., 2007). Pollution is transported from mid-latitudes and mixes with thin clouds, effectively trapping the pollution and heat more easily. The global transport of BC is discussed further in ***Section 3.1*** of this report.

Sources of BC emit a complex mixture of substances, including OC, sulphur dioxide (SO_2), and nitrogen oxides (NO_x). Although BC is thought to have both a direct warming effect by absorbing both incoming and reflected solar radiation in the atmosphere, and an additional warming effect by reducing the albedo of snow and ice, OC is generally thought to have a direct cooling effect by reflecting or scattering incoming solar radiation. BC warms much more than OC cools per ton of emissions (Lesins et al., 2002; Saathoff et al., 2003). Some sources emit much more OC than BC, and other co-emitted aerosols (nitrates and sulphates) also have cooling effects such that whether an emissions source is net warming or cooling can depend on the specific mix of emissions. However, the potential for offsetting cooling effects is weaker in the Arctic for two reasons: (1) cooling from non-black aerosols (e.g., OC) is weaker, and (2) warming from BC is stronger. The same substances that might cool the climate in other regions (such as OC) may cause warming over highly reflective surfaces in the Arctic because these substances are still darker than sea ice and snow. Thus, the warming impacts of BC and OC are magnified when they physically deposit on snow or ice in the Arctic and cause additional melting.

The magnitude of the forcing and temperature response of SLCFs is seasonally dependent, with studies suggesting that transport to the Arctic is greatest during the spring and summer, which is also the season in which the efficacy of BC is largest (Shindell et al., 2008). Magnitude and forcing effects are controlled by interactions between the seasonal timing of transport, available solar radiation, snow/ice melt, and deposition, as presented in **Table 2-1** (Quinn et al., 2008). Pollutants from the mid-latitudes are transported to the Arctic most efficiently during winter and early spring, when the amount of sunlight is at its lowest. Black carbon concentrations are elevated in the Arctic during the winter and spring due to the transport of Arctic haze. Warming occurs above and below the Arctic haze layer as BC absorbs radiation. The warming effects of BC are at a maximum during the spring and summer, when the snow/ice albedo feedback maximizes.

As stated above, the contribution to warming from BC emission sources is made even more complex due to the existence of less well-understood effects involving the interaction of BC and the reflective aerosols with clouds and issues involving how BC "ages" in the atmosphere as BC particles mix with other substances, thereby causing the absorption characteristics to undergo further change. These co-emissions and indirect effects lead to questions about whether the net effect of a given BC source is warming or cooling on globally and regionally averaged scales.

Figure 2-2. Arctic September sea ice extent (10^6 km^2) from observations (thick red line) and 13 IPCC AR4 climate models, together with the multi-model ensemble mean (solid black line) and +/- standard deviation (dotted black line). (Stroeve et al., 2007)



National Snow and Ice Data Center, and NASA, 2008

Table 2-1. Seasonal impacts of solar radiation, sources, and transport in the Arctic

Winter/Early Spring	Spring	Late Spring/Summer
• Solar radiation is limited so that the radiation balance is driven primarily by thermal fluxes • Transport of pollutants from the mid-latitudes is most efficient (Arctic haze) • There is build-up of ozone and aerosol precursors	• Solar radiation becomes available for photochemical production of ozone and aerosols • Transport of pollutants from mid-latitudes is still efficient (Arctic haze) • Open biomass burning is prevalent in lower latitudes	• Solar radiation is at a maximum • Surface melt begins • Snow albedo feedback maximizes • There are more powerful greenhouse effects due to warmer temperatures • Boreal forest fire season is at a maximum

Source: Quinn et al., 2008

2.1.2 Recent AMAP Analyses

The AMAP has recently investigated the impacts of BC on Arctic radiative forcing, and their conclusions are presented in the text box on the following page. The AMAP model-based assessment determined the sources of BC that yield a positive radiative forcing in the Arctic. However, a full climate model, which was beyond the scope of this study, is required to determine the resulting temperature response (AMAP, 2011). The radiative forcing by methane and ozone was not assessed. Thus, the conclusions presented in the text box represent a partial perspective on the influence of SLCFs on the Arctic climate.

Comparisons of modelled BC concentrations with BC measurements in the Arctic reveal that almost all models still have considerable problems capturing the Arctic BC concentrations, both at the surface and aloft, despite recent model improvements. The two models used in the AMAP (2011) assessment are no exception. Therefore, radiative forcing calculations based on these models are highly uncertain. The conclusions presented in the text box are guided by the model results, but are also based on the available literature and the AMAP expert groups' subjective expert opinion of relevant processes.

Summary Findings on Impacts of BC on the Arctic Climate and Relevance to Mitigation Actions (AMAP, 2011)

- Reductions in the emissions of CO_2 are the backbone of any meaningful effort to mitigate climate change. The limited focus of this assessment on BC is not meant to distract from primary efforts on CO_2 reductions or mislead mitigation action toward a sole focus on BC.
- BC deposited to Arctic snow and ice results in a positive radiative forcing.
- BC deposited to Arctic snow and ice exerts a greater warming than the within-Arctic direct atmospheric radiative forcing.
- Climate models indicate that *global direct atmospheric forcing* due to BC leads to Arctic warming. Direct atmospheric forcing by BC that has been transported into the Arctic at high altitudes may have a relatively small impact on Arctic surface temperatures since warming at high altitudes reduces atmospheric energy transport into the Arctic. The positive forcing due to within-Arctic BC sources is more likely to cause surface warming because of solar heating near the surface and greater likelihood of BC deposition to snow and ice surfaces.
- Arctic climate is strongly coupled with Northern Hemisphere climate and thus sensitive also to extra Arctic radiative forcings.
- The global forcing due to BC results in pole-ward transfer of heat energy, indicating that global strategies to manage emissions must remain a priority to ameliorate Arctic climate change.
- OC species that are co-emitted with BC and that reach the Arctic are unlikely to compensate for the positive radiative forcing due to BC and, over snow- and ice-covered surfaces, may themselves exert a positive forcing within the Arctic.
- Highly scattering sulphate aerosol exerts a weakly negative forcing over snow. As fresh snow melts over the summer and the surface albedo decreases, sulphate aerosol forcing becomes more negative.
- Carbonaceous aerosol (BC and OC) emitted near or within the Arctic will have the greatest impact on Arctic climate. Emissions in close proximity to or within the Arctic are more likely to cause surface warming and to be deposited to snow/ice surfaces than emissions further south.
- The BC snow/ice *radiative forcing per unit of BC emitted* is larger for the Arctic Council nations or high latitude regions (> 40 °N) of Arctic Council nations than for the rest of the world. As a result, the Nordic countries are associated with the largest *forcing per unit of BC emission* due to emissions occurring at the highest latitudes.
- Within-Arctic BC sources (e.g., shipping, flaring) have a large impact on low altitude BC concentrations and BC deposition in the Arctic and, thus, likely have a large forcing *per unit emission.*
- Forest, grassland, and agricultural fires are the source types in Canada and Russia that dominate BC+OC radiative forcing in the Arctic. Fossil fuel combustion (e.g., diesel engines) is the dominant source in the United States, Nordic countries, and the rest of the world. Forest, grassland, and agricultural fires from Arctic Council nations dominate the within-Arctic forcing *per unit of emission*.
- Domestic (e.g., wood stove) sources within the Nordic countries and Russia have a substantial influence on within-Arctic forcing. Their relative importance is likely to increase following implementation of regulative measures on transport emissions.
- Both the sign and magnitude of aerosol indirect forcing in the Arctic are uncertain. Globally, the indirect and semi-direct effects are negative and lead to a cooling effect. For the Arctic, however, current studies indicate that the net aerosol indirect and semi-direct effects lead to smaller negative forcing than on the global average, or may even cause positive forcing.
- As snow and ice disappear from the Arctic, it is possible there will be a regime change shifting the relative influence of atmospheric forcing and snow/ice forcing such that, overall, forcing due to BC and co-emitted OC becomes more negative and less warming.
- Currently, there is no single appropriate environmental indicator to assess the Arctic climate response to changes in BC and OC emissions that are transported to Arctic regions. Hence, an integrated evaluation using observations, reported emissions, and models is required.

2.1.3 The Potential Role of Methane and Tropospheric Ozone in Arctic Climate Change

The climate effects of methane are much better understood than the climatic effects associated with BC (Forster et al., 2007). Though methane has been described as a SLCF by the Arctic Council Tromsø Declaration and others in the climate-change community, it remains in the atmosphere for roughly a decade, long enough to become globally well-mixed throughout the atmosphere. This means that, unlike the case for BC, the geographic location of methane emissions (and likewise the location of any methane mitigation measure) will not be as important for either the global or Arctic climate. Methane is included under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol as one of the six main GHGs. The IPCC in 2007 estimated that changes in methane concentrations are responsible for $+0.48 \pm 0.05\ \mathrm{Wm}^{-2}$ of global radiative forcing, second highest only to CO_2 (Forster et al., 2007).

Historical methane emissions have contributed to increasing tropospheric ozone and stratospheric water vapour concentrations, both warming influences. Ozone is not directly emitted, but is produced in the lower atmosphere from emissions of precursors, including carbon monoxide, methane, non-methane hydrocarbons, and NO_x, through chemical reactions with sunlight. Tropospheric ozone is estimated to be responsible for $+0.35$ (0.2 to 0.65) Wm^{-2} of global radiative forcing (Forster et al., 2007; IPCC, 2007).

The remainder of this report focuses almost exclusively on BC, for reasons stated previously, despite the importance of these other key SLCFs. The effectiveness of BC as a warming agent varies with respect to the emissions source type, region, transport pathway, and deposition location. In order to develop effective mitigation strategies, it is important to determine the relative importance of emissions from different source regions.

2.2 Brief Overview of Global Health Effects Related to SLCFs

In addition to climatic benefits, measures aimed at decreasing SLCF emissions in the Arctic region are expected to have positive health benefits. BC is a component of fine particulate matter (i.e., $PM_{2.5}$), and a large body of scientific evidence links exposures to fine particles to an array of adverse respiratory and cardiovascular health effects, including heart attacks; chronic respiratory disease; hospital admissions and emergency room visits for respiratory and cardiovascular diseases; and premature mortality (U.S. EPA, 2009). Recent evidence provides greater understanding of the underlying mechanisms for cardiovascular and respiratory effects for both short- and long-term exposures to $PM_{2.5}$. Methane contributes to background concentrations of tropospheric ozone, an air pollutant associated with respiratory symptoms and premature mortality.

Over the past decade, the scientific community has focused increasingly on trying to identify the health impacts of particular $PM_{2.5}$ constituents. The growing body of evidence for the health impacts of specific $PM_{2.5}$ constituents includes evidence of effects associated with BC. However, in general, the evidence from studies looking at the health effects of specific $PM_{2.5}$ constituents is not yet sufficient to establish consistent or robust patterns that would allow differentiation of those constituents or sources that are more closely related to specific health outcomes (U.S. EPA, 2009). Studies that have considered BC specifically have found that the effects observed are similar to those observed for $PM_{2.5}$ and other PM constituents, and thus, are not attributable solely to BC.

There is a small but emerging body of literature assessing the health benefits of global $PM_{2.5}$ and methane emission reductions. Many of these studies estimate the avoided premature mortalities associated with reductions in BC and other constituents, while other studies attempt to compare the costs and benefits of potential mitigation strategies. These studies indicate that a large number of premature deaths can be avoided annually by undertaking strategies to reduce BC emissions (Anenberg et al., 2011; Saikawa et al., 2009; Wilkinson, 2009). Global decreases in tropospheric ozone as a result of methane mitigation measures also result in substantial and widespread decreases in premature human mortality. West and colleagues (2006) found that using available technologies to reduce 20% of current global anthropogenic methane emissions will prevent approximately 30,000 premature mortalities in 2030 (approximately 0.04% of total projected mortalities), and approximately 370,000 mortalities from 2010 to 2030. Those studies that include a benefit-cost comparison show that estimated human health benefits significantly exceed the estimated costs for certain BC and methane mitigation strategies (Smith et al., 2008; Baron et al., 2009; Kandlikar et al., 2009).

The United Nations Environment Programme (UNEP) is currently conducting work on an integrated assessment on BC and tropospheric ozone mitigation. The assessment specifically addresses premature deaths caused by $PM_{2.5}$ from related heart disease and lung cancer, and those deaths caused by respiratory illness from ozone. Preliminary results show that without implementation of additional measures, premature deaths from ambient $PM_{2.5}$ and ozone concentrations in 2030 would vary regionally. Implementation of existing and proposed legislation is projected to lead to decreases of premature deaths in North America and Europe, but expected emissions growth in South, West, and Central Asia is expected to coincide with increases in premature deaths (UNEP, 2011).

Section 3

Current Black Carbon and Organic Carbon Emissions

Introduction

This section provides estimates of BC and OC emissions available for the most recent years. These estimates cover global emissions, Arctic Council–wide emissions, individual Arctic Council nation emissions, and emissions broken out by the seven sectors used in this report. The global and Arctic Council–wide emissions estimates are from two independent international BC and OC emissions inventories that are widely used and referred to in the research community—Bond (2009) and GAINS (Amann et al., submitted; Kupianien and Klimont, 2007). These international inventories also are used for the national emissions estimates in this section, in addition to the national emissions inventories developed and submitted by the Arctic Council nations. The methodology and emission factors used in the development of each national inventory vary, usually resulting in a range of estimated emissions for a given country and sector. Despite these variations, all of the inventories provide insights into the relative magnitude of the current BC and OC emissions from different nations and sectors, as well as where there may be a good or poor characterization of an emission source.

3.1 Arctic Region Emissions in the Global Context

This report concentrates on those emissions originating within the Arctic Council nations and territories; however, the Arctic region is also impacted by BC emitted from outside the Arctic region boundaries. Understanding how pollutants are transported is important for determining which global regions contribute the most to Arctic warming. While some BC is produced in the Arctic region (e.g., by ships travelling through the region), most is transported to the region from outside source locations. Therefore, it is important to discuss the role of global BC emissions.

Globally, Bond (2009) estimates that BC emissions are on the order of 8,000 gigagrams[7] per year (Gg/yr), or about 10 times the total BC emissions in the Arctic region, though there is considerable uncertainty surrounding that estimate. In addition, not all global emissions have an equal impact in the Arctic; emissions originating from regions distant from the Arctic will have much smaller effects on the Arctic climate (per unit emissions) than those emissions originating within or near the Arctic Circle (AMAP, 2011). Therefore, analysis of the impact of non-Arctic Council emissions must consider the source location of these emissions.

The Arctic region boundary is defined for the purposes of this work as spanning between 60 degrees north (°N) and 90 °N. A closed dome, referred to as the Arctic front, isolates the Arctic from the rest of the atmosphere (Quinn et al., 2008). During the summer, the Arctic front is confined to a smaller, higher latitude region, but can extend to as far south as 40 °N. Globally, the 40th parallel north (40 °N) passes through Europe, the United States (New York City), and Asia. This latitude (40 °N) is commonly used as an approximate latitude below which BC emissions are considered to have less potential of being transported to the Arctic region. In general, emissions originating from regions further from the Arctic will have smaller effects on radiative forcing and BC deposition on Arctic snow and ice (per unit emissions) than emissions originating nearer to or within the Arctic Circle (AMAP, 2011); thus, emissions from regions north

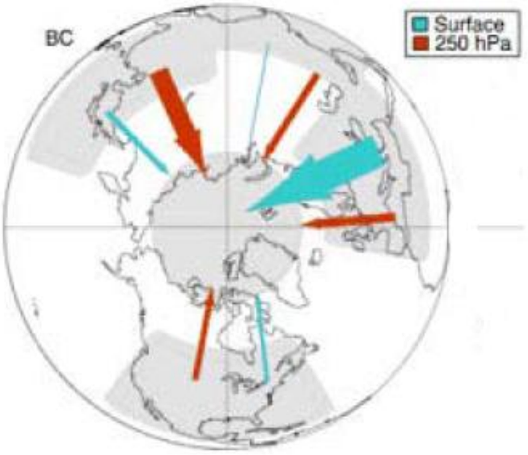
---

[7] 1 gigagram (Gg) = 1,000 metric tons

of 40 °N latitude are of particular concern in understanding the impacts of SLCFs, specifically BC, on the Arctic climate.

The AMAP (2011) report concluded that emissions south of this latitude have less impact per unit emissions than emissions between 40 and 50 °N, which have less impact than emissions between 50 and 60 °N, and so forth. Global transport has been studied both by modelling work (Stohl, 2006; Shindell et al., 2008; Rypdal et al., 2009) and by experimental work (McConnell et al., 2007). Stohl (2006) found that BC emissions from North America and Europe frequently make their way to the Arctic via high-altitude transport pathways. Greenland is more sensitive to deposition of BC from North America than the rest of the Arctic due to its high topography, which allows inflow of air from warmer source regions (Stohl, 2006). As shown in **Figure 3-1**, Shindell and colleagues (2008) also found that European sources contributed the largest amount to the annual average abundance of aerosol sulphate and BC at the Arctic surface. Europe was also found to be the largest contributor of sulphate and BC to the surface on a seasonal basis (winter, spring, summer, and fall), and emissions from Southern and Eastern Asia were found to be the largest contributor of BC in the upper troposphere (250 hectopascal [hPa]), which agrees with the Stohl (2006) findings that contributions from South Asian sources increased with altitude while European sources decreased at high altitudes.

Figure 3-1. Relative importance of source regions to annual mean Arctic concentrations at the surface and in the upper troposphere (250 hPa) for BC (Shindell et al., 2008) [8]



Another study, Rypdal and colleagues (2009) used a global aerosol transport model, Oslo CTM2, to calculate the BC radiative forcing in the Arctic due to emissions from 12 different regions and found that the direct radiative forcing of BC and the radiative forcing of BC on snow/ice albedo north of 60 °N is mainly due to emissions from North America, Europe, Russia, and Asia.

Figures 3-2 and 3-3 show global anthropogenic BC emissions by degree latitude for the year 2000 (Lamarque et al., 2010); an alternative presentation showing emissions per unit area would be slightly different as there is less area near the poles. As shown in

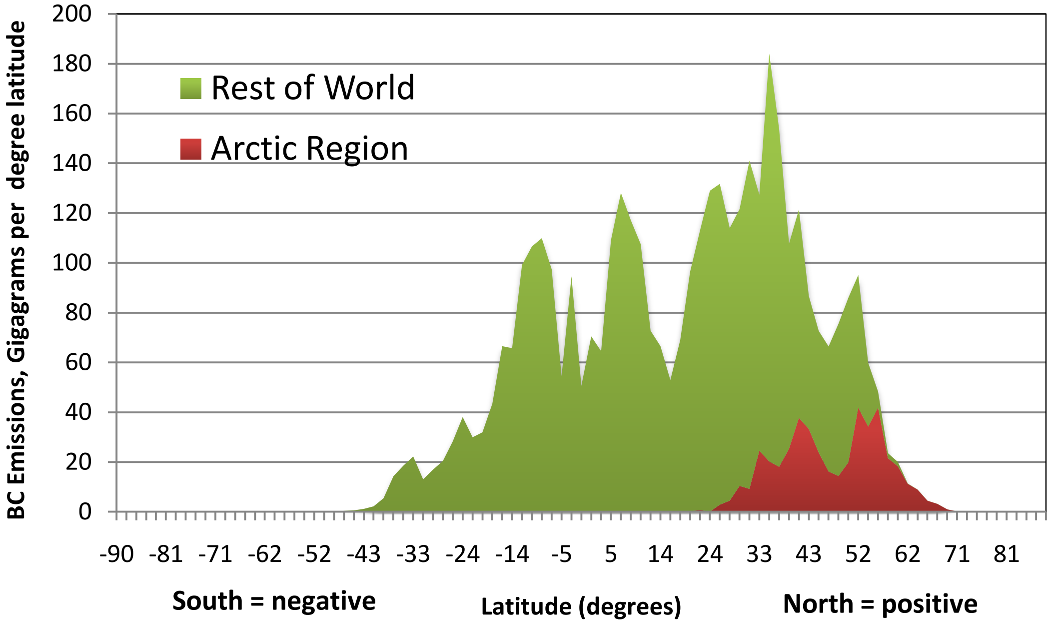
---

[8] Values are calculated from simulations of the response to 20% reduction in anthropogenic emissions of precursors from each region. Arrow width is proportional to the multi-model mean percent contribution from each region to the total from these four source regions (Shindell et al., 2008).

Figure 3-2, while Arctic Council nations contribute only 10% of global BC emissions, they contribute about 40% of the emissions north of 40 °N, almost 60% of emissions north of 50 °N, and almost 99% of emissions north of 60 °N (non-Arctic Council emissions north of this latitude consist mainly of international shipping emissions). BC emissions in the high Arctic (north of 70 °N latitude) are negligible.

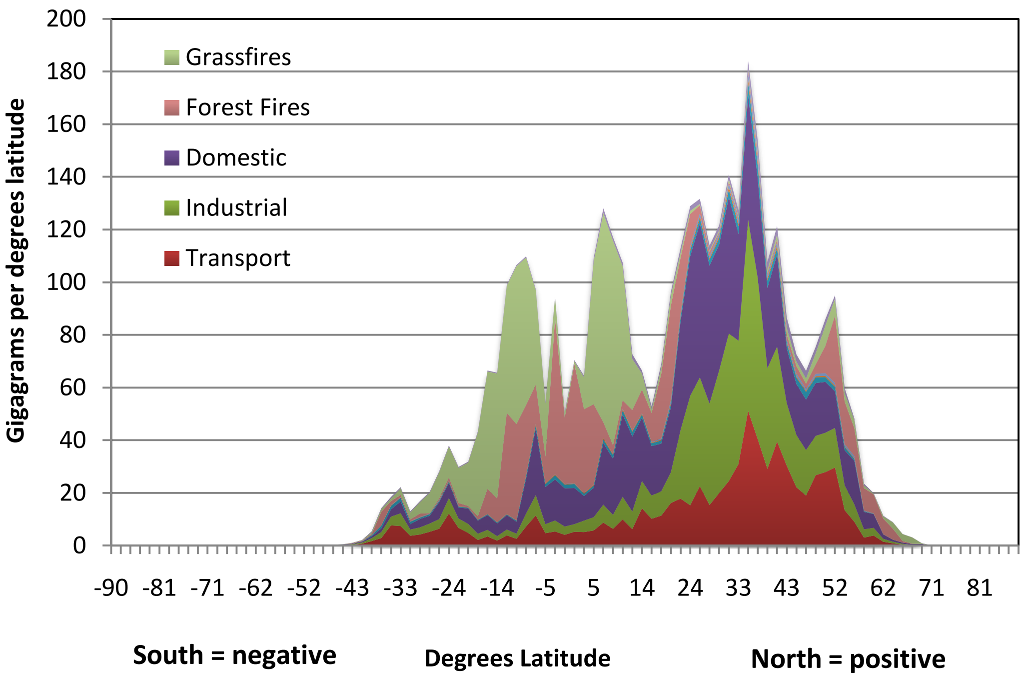
The industrial emissions shown in Figure 3-3 include off-road diesel equipment, and therefore, will be larger than the equivalent category in the national inventories in the remainder of this report, which depending on the Arctic Council nation, may be reported under a different source category, or not at all. For most inventories presented in this report, off-road diesel equipment is grouped within the Transport sector. Figure 3-3 also includes emission sources from other categories, including energy, waste, agricultural waste burning, and shipping; however, these emissions make up less than 1.5% of the total emissions and are considered relatively minor.

Figure 3-2. Global BC emissions by latitude for the Arctic region and the rest of the world (Gg/degree latitude).*



* Emissions estimates are based on Representative Concentration Pathway (RCP) emissions data from Lamarque et al., 2010. The y-axis is in Gigagrams per degree latitude and the x-axis is in degrees latitude.

Figure 3-2. Global BC emissions by source category for 2000 by latitude.*



* Emissions estimates are based on RCP emissions data from Lamarque and colleagues 2010. The y-axis is in Gigagrams per degrees latitude and the x-axis is in degrees latitude. Intentional burning activity is not included in the Lamarque and colleagues data. Industrial emissions include off-road diesel engines such as bulldozers.

Transportation is the largest source of global BC emissions north of the 40 °N, though grassfires and forest fires (open burning), residential burning, and industrial sources all contribute emissions north of 40 °N (see Figure 3-3). The major emissions sources of BC vary significantly across different regions of the world. For example, developing countries within Africa and Asia generate large amounts of BC emissions from cookstoves and wood stoves, high-sulphur diesel fuel, and high-emitting industrial processes such as brick kilns and coke ovens. Europe and North America are also major emitters, predominantly due to transportation.

3.2 Comparing Emission Inventories

The emissions inventories presented in this report all use a “bottom-up” approach to estimate BC and OC emissions. A bottom-up approach first pairs $PM_{2.5}$ emission factors with activity level data for each source category to generate $PM_{2.5}$ emissions estimates. A speciation factor is then applied to estimate the amount of BC (or other constituents) contained in the total mass of the $PM_{2.5}$ emissions. There are thousands of $PM_{2.5}$ source categories, but only a limited set of speciation profiles, so there may be considerable uncertainty associated with some BC emissions estimates. The $PM_{2.5}$ emission factors and the speciation factors can be based on fuel consumption data or actual measured source emissions from emissions testing. Depending on the availability of information, inventories may use a combination of approaches to generate a BC emissions inventory.

The two independent emissions inventories referenced in this report are the Bond emissions inventory (2009) and the GAINS emissions inventory (Amann et al., submitted; Kupianen and Klimont, 2007). These inventories each have the advantage of a consistent methodology when comparing emissions across the Arctic Council nations. However, these inventories may overlook important region- and country-specific information due to the use of default information where actual data are not available. The national inventories provided by the Arctic Council nations generally contain more detailed emissions information for the source sectors, but each tends to employ different estimation methods and source categories, making comparisons among Arctic Council nations and sectors difficult.

Both the Bond and GAINS inventories estimate BC and OC emissions by source category for each of the Arctic Council nations. The Bond emissions estimates build upon a 1996 inventory, where emissions for each fuel/source category combination are calculated as the sum of the contributions of all technologies within that category. The Bond data are estimated for a base year of 2000. The reader is referred to published literature for more details on the methods used and the uncertainties inherent in their methodology (Bond, 2004; Bond, 2007). The GAINS model, developed by IIASA (Amann et al., submitted; see also http:/gains.iiasa.ac.at/), estimates BC and OC emissions based on national-level activity data and country- and region-specific emissions factors for specific control technologies, and estimates mitigation measures that are most likely to provide combined benefits of reducing not only BC emissions, but also tropospheric ozone, OC, and SO_2.

A key difference between the GAINS and Bond inventories is that the emissions estimates from GAINS do not include data on open burning (forest and savannah fires), which is a significant source of both BC and OC globally and for key Arctic Council nations. ***The GAINS inventory also includes marine shipping and emissions from oil and gas flaring, while the Bond inventory does not.*** The GAINS model is apparently the only global inventory that estimates emissions from oil and gas flaring. Flaring emissions are estimated using data from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center and emission factors based on measurements taken by Johnson and colleagues (2011). However, the GAINS data on oil and gas flaring are minimal; therefore, emissions estimates by GAINS are considered preliminary.

In addition to these two international inventories, the Arctic Council nations provided national BC and OC emissions inventories utilizing country-specific data and models. To develop these inventories, the nations applied BC and OC fractions to national-scale $PM_{2.5}$ emission inventories for various country-specific source categories. Five of the eight Arctic Council nations provided emissions inventories for BC and OC; Iceland and the Russian Federation did not provide inventories. Due to the lack of country-specific emission factors, Norway did not provide a BC and OC emissions inventory; however, Norway did provide an inventory for $PM_{2.5}$ emissions.

In order to compare country-by-country emissions among the Arctic Council nations, the national emissions inventory data were aggregated into seven sectors: Domestic; Energy and Industrial Production, Waste; Transport; Agricultural; Open Biomass Burning; Flaring; and Other. These sectors were developed for this report based on the GAINS methodology and the categories and meta-categories used by the GAINS model. The GAINS meta-categories and sub-categories are shown in **Table 3-1**. **Table 3-2** provides clarification as to how the national emissions inventory data were aggregated to fit the seven sectors, so as to facilitate comparisons throughout this report.

The GAINS model does not estimate emissions from open biomass burning (wildfires and prescribed forest burning), whereas the Bond inventory and some Arctic Council nations do estimate these emissions. Where large differences between the country-derived estimates and those from Bond or the GAINS inventories exist, additional explanatory information is included to help clarify reasons underlying the apparent discrepancies. The appendices of this report present the data provided by the Arctic Council nations for each country-specific source category.

Uncertainties

While the process for compiling BC and OC emissions inventories is reasonably straightforward, there are important limitations in this process that introduce uncertainties in final BC and OC emissions estimates. These limitations include

- The reliability of the $PM_{2.5}$ emission factors used with some emission factors for point and nonpoint sources being more reliable than others.
- The reliability of condensable PM estimates by source category. Some sources include PM condensables as part of their testing protocol (fires, residential wood combustion). Others do not, and a generic emission factor (via U.S. EPA AP-42) is applied to estimate the amount of condensable PM the source emits; this introduces a level of uncertainty in determining final BC emissions that is not currently accounted for.
- Some activity levels are generated using process models, while some are generated using surrogate information.
- There is significant variability in the extent of wildfires (time of year, extent of area burned, etc.) and country-specific or region-specific emission factors.
- Finally, many “augmentations” are done in the emissions inventory processing steps. These augmentations may include scaling measured PM to $PM_{2.5}$, as well as assigning condensable emissions estimates to point and nonpoint sources that are not available via source testing. Some of the impacts of the uncertainties in doing this have been explored, but the issue has not been dealt with holistically.

Table 3-1. GAINS Meta Categories and Sub-Categories

Meta Category	Sub-Category
Domestic	Residential – Commercial: Fireplaces
	Residential – Commercial: Medium boilers – automatic or manual feed
	Residential – Commercial: Single house boilers – automatic or manual feed
	Residential – Commercial: Heating stoves
	Residential: Meat frying, food preparation, BBQ, cigarette smoking
	Waste: Open burning of residential waste
	Fuel production other than in power plants: Combustion (grate firing, fluidized bed, pulverized)
	Industrial combustion in boilers (grate firing, fluidized bed, pulverized)
	Industrial combustion, other (grate firing, fluidized bed, pulverized)
Domestic (continued)	Power plants: Existing (grate firing, fluidized bed, pulverized, wet bottom)

Meta Category	Sub-Category
	Power plants: New (grate firing, fluidized bed, pulverized, wet bottom)
	Industrial process: Cement production
	Industrial process: Lime production
	Industrial process: Aluminium production – secondary
	Industrial process: Bricks production
	Industrial process: Cast iron (grey iron foundries)
	Industrial process: Carbon black production
	Industrial process: Coke oven
	Industrial process: Electric arc furnace
	Industrial process: Glass production (flat, blown, container glass)
	Industrial process: Pig iron, blast furnace
	Industrial process: Crude oil & other products – input to petroleum refineries
	Industrial process: Agglomeration plant – sinter
Transport	Heavy- and light-duty vehicles: Leaded gasoline (exhaust)
	Other transport, off-road
	Other transport: Maritime, large vessels >1000 GRT
	Other transport: Maritime, medium vessels <1000GRT
	Other transport: Agriculture and forestry
	Other transport: Air traffic – civil aviation
	Other transport: Mobile sources in construction and industry
	Other transport: Inland waterways
	Other transport: Other off-road; sources with four-stroke engines (military, households, etc., for GAS also pipeline compressors)
	Other transport: Off-road; sources with two-stroke engines
	Other transport: Rail
	Heavy-duty vehicles – buses
	Heavy-duty vehicles – trucks
	Motorcycles, mopeds, and cars with two-stroke engines
	Light-duty vehicles: Cars and small buses with four-stroke engines
	Light-duty vehicles: Light commercial trucks with four-stroke engines
	Motorcycles with four-stroke engines
Agricultural*	Waste: Agricultural waste burning
Open Biomass Burning (forest burning and wildfires)	Not estimated by GAINS
Flaring	Flaring in gas and oil industry
Other	Other PM emissions not included separately in GAINS and statistical differences

* The GAINS Agricultural meta-category does not include open biomass burning, such as wildfires and prescribed burning.

Table 3-2. Aggregation Matrix of Country-specific Source Categories and the Broader Sectors Used in this Report

Arctic Council Nation	Sector and Country-Specific Source Categories						
	Domestic	**Transport**	**Energy & Industrial Production, Waste**	**Agricultural**	**Open Biomass Burning**	**Flaring**	**Other**
Canada	Residential Coal	Road Transport: Gasoline	Electricity & Heat Generation	Agriculture: Prescribed Burning	Natural Sources: Forest Fires & Other (Not Included In Projected Emissions)	Not Estimated	Other (Includes Forestry & Waste)
	Residential Wood	Road Transport: Diesel	Petroleum Refining				Open Sources: Road Dust
	Residential Other	Aviation	Other Energy Industries (Including Pipelines)				Open Sources: Other
		Marine	Mining				
		Off-Road: Gasoline, LPG, CNG	Manufacturing Industries & Construction				
		Off-Road: Diesel					
		Construction (Includes Off-Road Diesel and Gasoline Used for Construction Purposes)					
Denmark, Greenland, Faroe Islands	Commercial and Institutional Plants	Civil Aviation	Public Power	Plants In Agriculture, Forestry, and Aquaculture	Not Applicable	Not Estimated	Military (Mobile)
	Residential Plants	Road	District Heating Plants				
	Residential (Mobile)	Road Non-Exhaust	Petroleum Refining Plants				

Arctic Council Nation	Sector and Country-Specific Source Categories						
	Domestic	**Transport**	**Energy & Industrial Production, Waste**	**Agricultural**	**Open Biomass Burning**	**Flaring**	**Other**
Denmark, Greenland, Faroe Islands (cont.)		Railways	Coal Mining, Oil/Gas Extraction, Pipeline				
		Navigation	Combustion In Manufacturing Industry				
		Agriculture, Forestry, and Fishery *	Industry – Other (Mobile)				
Finland	Domestic Combustion: Wood	Road Traffic: Gasoline	Power Plants and Industrial Combustion: Coal, Peat, Wood, Waste, Black Liquor	Not Estimated	Not Applicable	Not Estimated	Other (e.g., Non-Combustion Sources)
	Domestic Combustion: Peat	Road Traffic: Diesel, Light Duty	Power Plants and Industrial Combustion: Oil, Gas				
	Domestic Combustion: Oil, Gas	Road Traffic: Diesel, Heavy Duty	Industrial Processes				
		Machinery, Off-Road, air And Marine Traffic					
Norway	A BC and OC emissions inventory has not been developed by Norway due to a lack of country-specific emission factors. A $PM_{2.5}$ emissions inventory is provided and discussed in ***Sections 3.4.4 and 4.2.4***.						
Sweden	Stationary Residential and Commercial	Road Traffic	Public Electricity and Heat Production	Agriculture (Non-combustion)	Not Applicable	Gas Flaring	None
		Civil Aviation	Refineries				
		Railways	Coke Ovens				
		Navigation	Industrial Combustion				
		Tyre and Road Abrasion	Working Machinery				
			Industrial Processes				
			Solvents				
			Waste Incineration				

Arctic Council Nation	Sector and Country-Specific Source Categories							
	Domestic	Transport	Energy & Industrial Production, Waste		Agricultural	Open Biomass Burning	Flaring	Other
United States	Residential Wood Combustion	Construction Dust	Charbroiling	Limestone Dust	Agricultural Burning	Prescribed Burning and Wildfires	Not Estimated	None
	Residential Coal Combustion	Paved Road Dust	Potato Deep-Frying	Sand & Gravel	Agricultural Soil			
	Residential Natural Gas Combustion	Unpaved Road Dust	Meat Frying	Asphalt Manufacturing	Crustal Material			
	Residual Oil Combustion	On-Road Gasoline	Wood-fired Boiler	Asphalt Roofing				
		On-Road Diesel	Bituminous Combustion	Auto Body Shredding				
		Off-Road Gasoline	Distillate Oil Combustion	Boric Acid Manufacturing				
		Off-Road Diesel	Natural Gas Combustion	Brink Grinding And Screening				
		Commercial Marine (C1 and C2)	PM/SO_2 Controlled Lignite Combustion	Calcium Carbide Furnace				
		Commercial Marine (C3)	Process Gas Combustion	Charcoal Manufacturing				
		Locomotive	Sub-Bituminous Combustion	Coke Calcining				
		Aircraft	Fly Ash	Fibreglass Manufacturing				
		Tire	Industrial Soil	Food & Ag – Handling				
		Brakewear	Aluminium Production	Glass Furnace				
			Ammonium Nitrate Production	Gypsum Manufacturing				
			Ammonium Sulphate Production	Inorganic Fertilizer				
			Cast Iron Cupola	Inorganic Chemical Manufacturing				

Arctic Council Nation	Sector and Country-Specific Source Categories							
	Domestic	Transport	Energy & Industrial Production, Waste		Agricultural	Open Biomass Burning	Flaring	Other
United States (cont.)			Catalytic Cracking	Lead Production				
			Cement Production	Overall Average Manufacturing				
			Chemical Manufacturing – Avg	Phosphate Manufacturing				
			Copper Production	Synthetic Residential Wood Combustion				
			Electric Arc Furnace	Sandblasting				
			Ferromanganese Furnace	Sea Salt				
			Stationary Diesel	Sludge Combustion				
			Heat Treating	Solid Waste Combustion				
			Industrial Manufacturing – Avg	Steel Desulfurization				
			Kraft Recovery Furnace	Urea Fertilizer				
			Lime Kiln	Wood Products – Drying				
			Mineral Products – Avg	Wood Products – Sanding				
			Open Hearth Furnace	Wood Products – Sawing				
			Petroleum Ind – Avg	Secondary Lead				
			Pulp & Paper – Avg	Sintering Furnace				
			Secondary Aluminium	Surface Coating				
			Secondary Copper					

* The emissions inventory for Denmark, Greenland, and the Faroe Islands estimates emissions from the Agriculture, Forestry, and Fishery source category as mobile sources and reported that over 99% of emissions in this source category are from the fishery industry. Therefore, these emissions are assumed to be from fuel use and are grouped within the Transport sector to be consistent with how other Arctic Council nations define source categories under the Agricultural sector.

3.3 Total Arctic Council Emission Estimates

3.3.1 Bond Emissions Estimates

The Bond inventory[9] calculated global BC and OC emissions using a "bottom-up" approach by applying mass-based BC and OC emissions factors to country-level fuel use and activity data. The Bond inventory takes into account regional technologies and emission controls to provide country-level emissions estimates.

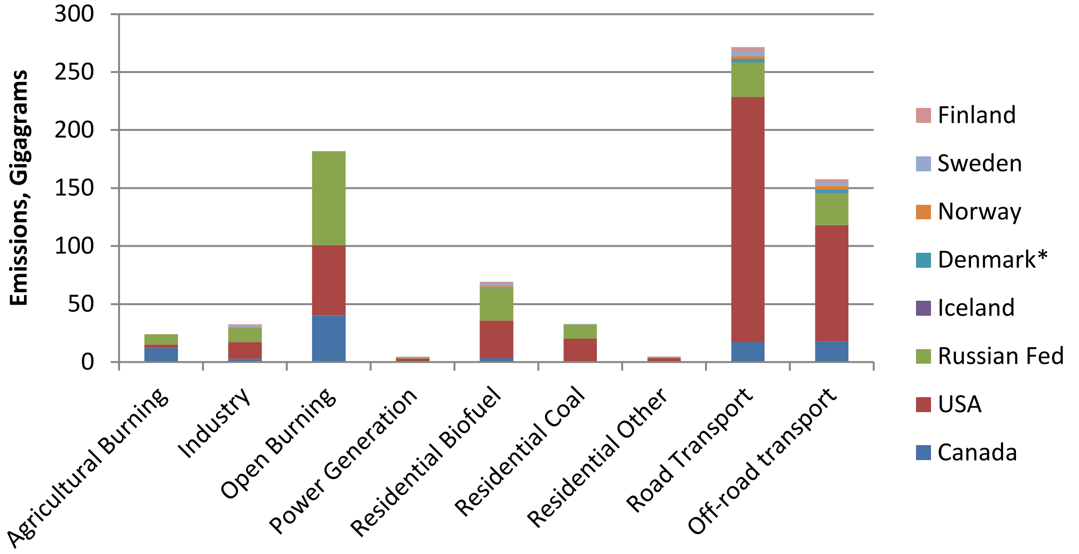
Figures 3-3 and 3-4 present BC and OC emissions, respectively, from the Bond inventory for each Arctic Council nation and major emission source for the year 2000. These emissions estimates include agricultural crop residue burning and open burning (savannah and forest fires), but do not include marine shipping or gas flaring. Open burning is a key source category for both BC and OC emissions, primarily for Canada, the Russian Federation, and the United States. The open burning emissions estimates developed by Bond are intended to be for a typical year rather than a specific year. There are large uncertainties surrounding open burning estimates, as described in the Bond and colleagues (2004) study and shown by the large difference of emissions estimates for Canada, the Russian Federation, and the United States. **Figure 3-5** shows the relative significance of BC emissions from road transport and off-road transport without the emissions from open burning. The Bond inventory source data are provided in ***Appendix H***.

The Bond inventory provides an estimate of a total of 778 Gg/yr and 3,538 Gg/yr for BC and OC, respectively, for the combined Arctic Council nations. These BC emissions represent about 10% of the total global BC emissions (8,000 Gg/yr) estimated by Bond. It is important to note that, currently, there is no robust estimate of the fraction of global BC emissions that actually enters the Arctic region. As a result, this report cannot quantify with confidence the extent to which the Arctic Council nations' BC emissions are responsible for BC-related climate effects in the Arctic or whether sources from outside the nations have a larger impact; instead we refer readers to the recent AMAP report (AMAP, 2011).

---

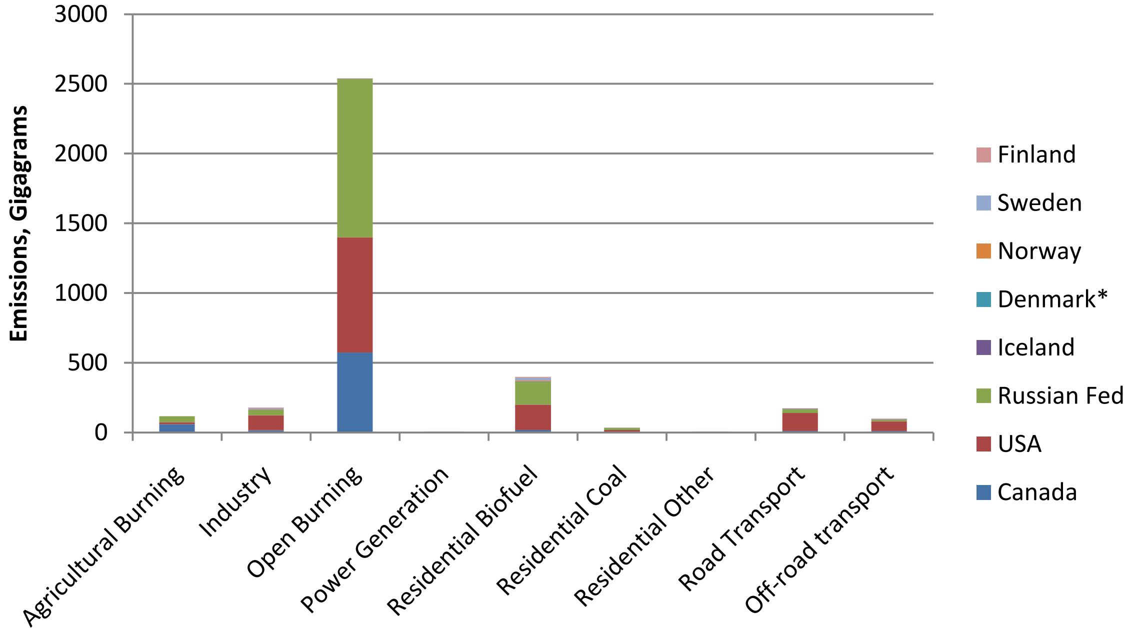
[9] Updated emissions based on the Bond et al. (2004) study. Please refer to this study for the methodology used.

Figure 3-3. Black carbon emissions by sector and Arctic Council nation for 2000 in Gg (Bond, 2009).



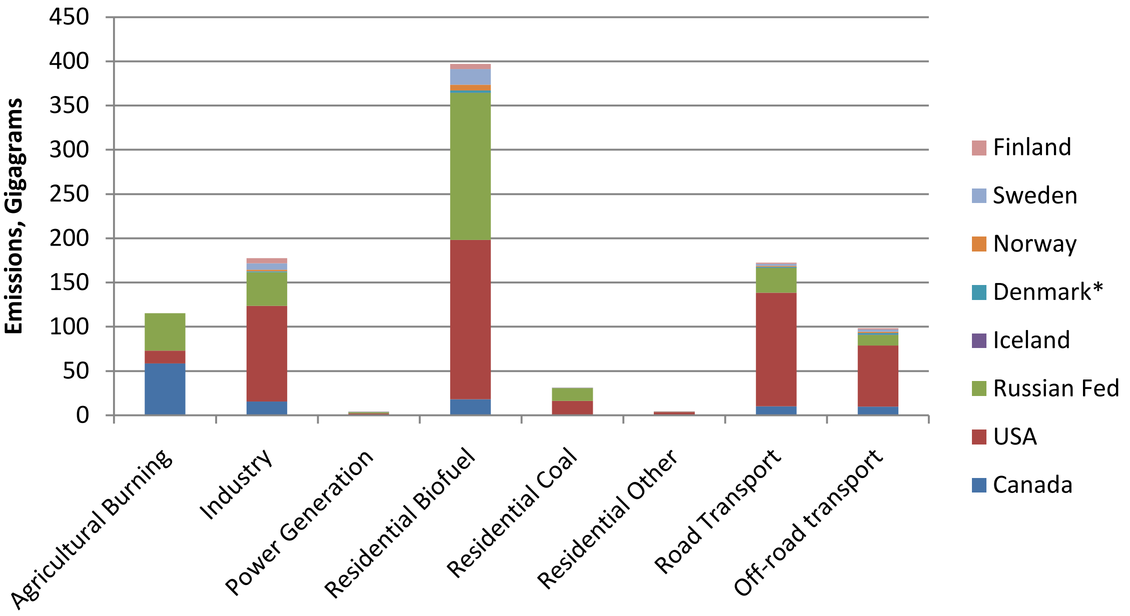
* Includes Denmark, Greenland, and the Faroe Islands.
Note: Open burning includes prescribed forest burning and wildfires.

Figure 3-4. Organic carbon emissions by sector and Arctic Council nation for 2000 in Gg (Bond, 2009); open burning included.



* Includes Denmark, Greenland, and the Faroe Islands.
Note: Open burning includes prescribed forest burning and wildfires.

Figure 3-5. Organic carbon emissions by sector and Arctic Council nation for 2000 in Gg (Bond, 2009); open burning not included.



* Includes Denmark, Greenland, and the Faroe Islands.

3.3.2 GAINS Emissions Estimates

The GAINS model estimates BC and OC emissions based on national-level activity data and country- and region-specific emissions factors for specific control technologies. Like the Bond inventory, the GAINS inventory also estimates total global BC and OC emissions and, for purposes of this report, we break out BC and OC emissions for each Arctic Council nation and their respective source categories. As stated above, a key difference of the GAINS inventory from the Bond inventory is that the emissions estimates from GAINS do not include open biomass burning (i.e., forest and savannah fires), which is a significant source of both BC and OC globally and for key Arctic Council nations (primarily Canada, the Russian Federation, and the United States). Another key difference of the GAINS inventory is that the GAINS model estimates emissions from marine shipping, whereas the Bond inventory does not.

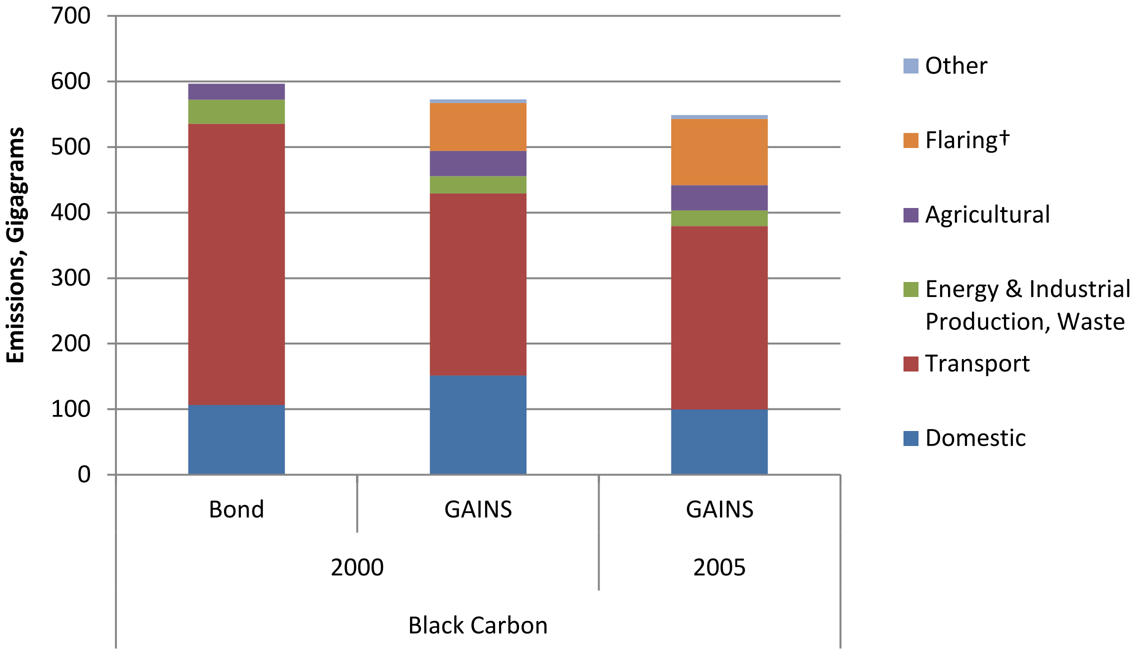
GAINS estimates that total Arctic Council nation emissions in the year 2000 were 573 Gg/yr, which is in very good agreement with the 596 Gg (excluding open biomass burning) estimated by Bond. Globally, the central estimate from GAINS for BC emissions is 5,005 Gg/yr in 2000 and 5,308 Gg/yr in 2005. This estimate is less than Bond's estimate of 8,000 Gg/yr, primarily due to the exclusion of BC emissions from open biomass burning by the GAINS model. GAINS estimates global OC emissions at 13,637 Gg/yr for 2000 and 13,618 Gg/yr for 2005.

Figures 3-6 and 3-7 compare total emissions estimates for BC and OC generated by Bond and GAINS for the year 2000, along with GAINS data for the year 2005. Open burning emissions for the Bond inventory are not included in Figures 3-6 and 3-7 to facilitate comparison with the GAINS inventory. For an overview of how country-specific source categories were aggregated to the seven sectors for this report (Domestic, Transport, Energy & Industrial Production and Waste, Open Biomass Burning, Flaring, and Other), please review Table 3-2.

The inventories are in general agreement for both BC and OC emissions, indicating that the Transport sector contributes the greatest amount of BC emissions from the Arctic Council nations, followed by the Domestic sector. The opposite is true for OC emissions, where wood combustion in the Domestic sector contributes the majority of OC emissions.

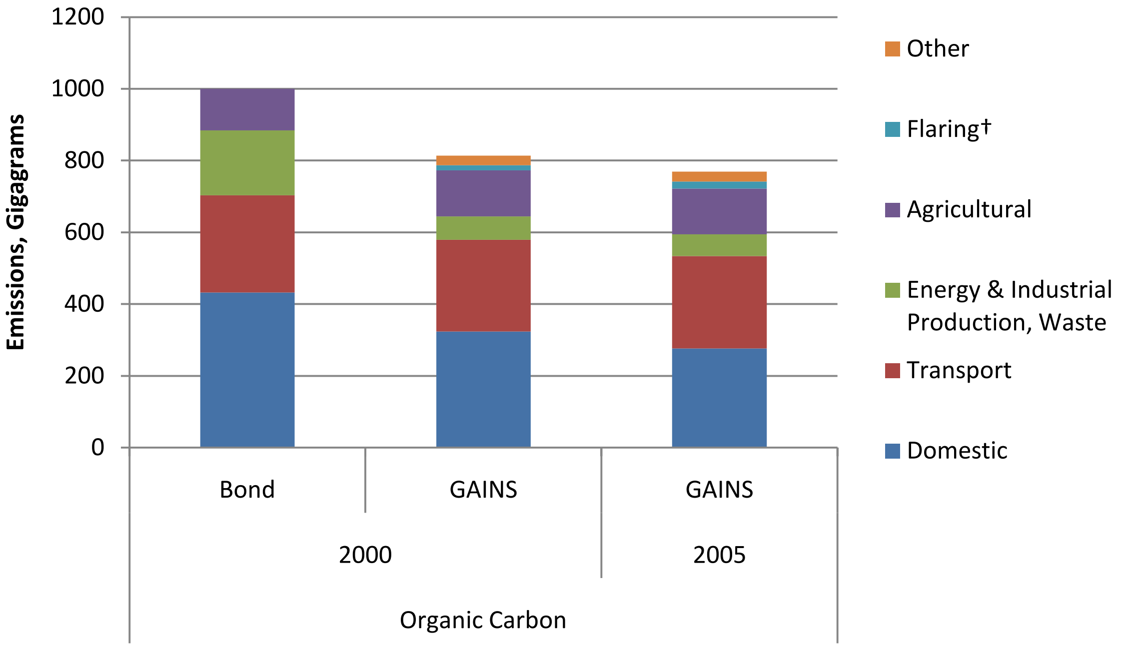
Supporting data for these figures and the GAINS inventories by Arctic Council Arctic Council nation can be found in ***Appendix G***.

Figure 3-6. BC emissions by sector for 2000 and 2005, not including open biomass burning, all Arctic Council nations (Gg/yr).*



* Open biomass burning (prescribed forest burning and wildfires) is not included in this figure for the Bond estimates.
† The Bond data do not include emissions from flaring.

Figure 3-7. OC emissions by sector for 2000 and 2005, all Arctic Council nations (Gg/yr).



* Open biomass burning (prescribed forest burning and wildfires) is not included in this figure for the Bond estimates.

† The Bond data do not include emissions from flaring.

3.3.3 Emissions Data Used by AMAP

The AMAP expert group use the Representative Concentration Pathways (RCP) database for their analysis of BC and OC emissions impacts on the Arctic (AMAP, 2011). The latitudinal data presented in ***Section 3.1*** from Lamarque and colleagues (2010) are also based on emissions from the RCP database. The RCP database was designed to provide emissions for the use of global climate models; therefore, the national inventories' emissions data would have not received careful scrutiny before the AMAP process. For grasslands and forest fire emissions, the RCP database relies on data from a historical wildfire reanalysis (Schultz et al., 2008) and satellite data on burning for the year 2000 (Van der Werf, 2006). For other emissions sources, the RCP database is based on some of the same sources as the Bond inventory; therefore, there are some similarities between the two datasets. Specific Arctic Council nation and sectoral comparisons show that the RCP emissions are within 20% of the Bond inventory emissions for most sectors and nations, with larger differences for Russian Federation emissions and for Canadian OC emissions. Also, the categorization of sectors by the RCP database is somewhat different than the seven sectors used in this report (for example, off-road vehicles in the RCP database are included in the industrial source category rather than in Transport sector).

3.4 National Emission Inventories of Arctic Council Nations

This technical report provides the first-ever compilation of Arctic Council nations' national emissions inventories, with a primary focus on BC emissions. Most Arctic Council nations provided national BC and OC emissions inventories utilizing country-specific data and models. Arctic Council nations used national-scale $PM_{2.5}$ inventories and applied BC and OC fractions to $PM_{2.5}$ emissions for various country-specific source categories.

The methodology and emission factors used in the development of each inventory vary. Despite these variations, the inventories provide insights into the relative magnitude of the current BC and OC emissions from different nations, as well as where there may be a good or poor characterization of an emission source. However, because the national emissions inventories differ by source category and methodology for each Arctic Council nation, country-by-country comparisons of the data are somewhat difficult. Also, due to the preliminary nature of some inventories, there may be large uncertainties associated with the estimated emissions.

In order to compare country-by-country emissions estimates, the data provided by the national inventories have been aggregated into the following seven sectors: Domestic; Energy & Industrial, Waste; Transport; Agricultural; Open Biomass Burning; Flaring; And Other. The national inventories' supporting data by country-specific source category are provided in each nation's appendix. Where large differences exist between country-derived estimates and those from Bond or the GAINS inventories, discussions are presented to help clarify the reasons underlying the apparent discrepancies.

The largest BC emission sources can be identified for each Arctic Council nation. The largest Arctic region emission sources are transportation (primarily on-road and off-road diesel vehicles), residential heating, open biomass burning (both intentional burning in agriculture and forestry sectors, and wildfires), and potentially, gas flaring from fossil fuel production. Marine shipping also is a potentially significant source due to the proximity of Arctic shipping routes to snow and ice.

3.4.1 Canada

Canada developed an initial BC and OC inventory to support the Task Force work using the Canadian $PM_{2.5}$ emissions inventory.[10] The $PM_{2.5}$ emissions inventory is part of the annual Criteria Air Contaminants (CAC) inventory, which includes the geographic distribution of $PM_{2.5}$ emissions for both point sources and area sources based on estimates and facility-reported data from the National Pollutant Release Inventory (NPRI). The $PM_{2.5}$ emissions inventory is categorized by Source Category Code (SCC) and used to allocate emissions to the various source categories (e.g., transportation, domestic heating), excluding the agricultural source category.

---

[10] The $PM_{2.5}$ emissions inventory is prepared by the Pollutant Inventories and Reporting Division (PIRD) of Environment Canada (EC).

Speciation profiles obtained from the U.S. Environmental Protection Agency's (U.S. EPA's) SPECIATE 4.2 database were used to estimate the approximate contribution of the BC and OC components to Canada's overall $PM_{2.5}$ species. BC and OC emissions were then estimated by multiplying $PM_{2.5}$ emissions by BC and OC mass fractions (from SPECIATE 4.2) for specific SCCs. This method was used to estimate emissions for all of the $PM_{2.5}$ data except those from the NPRI, which use facility-specific (North American Industry Classification System [NAICS]) codes instead of SCCs. The NAICS codes were manually matched to the appropriate SCC, and the speciation profile for the particular SCC was used to determine the emissions for that NAICS code.

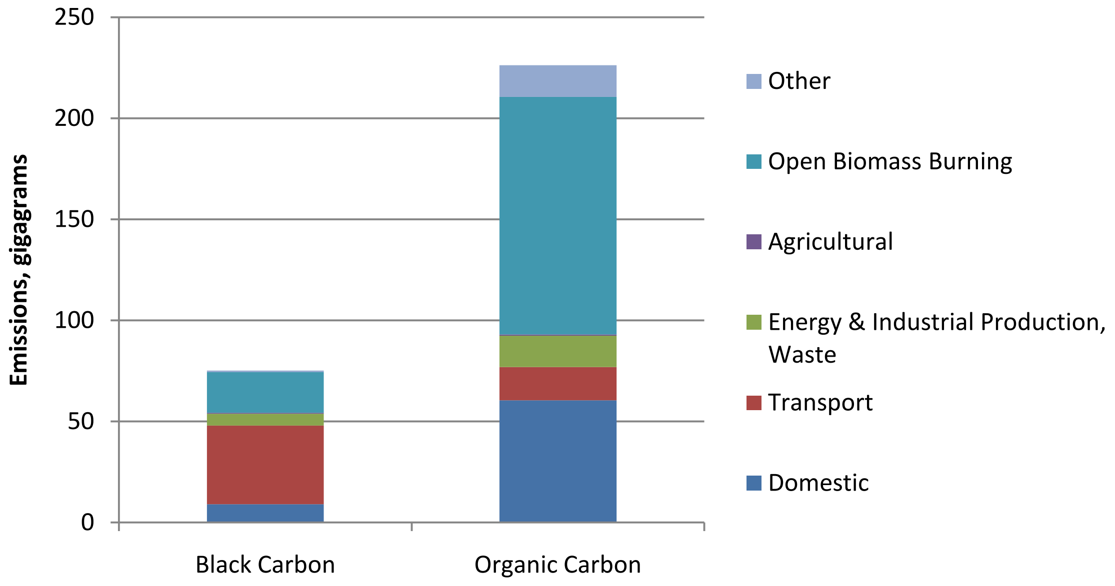
Transportation emissions were developed using an internal MOBILE6.2 model, which was revised to reflect Canadian conditions. Agricultural crop burning emissions were calculated using an emission factor from Andreae and Merlet (2001) and estimates of annual dry matter burned for different crops (i.e., spring wheat, winter wheat, oats, barley, mixed grains, flaxseed and canola). BC emissions from forest fires were estimated using a constant value of biomass consumed per area burned for all of Canada. Using a constant value does not reflect the great variability in pre-burn fuel load or the influence of burning conditions (e.g., temperature) on the quantity of biomass consumed. The $PM_{2.5}$ elemental carbon (EC) profile in the SPECIATE 4.2 database is derived from a small set of experimental data that are not representative of emissions from northern wildfires. In addition, the PM and/or $PM_{2.5}$ emission factors (on a mass basis) used are constant regardless of year, location, burning conditions, and completeness of the burn (i.e., combustion efficiency).

The current PM-based BC inventory would suggest that controlling the area burned is the obvious mitigation activity for Canada. Simplistically, this is true (i.e., no fire equals no BC emissions), but because of methodological weaknesses, the inventory wrongly suggests that reducing the area burned anywhere at any time has the same mitigation effectiveness. An assessment of the mitigation potential should rely on an inventory that shows how BC emissions vary with fire location, types, and circumstances, all of which affect the amount of biomass burned.

BC and OC emissions were aggregated into six of the seven sectors used in this report (flaring was not estimated), nationally as presented in **Figure 3-8** and by Canadian province and/or territory, as presented in **Figures 3-9 and 3-10**. **Table A-1** in ***Appendix A*** provides details on how the Canadian source categories were aggregated to the broader source sectors. **Tables A-2 and A-3** contain more detailed data on the sources used for the national estimates presented later in **Figure 3-16**. The full dataset for the provincial BC and OC emissions is presented in **Tables A-4 and A-5**.

BC and OC emissions from most sectors in Canada appear to have declined since 1990 (see **Tables A-2 and A-3** in ***Appendix A***). In 2006, approximately 75 Gg of BC emissions were emitted, with the Transport sector accounting for more than 52% of the total. If BC emissions from forest fires (20 Gg) are omitted, the Transport sector accounts for 71% of total BC emissions. Ontario, Alberta, and Quebec contributed approximately 62% of total transport-related BC emissions in 2006 (see **Figure 3-17**).

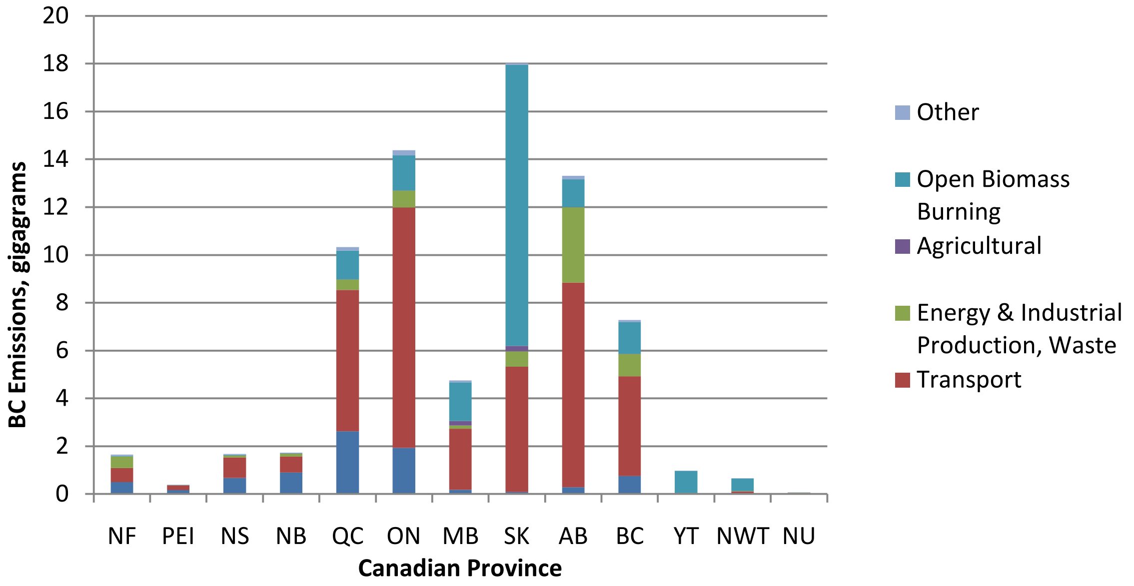
Figure 3-8. BC and OC emissions for 2006 by sector, Canada (Gg/yr).*



* Agricultural sector emissions for Canada include prescribed agricultural burning, and estimates in the Open Biomass Burning sector include emissions from forest fires. Flaring emissions were not estimated for Canada. Emissions from petroleum refineries include upstream emissions.

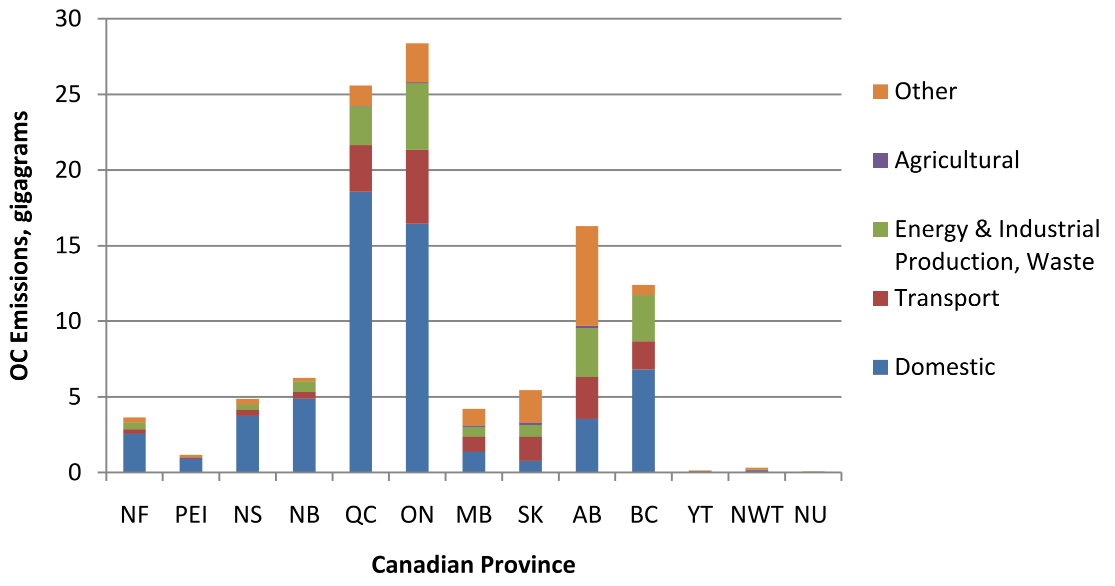
OC emissions (excluding forest fires and direct agricultural burning) totalled 109 Gg in 2006. OC emissions from forest fires were estimated to be approximately 118 Gg (see **Table A-5** in ***Appendix A***). With respect to OC, it is relevant to note that Chow and colleagues (2010) suggest that global OC emissions from open biomass burning exceed BC emissions by a factor of about 8; this is commensurate with the differences in BC and OC $PM_{2.5}$ mass fractions determined by Environment Canada's results for forest fires. Scientific literature suggests, however, that the ratio can vary from about 2.4 (for California alone in Chow and colleagues, 2010) to 12.8 (globally, in Bond et al., 1996).

Figure 3-9. Provincial breakdown of BC emissions in 2006 by sector, Canada (Gg/yr).*



The Canadian provinces are as follows: NF = Newfoundland; PEI = Prince Edward Island; NS = Nova Scotia; NB = New Brunswick; QC = Quebec; ON = Ontario; MB = Manitoba; SK = Saskatchewan; AB = Alberta; BC = British Columbia; YT = Yukon; NWT = Northwest Territories; NU = Nunavut.

Figure 3-10. Provincial breakdown of OC emissions in 2006 by sector, Canada (Gg/yr).*



* Open biomass burning emissions (forest fires) were not included in the total emissions presented in this figure. The Canadian provinces are as follows: NF = Newfoundland; PEI = Prince Edward Island; NS = Nova Scotia; NB = New Brunswick; QC = Quebec; ON = Ontario; MB = Manitoba; SK = Saskatchewan; AB = Alberta; BC = British Columbia; YT = Yukon; NWT = Northwest Territories; NU = Nunavut.

Several potential improvements could be made to further refine Canada’s initial BC and OC inventory. The approach taken to develop emissions estimates used for BC and OC was based on estimating the chemical speciation of the $PM_{2.5}$ inventory, except for emissions from residue burning on agricultural land, which were estimated by applying an emission factor directly to the residue biomass burned each year. There are a number of ways in which this could be improved, including

- Further refining estimates of the fractions of PM that are BC and OC;
- Developing improved ways of spatially allocating the estimates; and
- Obtaining better estimates of PM from forest fires, which would entail investigation into forest biomass burned annually at the appropriate spatial scale.

With regards to the estimates of BC and OC from all categories except agricultural and open biomass burning (open and natural sources), there are two primary areas for improvement. The first relates to speciation profiles. For many sources, the profiles relating to both EC and OC are relatively generic and may be improved upon through further research. Such research would involve collaboration with personnel familiar with PM (specifically $PM_{2.5}$) estimation, development, and testing methods.

The second possible improvement would be in relation to the surrogates used for the spatial allocation of the estimates. The only spatial allocation utilized for these estimates was based on provincial and territorial boundaries. More detailed allocations are possible, including population-based, or in the case of the transport sector, travel corridor–based models. To make progress in this area, cooperation and collaboration with air quality or atmospheric modelling groups would be required.

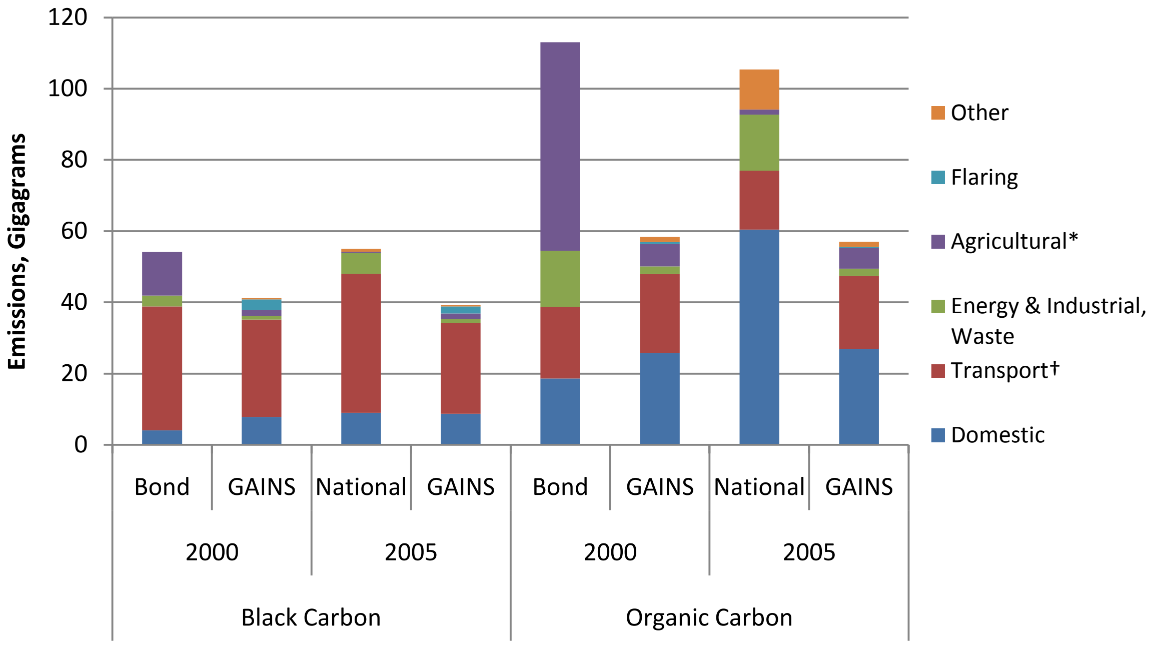
There seems to be a great deal of potential improvements possible in the estimation of BC and OC emissions from wildfires. One obvious improvement would be a statistical analysis of actual biomass burned by historical wildfires. One could also attempt to validate the current PM-based inventory estimates with estimates produced independently, based on biomass burned and indicators of burn completeness (e.g., CO emissions).

Sectoral Comparison of Canadian Emissions Estimates with the GAINS and Bond Inventories

Figure 3-11 compares the national inventory for Canada to the 2000 and 2005 GAINS and 2000 Bond inventories for each of the key source categories. There are large differences in emissions estimated for the Agricultural and Open Biomass Burning sectors for both BC and OC. Emissions from open biomass burning in Canada are considered highly uncertain. The national inventory methodology used a constant nationwide value of area burned, which does not reflect the great variability in pre-burn fuel load, nor the influence of burning conditions on the quantity of biomass consumed. The national inventory also uses a $PM_{2.5}$ emission factor from the SPECIATE 4.2 database that is not truly representative of emissions from northern wildfires; the emission factor used is also constant and does not reflect the year, location, burning conditions, and combustion efficiency. The Bond inventory also uses a “typical” year estimate for open biomass burning emissions. Forest fires vary considerably from year to year and emissions may be significantly higher or lower than the “typical” year emissions estimates. Bond used data from Environment Canada CAC emission summaries and emission factors from Andreae and Merlet (2001) to estimates emissions for 2000.

Other methodological differences can be attributed to the national inventory's OC emissions estimates for the Domestic sector, which are much larger than estimates from the GAINS and Bond inventories. The GAINS OC emissions estimate for the Energy & Industrial, Waste sector are lower than the estimates in the national and Bond inventories.

Figure 3-11. BC and OC emissions for 2000 and 2005 by sector, excluding open biomass burning, Canada in Gg/yr.



* National Agricultural sector estimates include agricultural crop waste burning.

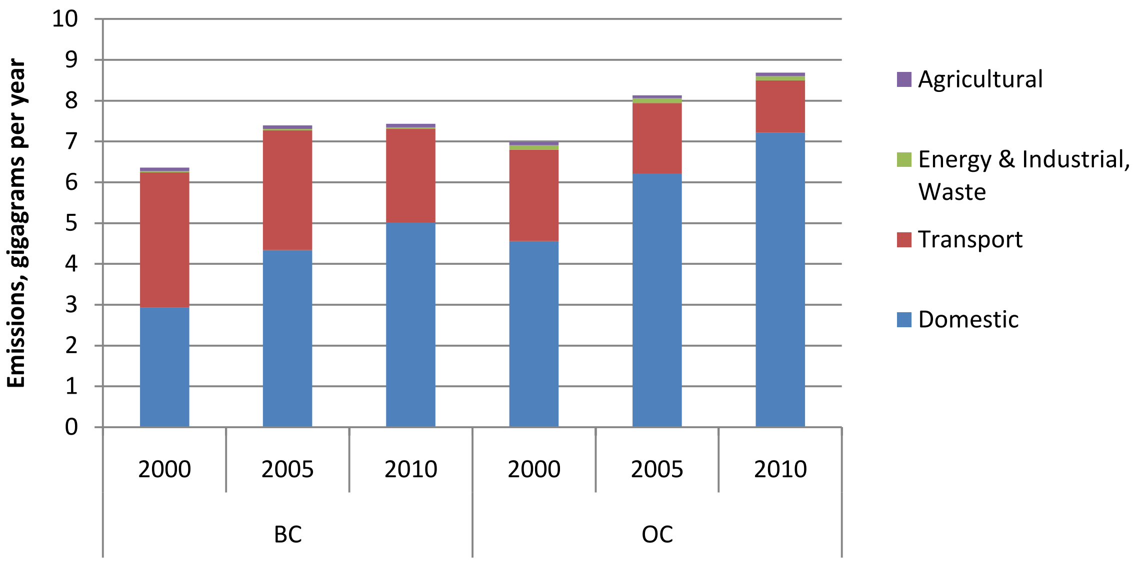
† GAINS estimates for the Transport sector include high emitting vehicles. National estimates for the Transport sector include marine and civil aviation.

3.4.2 Denmark, Greenland, and the Faroe Islands

The first national BC and OC emissions inventory (presented in **Figure 3-12**) for Denmark, Greenland, and the Faroe Islands is based on data from the Danish National Environmental Research Institute (NERI). Denmark and the self-governing territories of Greenland and the Faroe Islands constitute the Kingdom of Denmark. Separate inventories and text are provided for the larger of the two regions (Denmark and Greenland). Emissions from the Faroe Islands are minimal for all sectors and are not dealt with separately, but are included in the total Denmark inventory provided in the appendix. Henceforth, any discussion specific to Denmark includes the Faroe Islands and any discussion about the Kingdom of Denmark includes Denmark, the Faroe Islands, and Greenland. **Table B-1** in ***Appendix B*** provides a detailed breakdown of how the Kingdom of Denmark source categories were aggregated to the seven sectors used in this report. Open biomass burning is not practiced, and the Agricultural sector emissions consist of those from plants in the agriculture, forestry, and fishery source category. Emissions from the fishery source category are mainly from fuel and are therefore aggregated in the Transport sector.

The majority of BC and OC emissions are from sources in the Domestic sector (i.e., non-industrial combustion such as residential wood combustion for heating purposes) and the Transport sector, including those from the fishing industry and on- and off-road transportation. The Domestic sector has been responsible for an increasing percentage of total BC and OC emissions in Denmark and the Faroe Islands from 2000 to 2010, as shown in Figure 3-12 and **Table 3-3**. Emissions from the Domestic sector are primarily due to wood combustion in wood stoves (75%) and wood boilers (almost 25%), and to a lesser extent, pellet stoves and boilers. Emissions from on- and off-road transport have decreased from 2005 to 2010 due to various regulations, including EURO-based norms, and are estimated at 20% and 9% of the total BC and OC emissions, respectively, in 2010.

Figure 3-12. BC and OC emissions by sector for 2000, 2005, and 2010, Denmark and the Faroe Islands (Gg/yr).*



* Open biomass burning is not applicable for Denmark and the Faroe Islands. Flaring emissions were not estimated. No emissions were included in the Other sector.

Table 3-3. Percent of BC and OC Emissions from the Domestic and Transport Sectors in Denmark and the Faroe Islands for 2000, 2005, and 2010

Sector	Black Carbon			Organic Carbon		
	2000	2005	2010	2000	2005	2010
Domestic (Gg)	2.93	4.34	5.01	4.56	6.22	7.22
Domestic Percent of Total (%)	46	59	67	65	76	83.00
Transport (Gg)	3.31	2.94	2.29	2.24	1.73	1.29
Transport Percent of Total (%)	52	40	31	32	21	15.00
Total for all Sectors (Gg)	6.36	7.40	7.43	6.99	8.13	8.68

BC and OC emissions from international navigation and international civil aviation were also estimated for Denmark, as presented in **Table 3-4**. No emissions were estimated for these categories in Greenland and the Faroe Islands. Emissions from international civil aviation have remained relatively stable since 2000, while emissions for both BC and OC have decreased in the international navigation source category, presumably due to fuel regulations.

Table 3-4. BC and OC Emissions from International Navigation and International Civil Aviation in Denmark for 2000, 2005, and 2010, Gg

Source Category	Black Carbon			Organic Carbon		
	2000	2005	2010	2000	2005	2010
Civil Aviation, International	0.01	0.02	0.01	0.02	0.01	0.02
Navigation, International	3.50	2.34	2.39	1.60	0.58	0.39
Total	3.50	2.36	2.40	1.62	0.58	0.41

Greenland's BC and OC emissions inventory is presented in **Figure 3-13,** with supporting data for $PM_{2.5}$, BC, and OC emissions provided in **Tables B-2, B-3, and B-4,** respectively, in ***Appendix B.*** In 2010, BC and OC emissions in Greenland accounted for less than 0.35% and 0.2%, respectively, of the total emissions from the Kingdom of Denmark, but constitute a somewhat larger share of the total radiative forcing of the emissions due to the high north location. Greenland is currently exploring new possibilities for offshore oil and gas production, which may become a key source category in the future with respect to BC emissions.

The majority of Greenland's BC and OC emissions currently fall in the Transport sector. Agriculture, forestry, and fishery activities fall under a combined source category in Greenland; but 99% of emissions within this source category are from fishery activities.[11] For the purposes of this report, emissions from the Greenland agriculture, forestry, and fishery source category are assumed to be from fishery activities and are therefore included in the Transport sector because the majority of emissions stem from fuel use. This aggregation was done to be consistent with how other Arctic Council nation inventories define this sector. The fishery industry is the single most important industry in Greenland, accounting for 87% of annual exports and approximately 20% of CO_2 equivalent (CO_2e) emissions.[12] **Table 3-5** presents the emissions from the agriculture, forestry and fishery source category and the transport source category. More than 60% of emissions in the Transport sector can be attributed to the fishery industry in 2010. The large fluctuations of emissions from the fishery industry follow fluctuations in fishery activity due to changes in both fish stocks and changes in world market prices.

---

[11] Agriculture accounts for 1% of Greenland's CO_2 equivalent (CO_2e) emissions, and the net CO_2e removal from land use, land-use change, and forestry is only 0.08% of Greenland's total CO_2 emissions in 2008. This data can be found in the resubmission of Denmark's Greenhouse Gas reporting, 2010: Table 1 and Summary 2. Total emissions in the category "Other Sectors" is 47.2% of total emissions in 2008. Emissions from agriculture, forestry and fisheries (AFF) are 15.9% of total emissions. However, fisheries make up approximately 99% of the AFF emissions.

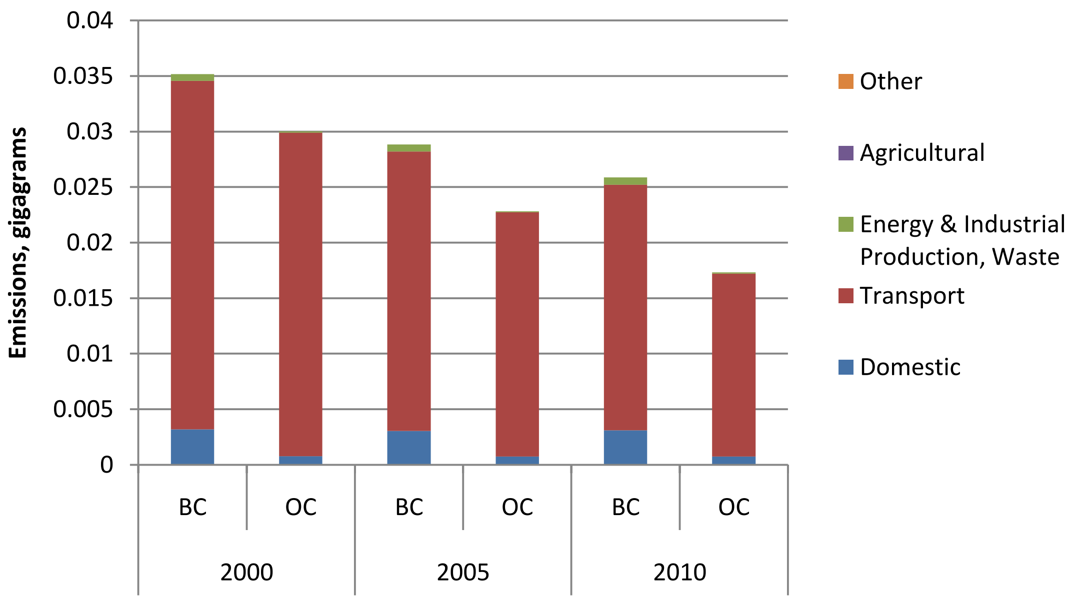
[12] Statistics Greenland (Grønlands Udenrigshandel), 2009: Table 3: Total export in 2008 and 2009, by products. Export of fish and seafood produce accounts for DKK 1,685,394 – equivalent to 87.62% of total export (DKK 1,923,363).

Table 3-5. Percent of BC and OC Emissions from the Transport and the Fishery Source Categories in Greenland for 2000, 2005, and 2010

	Black Carbon			Organic Carbon		
Source Category	**2000**	**2005**	**2010**	**2000**	**2005**	**2010**
Fishery (Gg)	21.18	16.33	15.55	14.88	11.47	10.93
Transport (Gg)	31.36	29.13	25.16	21.98	22.10	16.47
Total for all Sectors (Gg)	35.16	30.00	28.84	22.82	25.87	17.33
Fishery (Percent of Total Transport)	68%	56%	62%	68%	52%	66%
Fishery (Percent of Total Emissions)	60%	54%	54%	65%	44%	63%

Overall, BC and OC emissions in Greenland have both decreased by approximately 30% from 1990 to 2010. Mitigation of on-road transport emissions and technological advancements are the leading driver for these overall emissions reductions. Emissions from on-road transport have decreased 21% since 1990.

Figure 3-13. BC and OC emissions by sector for 2000, 2005, and 2010, Greenland (Gg/yr).*

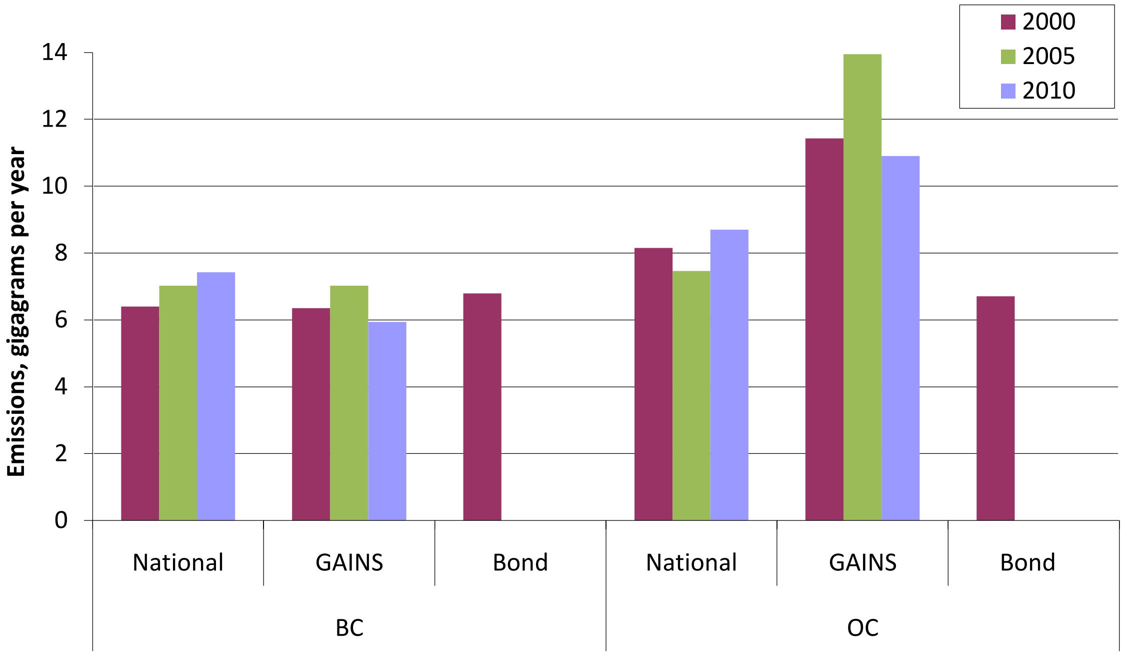


* Flaring and open biomass burning is not applicable for Greenland and were not estimated.

Comparison of National Emissions Estimates from Denmark, Greenland, and the Faroe Islands with the GAINS and Bond Inventories

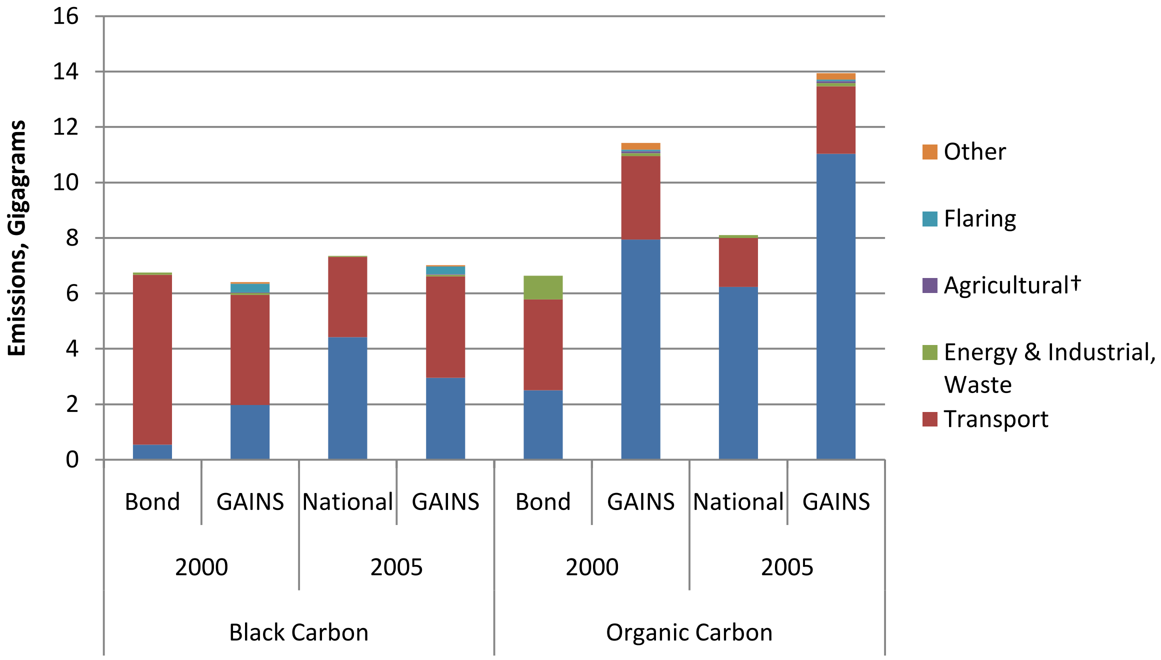
As shown in **Figure 3-14**, the emissions inventories from GAINS and Bond are relatively consistent with the Kingdom of Denmark inventory, particularly for the BC emissions. The GAINS OC emissions are larger than the other two inventories. The differences between the inventories are more evident when looking at the sector breakdown, as can be seen in **Figure 3-15**. The Bond data for both BC and OC appear to underestimate emissions from the Domestic sector.

Figure 3-14. Comparison of total BC and OC emissions inventories for Denmark, Greenland, and the Faroe Islands to GAINS and Bond (Gg/yr).*



* Open biomass burning is not applicable for Denmark, Greenland and the Faroe Islands.

Figure 3-15. BC and OC emissions for 2000 and 2005 by sector, Denmark, Greenland, and the Faroe Islands in Gg/yr.*



* Open biomass burning emissions are not included in this figure.
† Agricultural sector emissions consist of emissions from plants in the agricultural, forestry, and fishery sector.

3.4.3 Finland

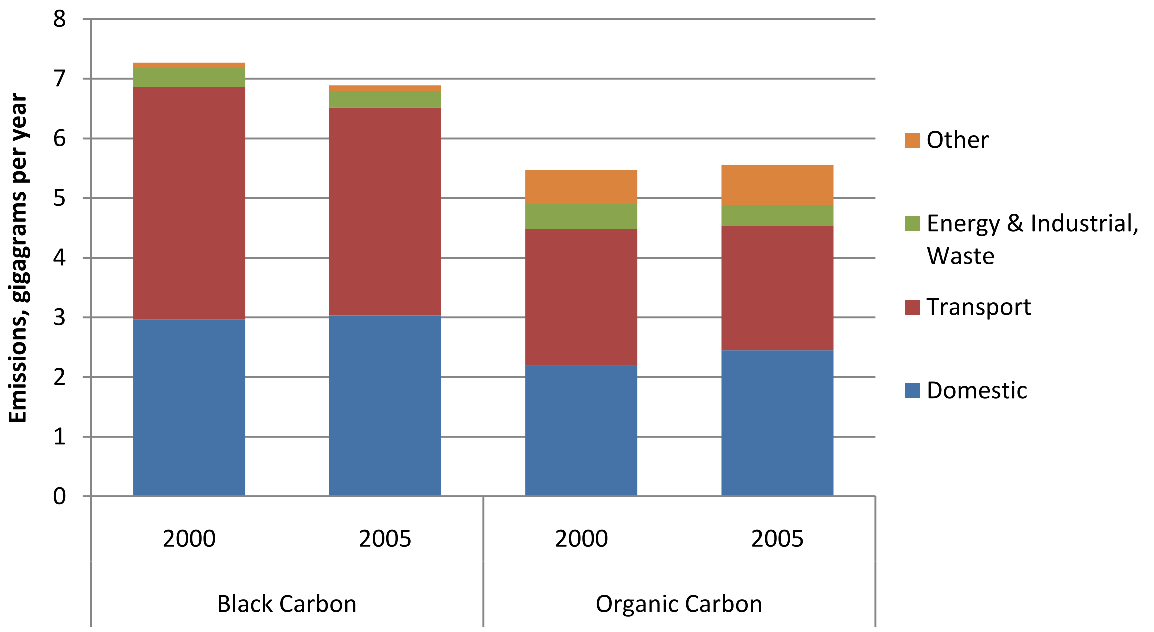
The BC and OC emissions for Finland were estimated using the Finnish Regional Emission Scenario Model (FRES) developed by the Finnish Environment Institute (SYKE). The model includes emissions of primary PM in different particle sizes, as well as several gaseous species (e.g., ozone and PM precursors and CO_2) from 1990 to 2020. The model describes large-scale energy combustion and industrial plants as point sources with plant-specific information, whereas small-scale industrial activities, residential combustion, traffic sources, and various fugitive dust and other non-combustion sources are treated as area sources and are based on more generalized parameterization. FRES comprises 102 sectors, 10 fuels, and several sector-specific mitigation technology options. A detailed model description can be found in Karvosenoja (2008).

Sector fuel technology–specific BC and OC emissions factors from national and international literature have been used to estimate BC and OC emissions. The documentation of the Finnish BC and OC inventory, with an uncertainty estimate, can be found in a peer-reviewed conference proceeding by Kupiainen and colleagues (2006). Emission parameters in the model have been updated for domestic and small-scale combustion plants for 2010 through the work of the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP) Black Carbon Expert Group. The review has been based on recent national emission measurement literature (Sippula et al., 2007; Tissari et al., 2007; Tissari et al., 2008; Frey et al., 2009; Sippula et al., 2009; Tissari et al., 2009).

The Finnish source categories have been aggregated to the seven broader sector categories used in this report, as presented in **Table C-1** in ***Appendix C***.

Figure 3-16 presents the Finnish national emissions for 2000 and 2005 aggregated to the seven broader source sectors used in this report; however, emissions for open biomass burning, agricultural, and flaring were not estimated for Finland, so only the Domestic; Transport; Energy& Industrial, Waste; and Other sectors are shown in this figure. More detailed BC and OC emissions, including source categories and associated fuels, are provided in **Table C-2** in ***Appendix C***. The key source categories for both BC and OC fall under the Domestic sector, due to wood combustion, and the Transport sector, due to diesel fuel consumption. Total BC and OC emissions in 2000 were 7.3 and 5.5 Gg/yr, respectively. Between 2000 and 2005, BC emissions declined in the Transport sector and slightly increased in the Domestic sector. The net effect of these sectoral changes has, however, led to a 5% decrease in overall emissions. OC emissions under the Domestic sector have slightly increased, despite declines in other sectors.

Figure 3-16. BC and OC emissions by sector for 2000 and 2005, Finland (Gg/yr).*



* Emissions for open biomass burning, agricultural, and flaring were not estimated for Finland. It is unclear if the Other category includes these sources, and if flaring is included in the oil and gas industry emissions, which are included in the Energy & Industrial, Waste sector.

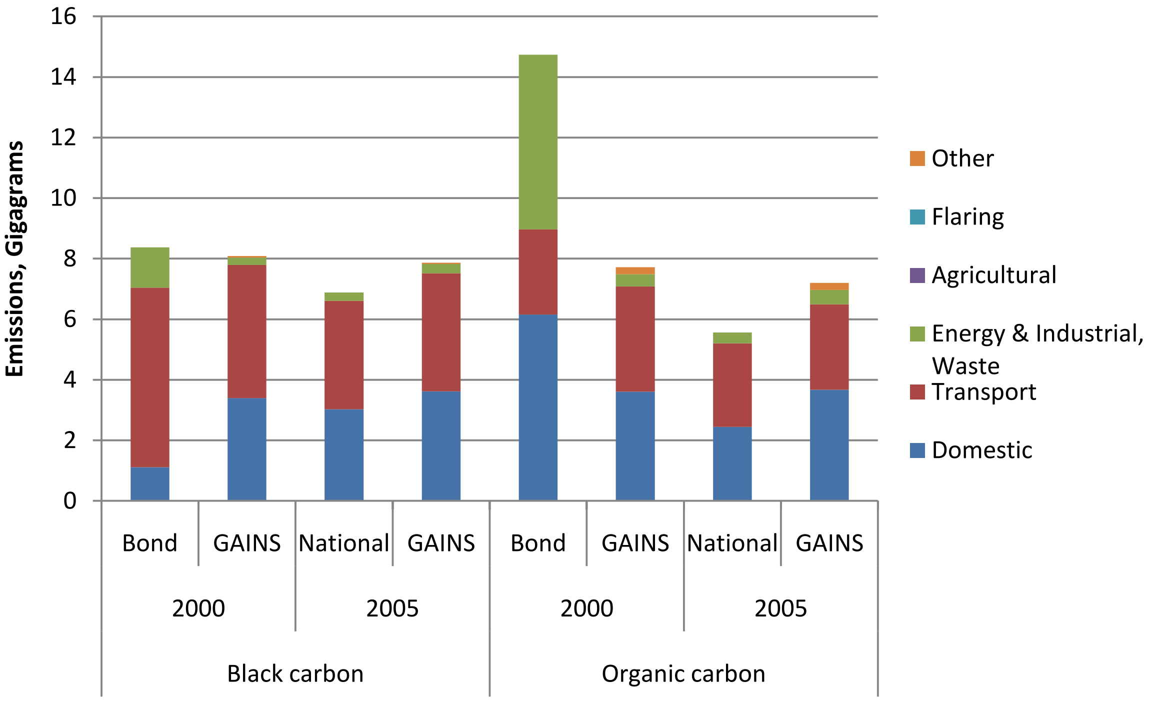
Comparison of Finnish National Emissions Estimates with the GAINS and Bond Inventories

Figure 3-17 compares the Finnish national BC and OC emissions inventory to emissions estimates from the Bond and GAINS inventories.

In general, all three inventories show that the Transport (on- and off-road mobile sources) and Domestic (wood burning) sectors are the most important with respect to BC and OC emissions in Finland. The estimates presented here vary somewhat, but generally agree among the inventories in terms of overall BC and OC emissions. There are large differences in the Bond OC inventory for Finland, primarily due to emissions in the Domestic and Energy & Industry Production, Waste sectors. It is unclear why the OC emissions estimated by Bond for the Domestic and Energy & Industry Production, Waste sectors are so large. Emissions estimates from the Energy & Industry Production, Waste sector in the national inventory include emissions from the oil and gas source categories (i.e., refineries) and from combustion of coal, peat, wood, waste, and black liquor at industrial facilities.

Estimates of BC and OC emissions for Finland have significant uncertainties owing to the lack of dedicated measurements that reflect on regional operating practices, fuels, and technologies, but also to poor activity statistics for some of the key source categories, such as residential biofuel combustion. The FRES and GAINS teams have worked with the CLRTAP Black Carbon Expert Group to compare and update the emissions estimates.

Figure 3-17. BC and OC emissions for 2000 and 2005 by sector, Finland in Gg/yr.*



* Open biomass burning emissions are not included in this figure and are expected to be minimal.
† No national agricultural emissions were estimated by Finland.

3.4.4 Norway

Norway currently does not have an official national inventory for BC and OC emissions due to the lack of country-specific emission factors. However, Norway has compared the GAINS $PM_{2.5}$ emissions inventory to the national Norwegian $PM_{2.5}$ inventory and found that the data correspond well. It would therefore appear that the historical BC data from the GAINS model adequately represent Norwegian BC emissions; therefore, the discussion in this section focuses on $PM_{2.5}$ emissions.

$PM_{2.5}$ emissions estimates for Norway for 1980, 1990, 1995, and 2000 to 2008, aggregated to the SNAP (selected nomenclature for air pollutants) categories, are presented in **Figure 3-18**.[13] Supporting data for the Norwegian $PM_{2.5}$ emissions estimates are provided in **Table D-1** in ***Appendix D***.

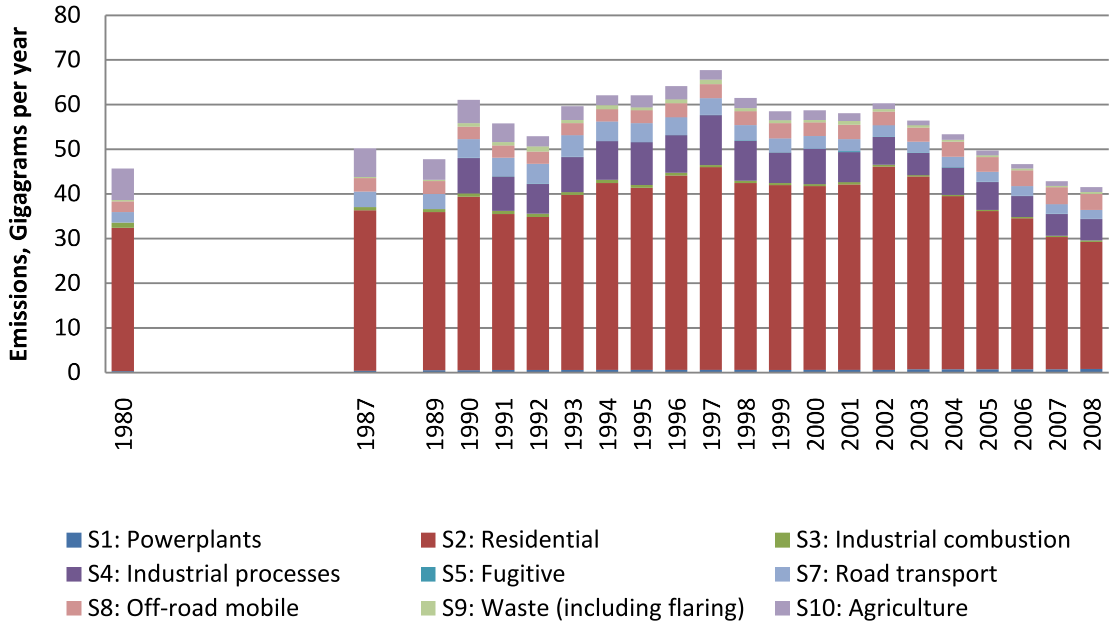
As presented later in **Figure 3-29**, $PM_{2.5}$ emissions from most SNAP categories have decreased since 1990, despite some fluctuation over the 1990 to 2002 timeframe. The absolute percentage decrease (between 1990 and 2008) ranges from as low as 30% (residential) to as high as 80% (agriculture). Since 2002, total $PM_{2.5}$ emissions have monotonically decreased by 31%, with the largest decreases observed in the residential

---

[13] Norway reports $PM_{2.5}$ data to the CLRTAP. The latest submission is available at: http://cdr.eionet.europa.eu/no/un/CLRTAP/colqv0ipg/envs3hqoa. Statistics Norway has documented the basis for the emissions in the report *The Norwegian Emission Inventory 2010* (SSB, 2010). Emissions from industrial processes, tire and break wear, road abrasion, international aviation and agriculture other than field burning are not included in the emissions estimates for 1980.

source category (37%), followed by industrial combustion (24%), industrial processes (23%), and agriculture (12%). $PM_{2.5}$ emissions from off-road mobile sources and power plants have increased since 2002, but their combined emissions are less than 1 Gg and do not significantly contribute to Norway's nationwide $PM_{2.5}$ emissions.

Figure 3-18. Historical trends in $PM_{2.5}$ emissions by SNAP category* for 1980, 1990, 1995, and 2000–2008,[14] Norway (Gg/yr).



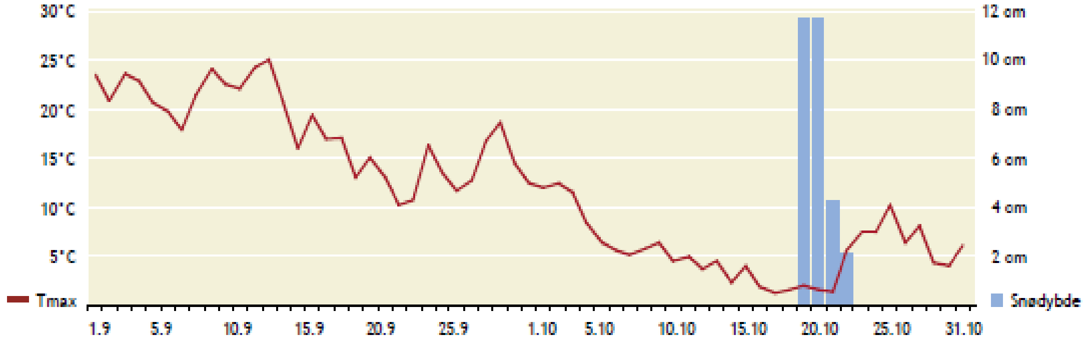
* SNAP categories are set of sub-sectoral categories. For more information, see the *EMEP/CORINAIR Emission Inventory Guidebook*, *Third Edition* (http://www.eea.europa.eu/publications/technical_report_2001_3).

Emissions from residential sources are primarily from wood combustion in heating stoves. Emissions have varied over the past 18 years with respect to temperature and the cost of electricity, but have monotonically decreased since 2002. New regulations for new residential heating stoves in force since 1998 may be responsible for the decrease in emissions between 1997 and 1998. A plausible explanation for the peak in emissions from the residential sources in 2002 is Norway's abnormally large and abrupt change in temperature from summer to autumn and winter that year. **Figure 3-19** shows how temperature and snowfall varied in Oslo between 1 September 2002, and 31 October 2002. Within one month, the temperature and snowfall changed from 20 °C and 0 cm of snow on 29 September, to 0 °C and 12 cm of snow (blue bars) on 20 October. Norway's temperatures were also lower than normal (1961–1990 normal) in November and December of that year, which may have led to an increase in wood consumption, and consequently, increased $PM_{2.5}$ emissions. A detailed discussion on emissions from wood burning is provided in the following section.

---

[14] Methodology prior to 1990 is not consistent with the 1990–2008 timeframe.

Figure 3-19. Temperature and snow cover in Oslo, Norway, in autumn 2002.



Source: Meteorologisk institutt, 2011.

The second largest source of $PM_{2.5}$ emissions in Norway is industrial processes at about (12% in 2008). Industrial emissions vary according to production intensity. Dust emissions are regulated through individual permits according to the Norwegian Pollution Control Act and the IPPC Directive (now the Directive on Industrial Emissions [IED]). There is no combustion associated with the production of iron, aluminium, and chemicals in Norway; therefore, carbonaceous aerosol emissions are not expected to be generated from these industries in Norway.

On-road transportation emissions have decreased since 1993, and it is expected that existing regulations and PM emission limits in place from the EURO standards will continue to reduce BC emissions in Norway's Transport sector. Norway has adopted all relevant European Union (EU) directives and standards for new passenger cars and light- and heavy-duty trucks, and these efforts have contributed to decreasing $PM_{2.5}$ emissions from road traffic.

Minimal agricultural waste burning occurs in Norway. Local authorities have regulated these activities since 2001, and as a result, agricultural waste burning emissions have stabilized to a current low level of 1 Gg/yr.

Emissions from Wood Burning in the Domestic Sector

In 2005, BC constituted a small fraction (7%) of Norway's $PM_{2.5}$ emissions from heating stoves, while the fraction of OC was much higher (68%). Because of this, targeting $PM_{2.5}$ through regulation will not reduce BC as efficiently as OC. Since 1990, Domestic sector emissions for Norway have shown a decreasing trend. This trend may be due to regulations on residential stoves put in place in 1998 that limit PM_{10} emissions for new stoves to 10 g/kg.

About 1.3 million (26%) Norwegian households reported using wood for heating in 2009. The total number of households with fireplaces in Norway is estimated to be 2 million; thus, far more households have the opportunity for wood heating and the potential for increased $PM_{2.5}$ emissions exists. Statistics Norway estimated in 2001 that nearly 60% of households in Norway used wood for heating in the winter of 1999/2000 (SSB, 2001). Total wood consumption has been estimated at approximately 1.3–1.4 million metric tons, or 276 kg/capita, in the past 5 years (2005–2009), although reliable wood consumption data are particularly difficult to obtain from sales statistics. Statistics

Norway, together with the Norwegian Water Resources and Energy Directorate and the Ministry of Agriculture and Food, carry out nationwide surveys on wood consumption for residential heating and the types of heating habits. These surveys are undertaken by phone and are conducted on a quarterly basis.

Table 3-6 shows that almost half (46%) of the wood burned in Norway is burned in stoves with new technology (i.e., emitting less than 10g PM_{10}/kg), and between 3% and 4% of the wood is burned in fireplaces.

Table 3-6. Wood Consumption Distributed on Different Technologies and PM_{10} Emission in Norway for 2009

	Unit	Total	Fireplace	Closed Stove, Old Technology	Closed Stove, New Technology
Wood Consumption in Residences	Gg	1332	46	667	619
Theoretical Energy Content	TWh	6.22	0.22	3.11	2.89
Net Energy	TWh	3.45	0.03	1.25	2.17
PM_{10} Emissions	Gg	26	0.657	22	3

TWh = TerraWatt-hours

Emission factors applied in the Norwegian $PM_{2.5}$ inventory for old stoves (40 g/kg) are based on national measurements and evaluation of typical load factors (Karlsvik et al., 1993). The load factor was found to be 1.0 to 1.25 kg wood/hour, which is lower than what is found in many other Arctic Council nations. In an update of this work, Karlsvik (2004) recommended using a lower emission factor (33 g/kg) for old stoves in urban areas due to differences in operational behaviour. The Foundation for Scientific and Industrial Research[15] (SINTEF) tested about 50 stoves with a new technology to confirm whether or not the emissions were within the emission limits set by the Norwegian regulation (NS3059). The average emission factor from these tests was 6.2 g/kg (SSB, 2001). The resulting factors for old and new stoves and for fireplaces in Norway are shown in **Table 3-7**. The average emission factor for closed stoves (new and old) is projected to decrease with time as the share of new stoves increases. In 2008, the average emission factor for stoves was estimated to 25.28 g/kg.

Table 3-7. Emission Factors Applied in the Norwegian $PM_{2.5}$ Inventory

Type of Stove	EF $PM_{2.5}$ (g/kg)	Source
Fireplace	17.3	U.S. EPA, 1995
Closed Stove, Old Technology, Rural Areas	40	Karlsvik, 1993
Closed Stove, Old Technology, Urban Areas (Oslo)	33	Karlsvik, 2004
Closed Stove, New Technology	6.2	SSB, 2001

An average $PM_{2.5}$ emission factor of 24g/kg is applied for wood burning in Norway's $PM_{2.5}$ emissions inventory (SSB, 2010). In the reviews of emissions data performed under the CLRTAP, Norway has received feedback that emission factors for wood burning are high compared to other nations. There is also some evidence from

---

[15] SINTEF stands for *Stiftelsen for industriell og teknisk forskning* in Norwegian. It is headquartered in Trondheim, Norway at the Norwegian Institute of Technology (NTH) and is the largest independent research organisation in Scandinavia.

measurements of particulates in Norway that suggests that this might be the case. In 2011, Norway will revise and update national source testing through a study that will also provide recommendations on BC emission factors for wood burning. The 2011 study will also include and give recommendations on BC emission factors for wood burning to be applied in a forthcoming national inventory.

Norway has performed several studies on emission factors from wood combustion and has identified that differences between nations' load factors (wood burned per hour) and combustion intensity could be plausible explanations for the differences in emission factors between Norway and many other European countries. The surveys[16] about residential heating habits have shown that a rather low load factor of 1 kg/hour and low combustion intensity is representative for Norwegian households. This operational practice leads to high PM emissions compared to other nations. It is therefore important that the basis for the tests of stoves are known before comparisons are made and conclusions are drawn.

Emissions from Flaring

According to the Norwegian national $PM_{2.5}$ inventory, particulate emissions generated from off-shore and on-shore flaring of hydrocarbons from petroleum prospecting, production installations, and refineries are minor. In concert with the possibility of ice-free Arctic waters due to climatic warming and concerns that the petroleum industry will move northwards, new interest has emerged to understand how BC emissions from flaring could contribute to accelerated melting of sea ice and snow in the Arctic.

There are three major combustion sources offshore: diesel engines, turbines, and flaring. Of these three sources, flaring is by far the largest source of particulate emissions. In Norway, flaring (mainly of natural gas) is generally conducted during well testing and for safety reasons. The total volume of gas and liquid fuels flared in the Norwegian petroleum sector has decreased significantly over the years due to the introduction of a CO_2 tax for offshore activities in 1991. In 2010, the tax for the petroleum industry was 201 Norwegian Krone per tonne (NOK/tonne), or about 25 Euros per tonne, for offshore activities,[17] and 271 NOK/tonne (34 Euro/tonne) for condensate. More information about the CO_2 tax can be found in Norway's *Fifth National Communication under the UNFCC* (MD, 2009).

The amount of hydrocarbons flared by Norwegian petroleum companies is reported to the Norwegian Petroleum Directorate (NPD). The volumes flared have varied over the years, but are in the order of about 20 Petajoule (PJ), or 400 to 500 million standard cubic meters (Sm^3), of gas per year. The authors from Norway feel confident that the reported volumes flared are reliable. **Figure 3-20** shows the ratio between produced and flared hydrocarbons decreased by 50% over the 1990 to 2008 time period.

PM emission factors associated with flaring are documented in the *The Norwegian Emission Inventory 2010, Documentation of Methodologies for Estimating Emissions*

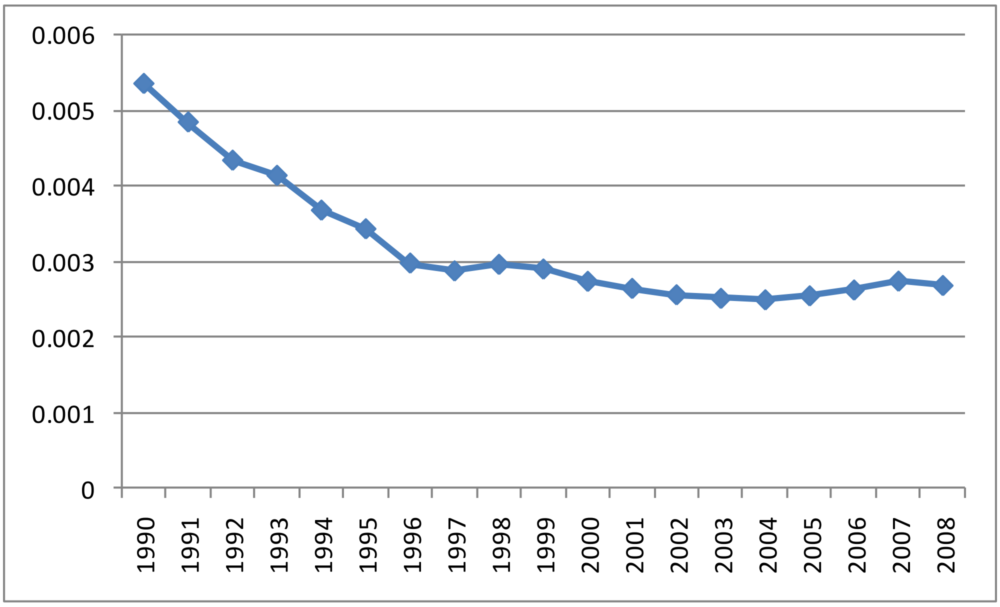
---

[16] Reise- og ferieundersøkelsen (The Travel and Vacation Survey). Norwegian households are asked about their wood consumption, type of fireplace, and the age of the fireplace. Results are published at Statistics Norway, http://www.ssb.no/magasinet/miljo/art-2010-11-09-01.html (in Norwegian).

[17] Natural gas, condensate, and oil have the same tax per consumed amount of fossil fuel, but the tax will differ due to the difference in density and emissions per unit fuel.

Of Greenhouse Gases and Long-range Transboundary Air Pollutants (SSB, 2010) and also in a separate report, *Emissions to Air from Wood Combustion*[18] dedicated to the emissions of PM (SSB, 2001). The emission factors applied in the national inventory for flaring during well testing are taken from a study by The Norwegian Oil Industry Association (OLF; OLF, 1993). OLF performed a full-scale test on-shore because it was considered impossible to collect samples offshore. Twenty-six tests were conducted, with a test length of 5 to 20 minutes. Oil volumes collected ranged from 65 to 440 litres/minute (L/min). The average result for emissions of BC in these tests was 25 g carbon (soot)/kg oil. This factor is used to estimate the emissions of total solid particulate (TSP) from well testing in the Norwegian emissions inventory. The emissions factors applied for PM_{10} and $PM_{2.5}$ are lower at 21.5 and 14 g particulates/kg oil, respectively, based on a combination of the OLF study and information about size distribution from U.S. EPA (2002).

Figure 3-20. Ratio between flared and produced petroleum in Norway, 1990–2008.



Unit: Petajoules per Petajoules (PJ/PJ)

Emissions from natural gas flaring applied in the Norwegian $PM_{2.5}$ inventory are estimated using emission factors derived from U.S. EPA (2002), as presented in **Table 3-8**.

---

[18] The SSB (2001) report is in Norwegian.

Table 3-8. Emission Factors for Flare Operations* from U.S. EPA (2002)

Component	Emission Factor ($lb/10^6$ Btu)
Total Hydrocarbon†	0.14
Carbon Monoxide	0.37
Nitrogen Oxides	0.068
Soot‡	0–274

* Source: U.S. EPA, 2002; based on a flare efficient study conducted by McDaniel (1983) involving tests using crude propylene containing 80% propylene and 20% propane.

† Measured as methane equivalent.

‡ Soot in concentration values: non-smoking flares, 0 micrograms per litre (µg/L); lightly smoking flares, 40 µg/L; average smoking flares, 177 µg/L; and heavily smoking flares, 274 µg/L.

The emissions factor for propylene (177µg soot/Litre) used in McDaniel (1983) is converted to 0.002 gram particulates/Sm^3 natural gas in the Norwegian inventory.

Comparison of Norwegian Emissions with the GAINS and Bond Inventory

Because there is a lack of country-specific emission factors for BC, Norway reviewed the BC data representing Norway in the GAINS model. The focus of this work was to assure that the activity data in the GAINS model and its distribution upon different technologies corresponds well with the input to Norway's $PM_{2.5}$ national inventory. **Figure 3-21** shows the $PM_{2.5}$ emissions data in the 2010 Norwegian inventory[19] compared to the GAINS $PM_{2.5}$ emissions as of 29 June 2010 (not including flaring emissions[20]). The comparison indicates that there is very good agreement between the Norwegian inventory and the GAINS data. The emissions data per sector compare well, and the total emissions and sectoral distribution is nearly identical for the latest year, 2005. Norway is therefore confident that the BC data from the GAINS model adequately represent Norwegian emissions.

According to GAINS data, BC emissions totalled 5 Gg for Norway in 2005. The key source categories include residential wood heating stoves, followed by different modes of diesel transportation (trucks, ships, machinery) and fireplaces.

Figure 3-22 compares the GAINS and Bond BC and OC emissions inventory for the year 2000 and also presents GAINS data for 2005. There are large differences between Bond and GAINS OC emissions estimates for the Domestic sector in 2000. The BC emissions estimates compare favourably.

---

[19] Reported to the CLRTAP on 15 February 2010.

[20] Emissions from flaring are regarded as highly uncertain by IIASA and are thus not included in the GAINS data applied for this report. Preliminary estimates of BC emissions from flaring in the GAINS model total 1 Gg for 2005.

Figure 3-21. Comparison of Norwegian and GAINS $PM_{2.5}$ emissions for 1990–2005, aggregated to SNAP categories in Gg/yr.

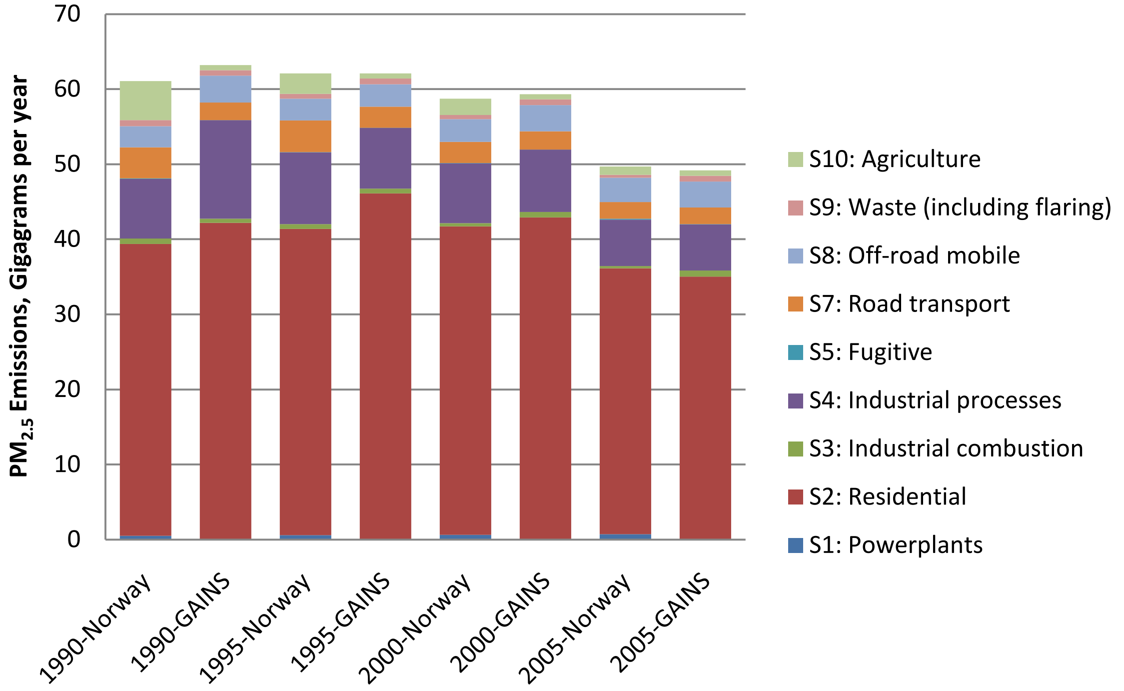
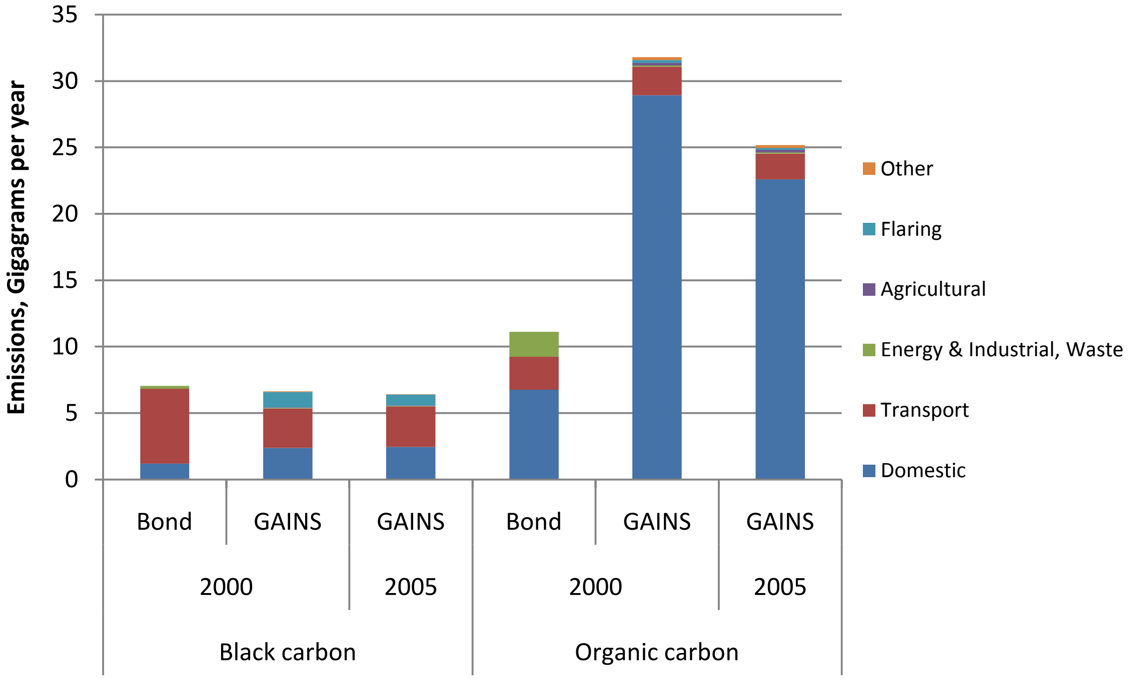


Figure 3-22. BC and OC emissions for 2000 and 2005 by sector, Norway (Gg/yr).*



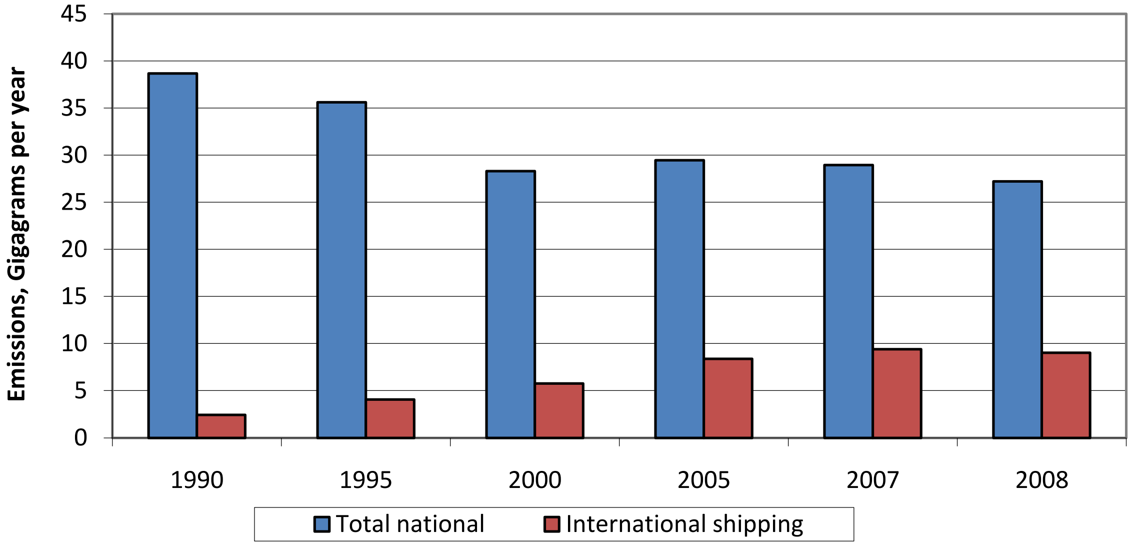
* Norway did not provide a national BC and OC emissions inventory for 2005. Open biomass burning emissions are not included in this figure and are expected to be minimal.

3.4.5 Sweden

Sweden's national inventory includes emissions of air pollutants and GHG emissions inventoried in accordance with the CLRTAP and the UNFCCC, respectively. Currently, BC emissions are not part of these conventions; therefore, $PM_{2.5}$ emissions are used as the best available proxy to estimate BC and OC emissions for the purposes of this report (Kupianen and Klimont, 2007). In accordance with the CLRTAP, Sweden compiles an annual emissions inventory (Sweden's Informative Inventory Report) for $PM_{2.5}$, in addition to SO_2, NO_X, non-methane VOCs, CO, ammonia, PM, various heavy metals, and persistent organic pollutants (POPs). Historic emissions previously reported are reviewed each inventory year and updated if necessary.[21]

Since 1990, $PM_{2.5}$ emissions in Sweden have decreased by 30%. In the same period, emissions from international shipping bunkering fuel have increased 400% (see **Figure 3-23**).

Figure 3-23. Total emissions of $PM_{2.5}$ for 1990–2008, Sweden (Gg/yr).



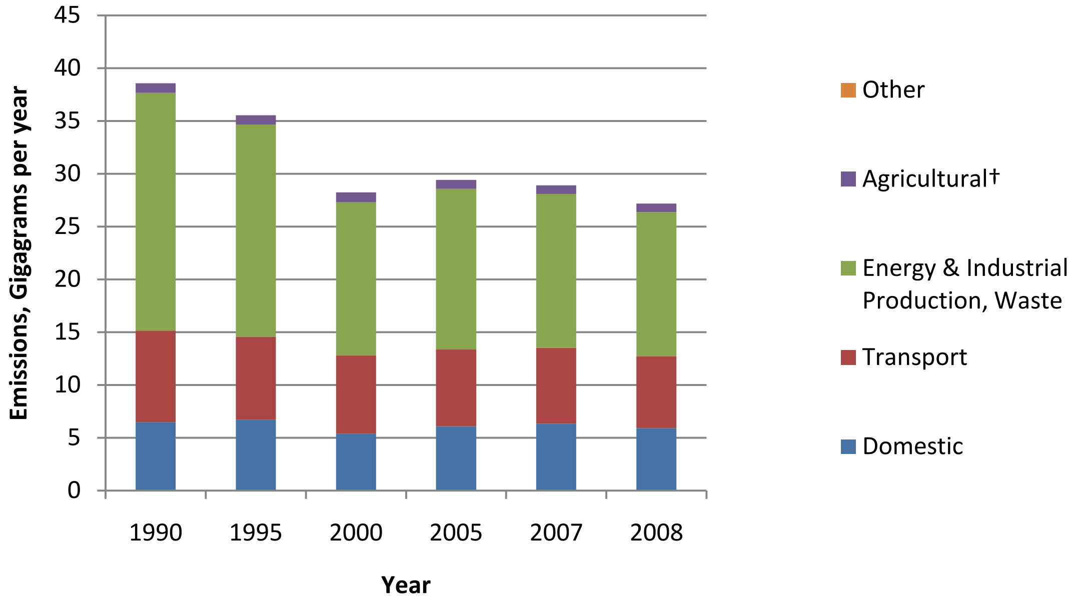
Since 1990, $PM_{2.5}$ emissions in Sweden have increased 56% since 1990 in the energy, public electricity, and heat production source categories (part of the Energy & Industrial, Waste sector used in GAINS and this report), specifically caused by a switch from fossil fuel use to biomass. In addition, many of the country's residential and commercial heating boilers have been replaced with district heating, resulting in an increase of heat production and increases in Domestic sector emissions. In other key source categories, such as road traffic and working machinery (part of the Transport sector), $PM_{2.5}$ emissions have decreased by 60% and 40%, respectively, since 1990, in spite of increased energy use. This decrease in emissions can be attributed to the introduction of successively more stringent tailpipe emission requirements.

---

[21] The QA/QC for the Swedish $PM_{2.5}$ emission inventory system complies with the Tier 1 procedures outlined in the IPCC *Good Practice Guidance* (2000). Uncertainty estimates of the 2010 submission were made in accordance with the Tier 1 methodology described in the EMEP *CORINAIR Guidebook 2009* (Sweden's Informative Inventory Report), 2010.

Figure 3-24 presents details of $PM_{2.5}$ emissions for Sweden, broken down by the sectors used in this report, excluding international shipping. **Table E-1** in ***Appendix E*** provides detail on how the Swedish source categories were aggregated to the 7 major sectors.

Figure 3-24. Detailed emissions breakdown of $PM_{2.5}$ emissions in Sweden for 1990–2008, excluding international shipping (Gg/yr).*

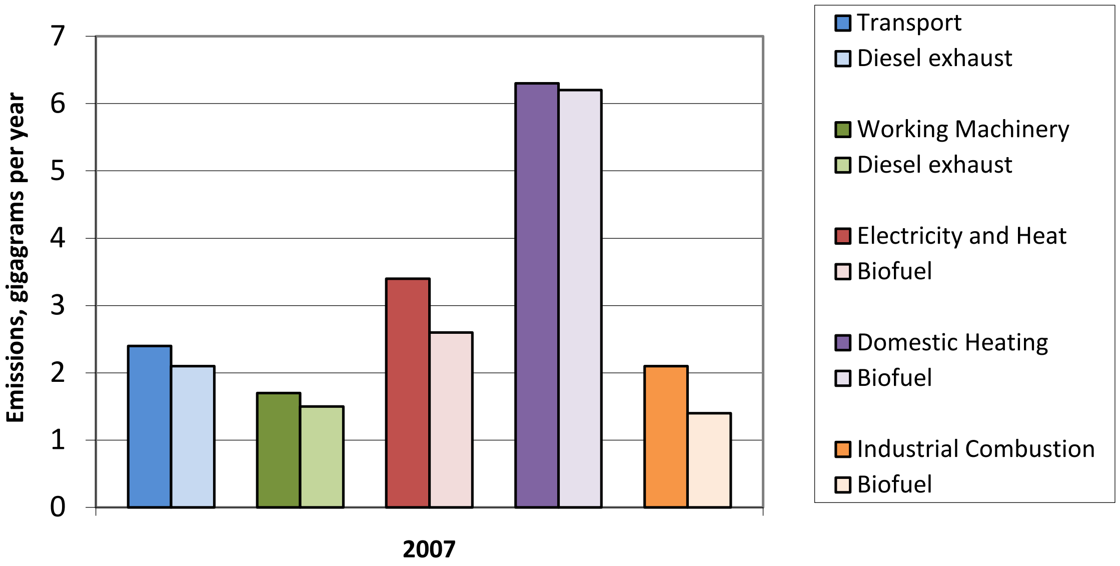


* Open biomass burning and flaring are not considered applicable and were not estimated.
† Emissions included in the Agricultural sector are non-combustion related.

Figure 3-25 presents $PM_{2.5}$ emissions from the major combustion sources in Sweden in 2007. Electricity and heat production, which is mainly fuelled by biomass and waste, generated the largest amount of $PM_{2.5}$ emissions in 2007. In 2008, about 60% of all fuels used for district heating were biomass, while waste accounted for approximately 20%, in comparison with 1990 when 15% of fuels used were biomass and 15% were waste, with the remainder from fossil fuels. During the same period, there has been a large increase in the use of district heating from 90 PJ (1990) to 171 PJ (2008).

The pulp and paper industry, iron and steel works, and the chemical industry together account for about 70% of industrial energy use in Sweden. Despite rising industrial production, oil consumption has fallen due to increased use of electricity, improved energy efficiency, and increased use of bioenergy sources. Approximately 80% of the country's $PM_{2.5}$ emissions from industrial combustion originate from the combustion of black liquor in the pulp and paper industry and other biomass fuels.

Figure 3-25. Emissions of $PM_{2.5}$ in 2007 from combustion sources and the amount derived from different fuels, Sweden (Gg/yr).*



* For each sector, the $PM_{2.5}$ emissions from combustion are indicated by the bar on the right, and the single fuel that accounts for the majority of emissions in that sector is indicated by the bar on the left.

BC and OC emissions were estimated using assumed BC and OC fractions (see **Table 3-9**) and Sweden's $PM_{2.5}$ emissions inventory data for several source categories. The assumed BC and OC fractions presented in Table 3-9 are approximate values estimated from the work of Kupiainen and Klimont (2007) and by IIASA for the CLRTAP's ad hoc Black Carbon Expert Group and for the Task Force on SLCF. 2007 data are used because fuel consumption has been extracted and associated with source category $PM_{2.5}$ emissions. Emissions totalled 5.1 and 6.5 Gg for BC and OC, respectively (see **Figure 3-26** and supporting data in **Tables G-2 through G-4** in ***Appendix G***).

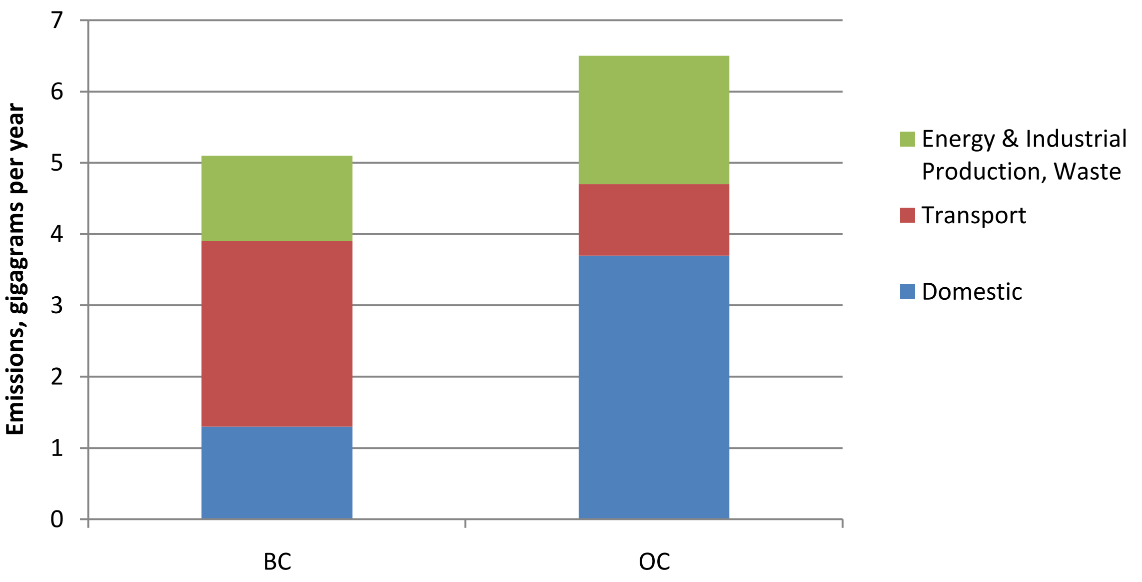
Table 3-9. Assumed Fractions of BC and OC Per Unit $PM_{2.5}$ Emissions for Source-specific Categories in Sweden for 2007*

Category	BC Fraction	OC Fraction
Transport		
Diesel (30% LDV, 45% HDV, 20% navigation) †	0.7	0.2
Other Fuels (mainly gasoline)	0.2	0.7
Working Machinery (Off-Road Mobile Sources)		
Diesel	0.7	0.2
Gasoline	0.2	0.7
Public Electricity and Heat Production		
Biofuels	0.2	0.5
Other	0.4	0.1
Individual Heating of Houses		
Biofuels	0.2	0.6
Other	0.8	0.1
Industrial Combustion		
Biofuels	0.1	0.2
Other	0.3	0.1

* Based on Kupiainen and Klimont (2007). Primary emissions of fine carbonaceous particles in Europe 2007, and information from ongoing work by IIASA (Amann et al., submitted; Kupianen and Klimont, 2007) for the CLRTAP's ad hoc Black Carbon Expert Group and for the Task Force on SLCF.

† Percent figures relate to share of $PM_{2.5}$ emissions.

Figure 3-26. BC and OC emissions by sector for 2007, Sweden (Gg/yr).*



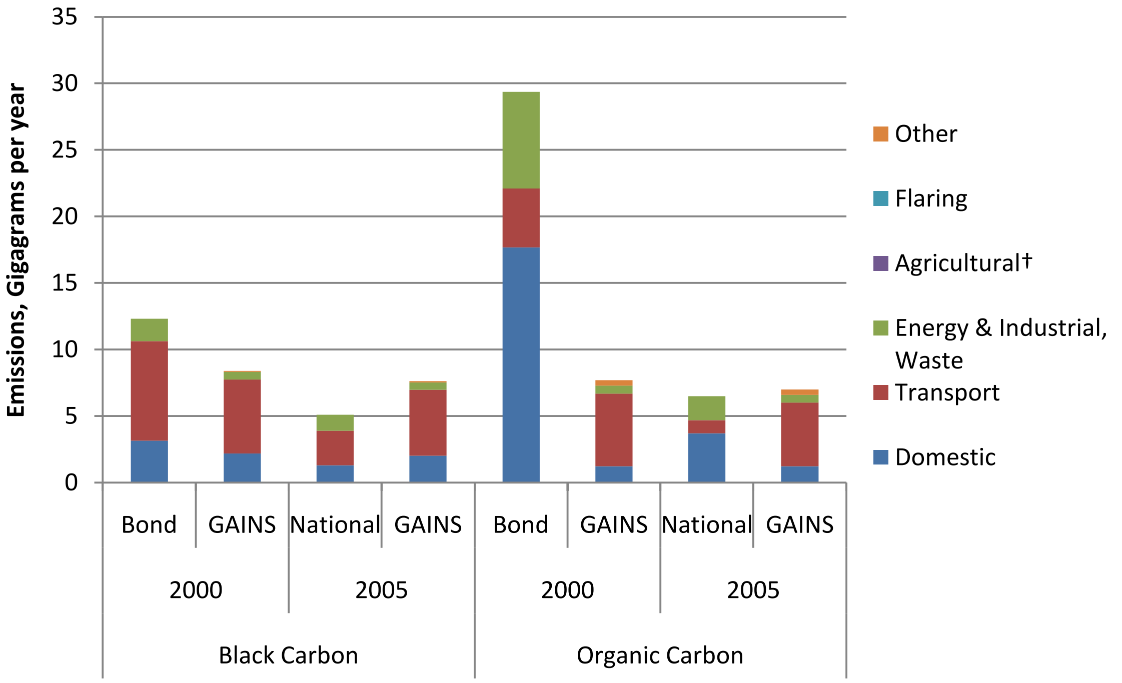
* Emissions from open biomass burning and agricultural are not considered applicable and were not estimated. BC and OC emissions were not estimated for flaring.

Comparison of Swedish Emissions to GAINS and Bond Emissions Inventories

Figure 3-27 compares Sweden's BC and OC emissions inventory to that of GAINS and Bond for the year 2000. Large differences are evident in the Transport, Domestic, and Energy & Industrial Production, Waste sectors. The largest difference lies with the

Bond inventory's OC emissions estimates for the Domestic sector, which dwarf all other emissions. The consumption of biofuels in the Domestic sector is difficult to estimate, and there are fairly large uncertainties associated with activity data and emission factors for different stove and boiler technologies.

Figure 3-27. BC and OC emissions for 2000 and 2005 by sector, Sweden (Gg/yr).*



* Open biomass burning emissions are not included in this figure and are expected to be minimal.

† Agricultural sector emissions in the national inventory consist of agricultural non-combustion sources; tractors and other mobile sources are included under the Transport sector.

3.4.6 United States

The emissions data presented here are found in EPA's draft Report to Congress on Black Carbon (EPA, 2011). As that report is undergoing peer review at the time of this writing, the emission numbers herein are subject to further change.

The U.S. emissions inventory uses estimates of $PM_{2.5}$ emissions to derive information on direct emissions of carbonaceous particles, including BC (or EC, if actual measurements are made) and OC. Therefore, all of the available emissions inventory information on light-absorbing carbon emissions in the United States is restricted to those source categories with sufficient $PM_{2.5}$ emissions estimates to support this estimation. BC emissions for most sources are estimated by matching $PM_{2.5}$ emissions for source categories from the National Emissions Inventory (NEI) to source-specific BC speciation profiles from the SPECIATE database. The one exception is on-road mobile sources, for which BC emissions are estimated directly through models. [22]

---

[22] Readers are referred to Appendix 2 of the 2011 *Draft Black Carbon Report to Congress* (U.S. EPA, 2011) for more detailed information regarding the methods used to generate United States emissions inventories.

The activity patterns used for point and nonpoint sources are each obtained in different ways, owing to the differing nature of the sources. Most point sources or industrial sources operate with local permits, and these require information about process emissions, including temporal characteristics. For sources with Continuous Emissions Monitoring technology (CEMs) for monitoring opacity (which is roughly proportional to fine PM loading), such as large utility boilers, real-time data are available to derive activity patterns and deduce emission variability over extended time periods. Further, point sources keep and report records of output during operating periods and of maintenance or other down times.

There is a great deal of complexity in acquiring activity data for nonpoint sources (e.g., the construction industry, open biomass burning, residential wood burning), which are diverse in character, individually small, and often intermittent, but collectively significant. Though such sources are difficult to characterize, they are generally important to estimating PM emissions because their aggregated mass emissions can be large and their chemical composition (e.g., BC) may be important for estimating source attribution. One good example of such a category is open biomass burning, specifically forest fires, burning of land-clearing debris, and agricultural burning.

For nonpoint sources, emissions can be estimated coarsely from “top-down” measures using activity level data for demographics, land use, and economic activity at the state or national level. The construction industry, for example, is based on the total annual expenditures at the regional level. These estimates are then allocated by county, using a procedure linked with construction costs and estimated area under construction. Because of their potential importance as PM sources, considerable effort has been devoted recently to the characterization of emissions and activity patterns for nonpoint sources. Another example is estimation of emissions from fires (i.e., open biomass burning), which depends upon knowledge of the time, location, and areal extent of the burn; fuel loading; types of combustible material; and moisture content. Open biomass burning emissions come from inventories developed by Regional Planning Organizations (RPOs). The RPO open biomass burning emissions data use ground-level activity information in the form of U.S. state and/or federal agency databases. This information is lacking in many areas. In these instances, ground-level activity information was determined using area knowledge or surveys sent to the state agencies. Since the emissions inventories are based on ground-level fire activity information, fire type categorization (prescribed forest burning, wildfires, and agricultural burning) was not an issue as it is sometimes is when using satellite data, which cannot distinguish between the fire type categories. Emissions estimates for agricultural burning and prescribed forest burns are not expected to change significantly from year to year. Wildfire emissions estimates represent average emissions over a longer period of time.

Residential wood combustion is also an important local source of PM and BC. Quantification of emissions from this source category has been estimated using data on the quantity of fuel burned in fireplaces and woodstoves based on national consumption estimates. Where this source is a large contributor to PM, local surveys of firewood use are used to supplement and improve activity level estimates.

The United States is estimated to emit approximately 6% of the total global BC emissions each year, or about 578,000 metric tons out or more than 8.2 million metric tons globally, making it the seventh largest emitter worldwide (Lamarque et al., 2010).[23] The majority of BC and OC emissions come from mobile sources (predominantly diesel), agricultural burning, and open biomass burning (prescribed forest burning and wildfires). In 2005, about 65% of total U.S. BC was emitted in urban counties and, in the case of mobile sources, more than 70% of the total U.S. BC emissions occur in urban counties. From 1990 to 2005, BC emissions in the United States declined by about 30% and are expected to decline by an additional 80% by 2030, compared to 2005 levels, largely due to PM regulations on emissions from mobile sources.

Total primary $PM_{2.5}$ emissions in the United States in 2005 are estimated to be about 5,009 Gg (5,521,456 short tons), of which approximately 12% (637,167 short tons or 578 Gg) is BC and about 30% (1,662,164 short tons or 1,508 Gg) is primary OC. Thus, at a national level, there is more than twice as much OC emitted from domestic sources as BC, as can be seen in **Figure 3-28**.

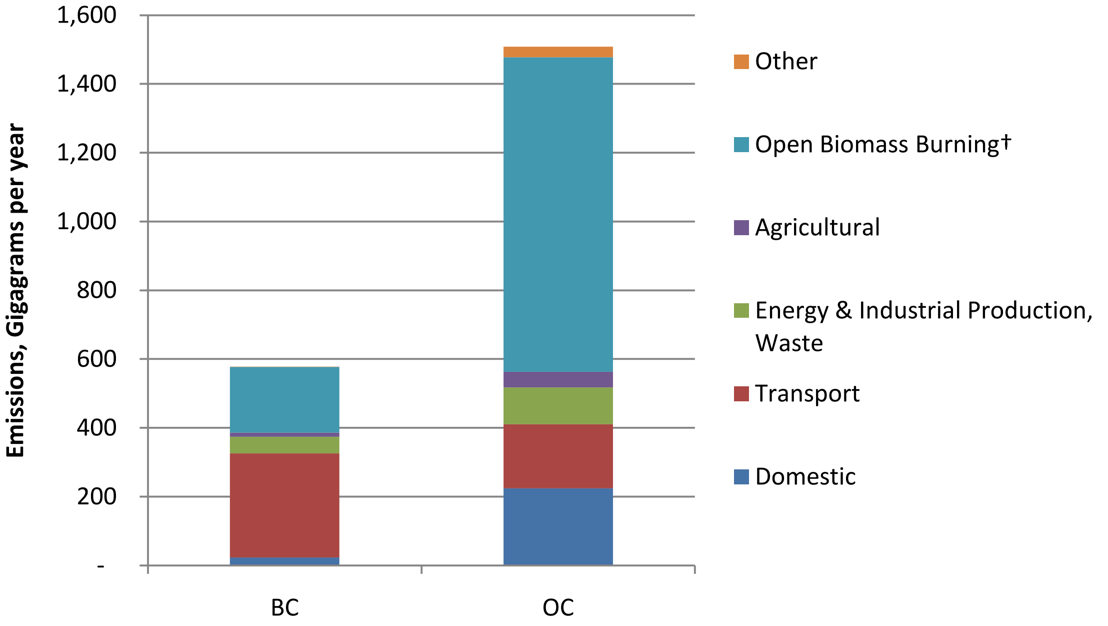
To facilitate comparisons with the national inventories of the other Arctic Council nations, the U.S. source categories have been aggregated to the seven sectors used in this report. **Table F-1** in ***Appendix F*** provides more detail as to how the U.S. inventory was categorized. Figure 3-28 clearly shows the Transport sector (i.e., mobile sources, which include all exhaust emissions, plus tire and brake wear) to be the dominant contributor of the total BC emissions in the United States in 2005. The Transport sector contributes 52% of the total BC emissions, followed by the Open Biomass Burning sector (prescribed forest burning and wildfires, 33%) and fossil fuel combustion source categories in the Energy and Industrial Production, Waste sector (8%).

The Open Biomass Burning and Agricultural sectors contribute the majority of total OC emissions (64%) for the United States, followed by the fossil fuel combustion sources in the Domestic sector (15%), and then the Transport (12%) sector. Approximately 54% of total wildfire emissions originate in Alaska.

---

[23] Based on emissions estimates for the year 2005 for all source categories except open biomass burning, which are based on a 2002 inventory.

Figure 3-28. BC and OC emissions by sector for 2005, United States (Gg/yr).*



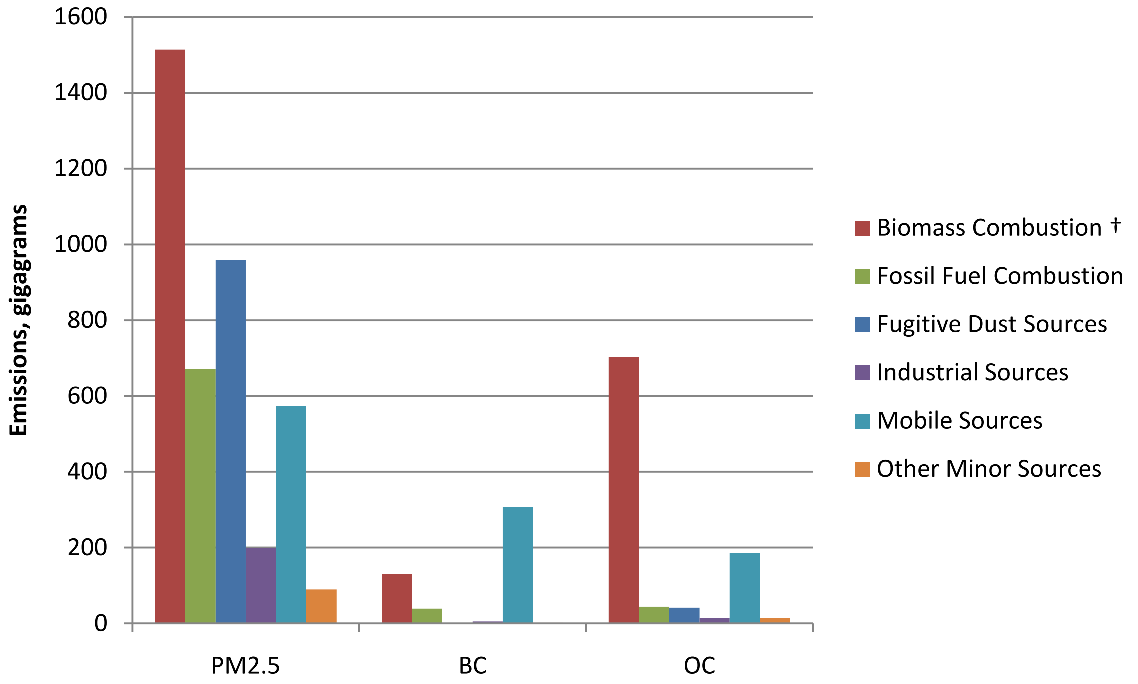
* All emissions data are from the Draft *Report to Congress on Black Carbon (U.S. EPA, 2011)*. Emissions from flaring were not estimated. At the time of publication, this report was in the peer-review draft stage; emissions data are subject to change.

† Open biomass burning includes prescribed burns, agricultural burns, slash burning, and wildfires. The open biomass burning emissions are from a 2002 inventory developed by five RPOs across the United States, which are partially funded by the U.S. EPA.

Figure 3-29 displays the breakdown of total U.S. primary $PM_{2.5}$, BC, and OC emissions for six source categories: biomass combustion; fossil fuel combustion (which includes natural gas, coal, and oil from residential, industrial, commercial, and electric generation); fugitive dust sources; industrial sources; mobile sources; and other minor sources. Supporting data showing the actual tons of emissions and key emission ratios can be found in **Tables F-2 and F-3** in ***Appendix F***.

It is important to note that the national inventories do not account for secondary formation of particles in the atmosphere. While this is not significant for BC, as there is very little secondary formation for BC, it is more important for OC, where secondary organic compounds can form a significant part of atmospheric OC. Also, the inventories do not account for the mass that is generally attached to OC in the atmosphere, to form a total organic mass (OM). Most air quality and climate models rely on estimates of OM, rather than OC, to calculate atmospheric reactions and impacts.

Figure 3-29. Emissions of $PM_{2.5}$, OC, and BC by source category in 2005, United States (Gg/yr).*



* All emissions data are from the Draft *Report to Congress on Black Carbon* (U.S. EPA, 2011).

† Biomass combustion includes open biomass burning (prescribed burns, agricultural burns, slash burning, and wildfires), residential wood combustion, wood-fired boilers, meat frying, charbroiling, and potato deep-frying.

The general category of biomass combustion in the U.S. 2005 inventory includes agricultural burning and open biomass burning (prescribed forest burning and wildfires) and other categories, such as charbroiling, potato-deep frying, meat frying, residential wood combustion, and wood-fired boilers. Following the suggestion of Bond and colleagues (2004, 2007) on a way to disaggregate sources within biomass burning to better deal with mitigation options, the source categories shown in **Table 3-10** are divided into four categories: agricultural burning, open biomass burning (prescribed burns and wildfires), residential heating/cooking (residential wood burning), and biomass fired stationary sources (charbroiling, potato deep-frying, meat frying, and wood fired boilers). Prescribed forest burning is considered a mitigation option for wildfires. These same distinctions are made to the sources shown above and tabulated appropriately in **Table F-2** in ***Appendix F*** and shown graphically in **Figure 3-30.**

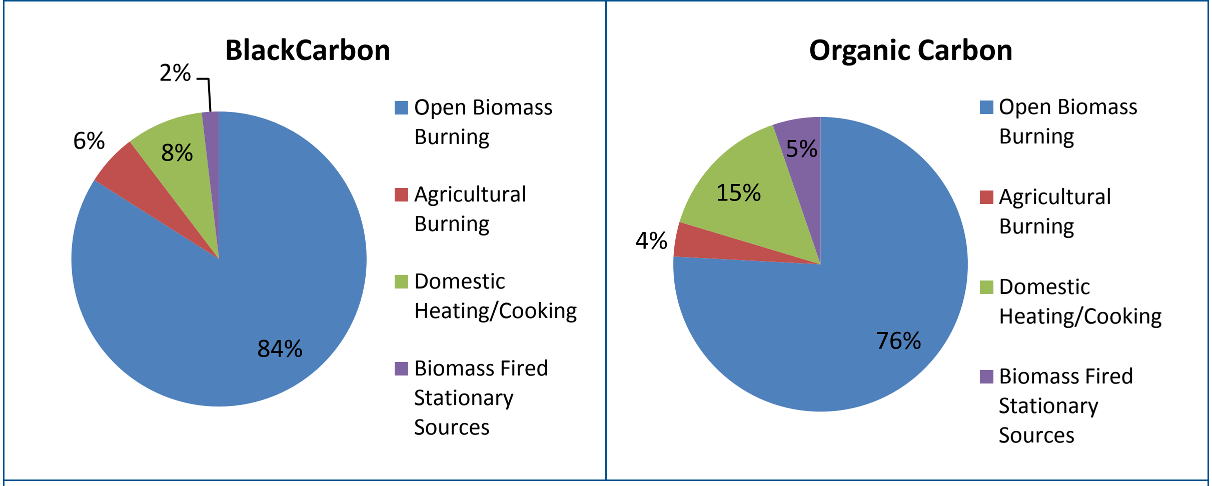
Table 3-10 and Figure 3-30 show that open biomass burning (mostly wildfires) dominated both the BC (84%) and OC (76%) emissions inventory in 2005 as a fraction of all burning categories. Wildfires are estimated to be the largest source of open burning emissions of both BC and OC, contributing to about 68% and 70% respectively. Emissions from wildfires can vary greatly from year to year; however, the single year estimated provided in the draft EPA (2011) report is consistent with an average of wildfire activity in the U.S. over the ten year period from 2001 to 2010.

Emissions from residential wood combustion are seen to be the second highest contributor within all the biomass burning categories.[24] Supporting data can be found in **Table F-4** in ***Appendix F***. There are large uncertainties surrounding the emissions estimates for open biomass burning due to limited data on the percent of land area affected by different types of burning. BC:OC ratios for biomass combustion sources are generally much greater than one, indicating a predominance of OC emissions (about 80% on average).

Table 3-10. 2005 Biomass Burning Emissions from Grouped Subcategories in Gg

Biomass Combustion Category	$PM_{2.5}$	BC	OC	BC:OC	BC:PM
Open Biomass Burning (Prescribed Forest Burns and Wildfires)	1,937.73	190.85	914.28	4.73	0.10
Prescribed Forest Burning	*485.91*	*53.09*	*243.87*	*4.59*	*0.11*
Wildfires	*1,451.82*	*137.76*	*670.41*	*4.87*	*0.09*
Agricultural Burning	118.41	12.91	45.97	3.56	0.11
Domestic Heating/Cooking	344.62	19.23	182.02	9.00	0.06
Biomass Fired Stationary Sources	120.49	4.26	63.39	13.53	0.03
Total	2,521.26	227.25	1,205.66	8.96	0.09

Figure 3-30. Percent of BC and OC emissions in Gg for 2005, grouped by combustion categories, United States.*



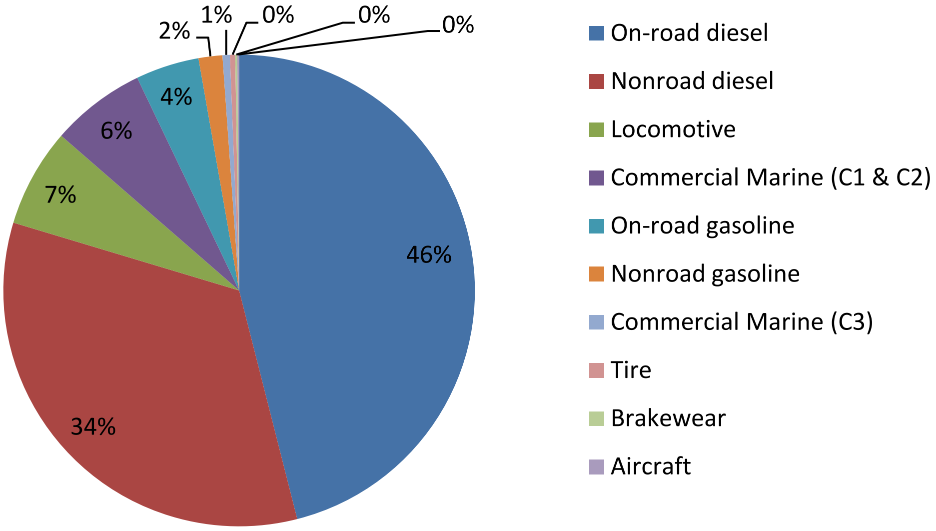
* Open biomass burning includes prescribed forest burning and wildfires. All emissions data are from the Draft *Report to Congress on Black Carbon* (U.S. EPA, 2011).

Within the Transport sector, emissions from diesel mobile sources (both on- and off-road) dominate, accounting for about 80% of BC emissions. Gasoline vehicles and/or engines are responsible for the remaining 6% of BC emissions from the mobile source category. **Figure 3-31** shows a more detailed breakout of mobile source BC emissions. In general, diesel $PM_{2.5}$ consists of about 70% to 80% BC and about 20% OC. Gasoline $PM_{2.5}$, in contrast, consists of about 20% BC, with the remainder being mostly OC. Diesel PM is thus unique in having a very high ratio of BC to OC.

---

[24] Because of the limited amount of speciated emissions data available, many subcategories under the domestic heating/cooking sub-category were "composited" to arrive at these emission estimates (for example, woodstoves were combined with fireplaces, when the two are in actuality mitigated differently).

Figure 3-31. Detailed breakdown of BC emissions (total of 308 Gg) in the Transport sector, United States 2005 NEI (U.S. EPA, 2011).



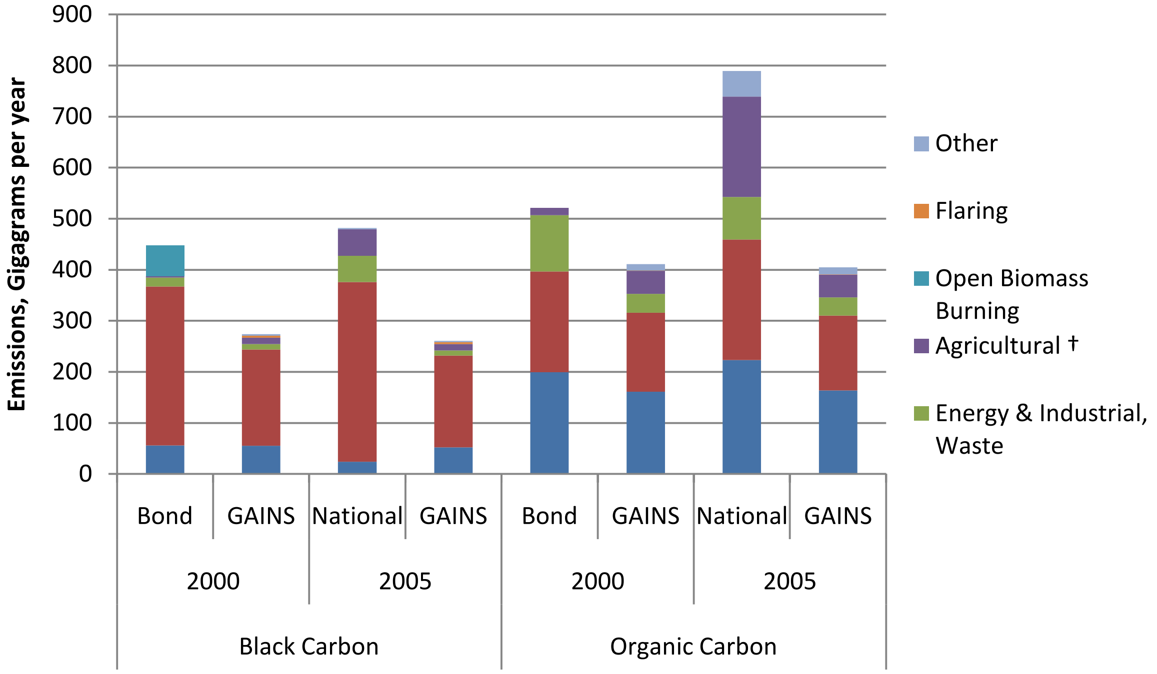
Fossil fuel combustion in the energy and power generation sector contributes approximately 7% of U.S. BC emissions and includes a range of emission source categories (i.e., bituminous combustion, distillate oil combustion, natural gas combustion, PM-SO_2 controlled lignite combustion, process gas combustion, residential coal combustion, residential natural gas combustion, residual oil combustion, and sub-bituminous combustion). In general, emissions from these sources are split fairly evenly between BC and OC. Within the energy and power generation sector, the largest fossil fuel combustion source of BC emissions according to the 2005 NEI is natural gas combustion (U.S. EPA, 2005); however, estimates of the amount of BC compared to OC in direct $PM_{2.5}$ emissions from this source category are highly uncertain. The bituminous and sub-bituminous categories, both of which primarily represent EGUs but may also reflect small contributions from commercial and institutional sources, represent relatively small contributions to BC emissions in the United States (a little more than 1% each). This is quite different from these sources' contribution to emissions of long-lived GHGs, where they dominate the inventory (e.g., EGUs account for 40% of CO_2 emissions).

The remaining three meta-categories of industrial sources, fugitive dust sources, and other minor sources have a fractional contribution of approximately 2%. Direct $PM_{2.5}$ emissions from industrial sources in the United States are small compared to emissions of other co-emitted pollutants and also have been well controlled over time through use of various technologies to capture PM emissions for a variety of stationary/industrial sources. The one industrial source of potential interest is stationary source diesel engines (e.g., generators, emergency equipment), which has a high BC/OC ratio and contributes more than half of the BC emissions to the industrial sources source category.

Comparison of United States Emissions with GAINS and Bond Inventories

Figure 3-32 compares the data from the national United States BC and OC emissions inventory to the Bond and GAINS inventories, aggregated to the sectors used in this report. Open biomass burning emissions are not included in Figure 3-32. There is good agreement between the inventories, with the largest variations seen in the BC emissions estimates for the Transport sector and OC emissions in the Agricultural sector, particularly in the national 2005 OC emissions estimates.

Figure 3-32. BC and OC emissions for 2000 and 2005 by sector, United States (Gg/yr).*

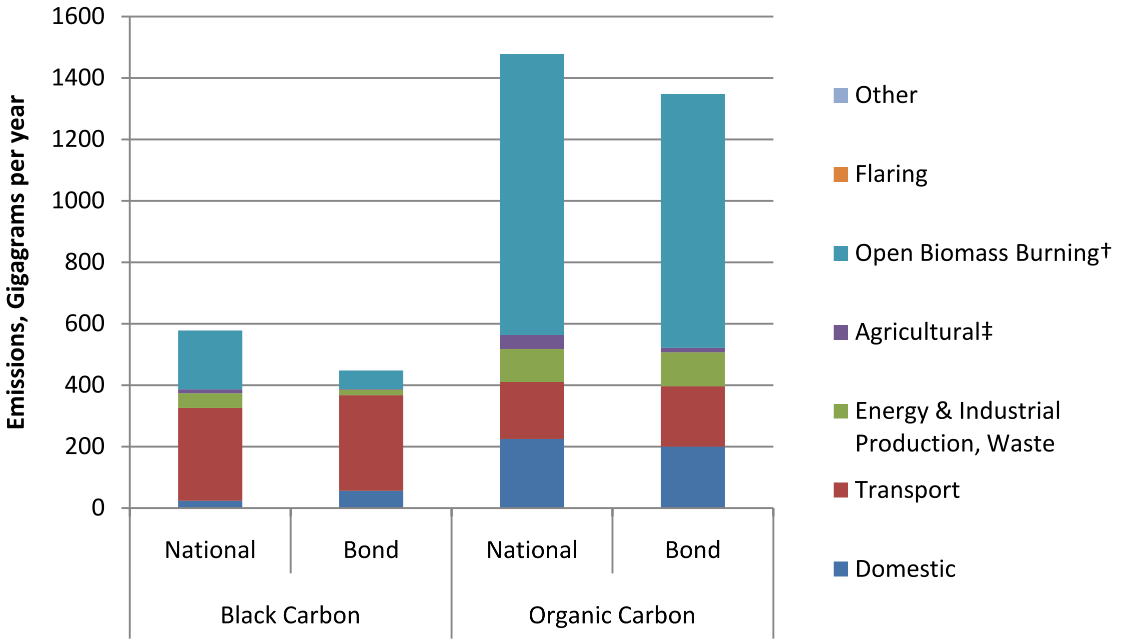


* All national emissions data are from the Draft *Report to Congress on Black Carbon* (U.S. EPA, 2011). Open biomass burning emissions are not included in this figure.

† The Agricultural sector estimates include emissions from agricultural crop burning, agricultural soil, and crustal materials.

Figure 3-33 compares the national United States emissions inventory to the Bond emissions inventory for 2000; emissions from open biomass burning are included. Both the BC and OC emissions estimates are closely aligned in both inventories.

Figure 3-33. BC and OC emissions for 2000 and 2005 by sector, United States (Gg/yr).



* All national emissions data are from the Draft *Report to Congress on Black Carbon* (U.S. EPA, 2011).
† Open biomass burning emissions include prescribed forest burning and wildfires.
‡ The Agricultural sector estimates include emissions from agricultural crop burning, agricultural soil, and crustal materials.

3.5 Synthesis of Emissions Inventories

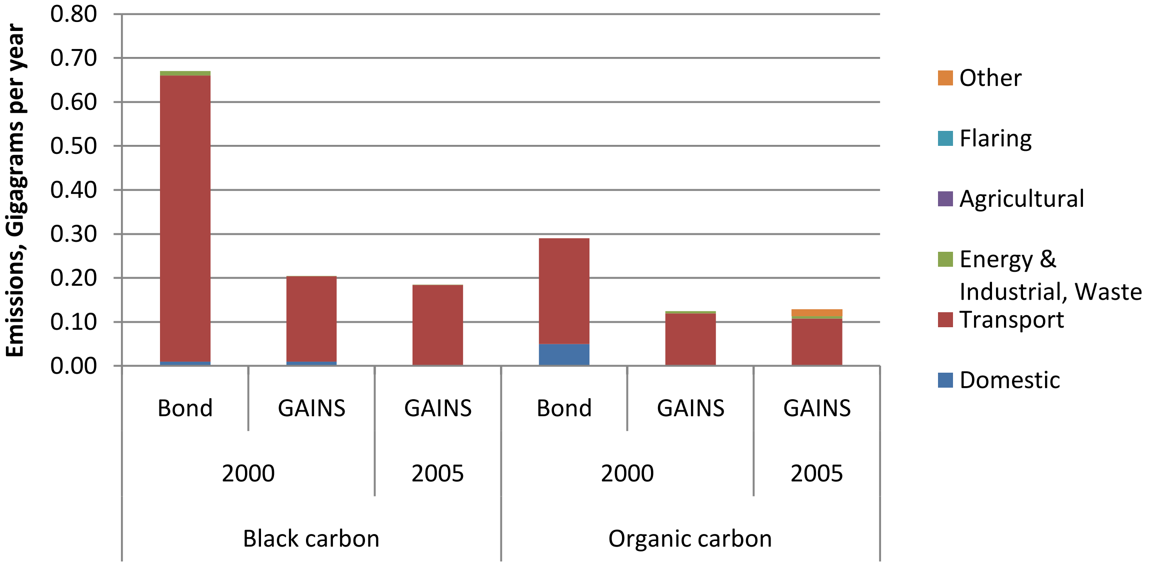
In general, the overall BC and OC emissions estimates agree well between the Bond, GAINS, and those national inventories of Arctic Council nations that were available for this report despite the fact that the base year for comparison may not be exactly the same (i.e., Bond uses 2000, GAINS uses 2000 and 2005, and the national inventory base years vary from 2000 to 2010). However, the emissions estimates for specific source sectors often show large disparities, which can be attributed to methodological differences. According to the GAINS methodology, the Domestic and Transport sectors generate the largest amount of both BC and OC emissions in the Arctic Council region. The largest sectoral differences between the inventories can be identified for each Arctic Council nation:

- **Canada** – The Canadian inventory's OC emissions for the Domestic sector are much higher than indicated by the GAINS emission inventory, presumably due to methodological differences and a different base year (see Figure 3-11).
- **Denmark, Greenland, and the Faroe Islands** – There is generally pretty good agreement between the Bond, GAINS, and national inventories, although the GAINS inventory for 2000 and 2005 has significantly higher OC emissions for the Domestic sector compared to Bond and the national inventories, respectively.
- **Finland** – The Bond inventory's OC emissions estimates for the Energy & Industrial Production, Waste sector are much higher than the estimates provided in

the national and GAINS inventories. The Bond inventory's OC emissions for the Domestic sector are also much higher than the other two inventories.

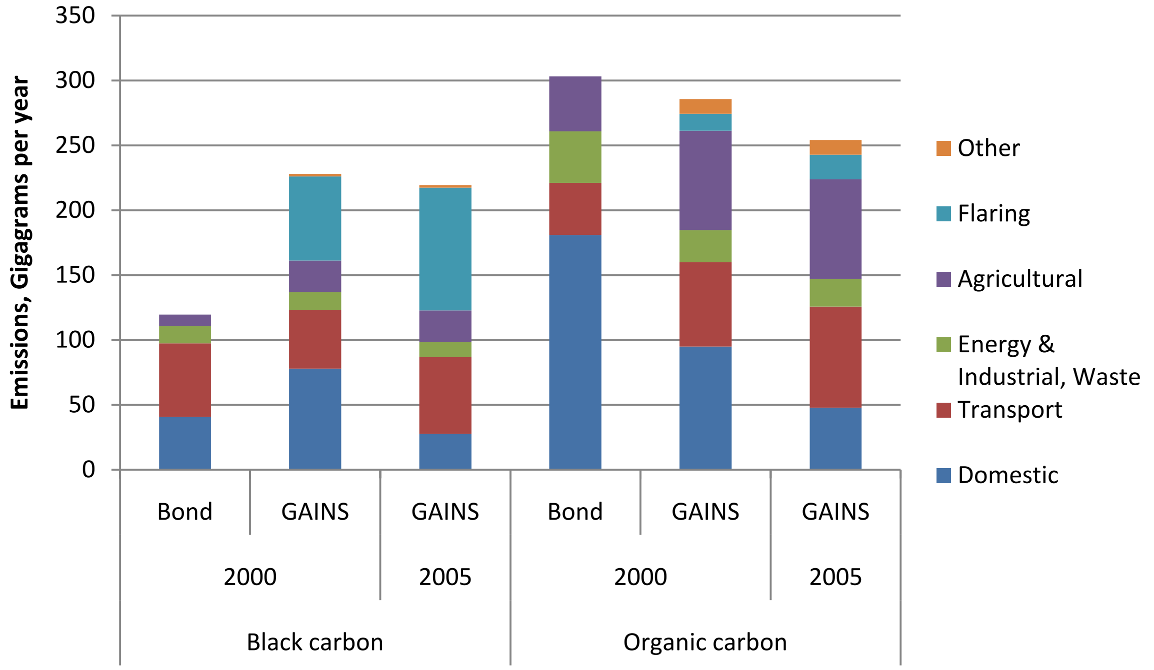
- **Sweden** – The Bond inventory's OC emissions estimates for the Domestic and Energy & Industrial Production, Waste sectors are much larger than estimates provided in the GAINS and national inventories.
- **Iceland and the Russian Federation** did not submit national inventories. The GAINS and Bond emissions inventories for Iceland and the Russian Federation are shown in **Figures 3-34 and 3-35**. The Bond inventory estimates more BC emissions from the Transport sector; but the emissions are minimal so it is not seen as a significant discrepancy. Emissions from the Russian Federation are highly uncertain due to a lack of data. There are large differences shown by emissions estimated by Bond and GAINS, but this appears largely due to the absence of gas flaring emissions in the Bond inventory.

Figure 3-34. BC and OC emissions for 2000 and 2005 by sector, Iceland (Gg/yr).*



* Iceland did not provide a national inventory for 2005 emissions. Open biomass burning emissions are not included in this figure and are expected to be minimal.

Figure 3-35. BC and OC emissions for 2000 and 2005 by sector, the Russian Federation (Gg/yr).*



* The Russian Federation did not provide a national inventory for 2005 emissions. Open biomass burning emissions are not included in this figure. The Bond data do not include flaring.

- **United States** – There is fairly good agreement among the inventories for the Domestic sector, although the national inventory's emissions estimates for the Transport sector in 2005 are somewhat higher than the estimates provided in the GAINS inventory. The national inventory also has higher emissions for the Energy & Industrial Production, Waste sector, most likely due to the large number of meta-categories used in the U.S. national inventory compared to the GAINS inventory. This same scenario plays out when comparing the OC emissions estimates. The 2005 national inventory emissions estimates are higher for most meta-categories than those provided by the GAINS data, particularly for the Agricultural sector.

Section 4

Projected Future Emissions

Introduction

This section presents projected BC and OC emissions through 2030. ***Section 4.1*** presents predictions using the GAINS model, while predictions from each Arctic Council nation are presented in ***Section 4.2***. Overall BC emissions in the Arctic region are projected to decrease in coming decades, primarily because of decreased emissions in the Transport sector due to stronger PM (i.e., $PM_{2.5}$) controls on diesel vehicles and equipment. The implementation of these controls is primarily motivated by health and other air quality benefits, not by Arctic climate concerns. The projected decrease in BC emissions will be highly dependent on the effectiveness of current and future adopted legislation and on how rapidly older vehicles that are not covered by the new legislation are retired.

A number of studies have projected future global BC emissions, including Streets (2007), Cofala and colleagues (2007), and Rypdal and colleagues (2010). These studies show BC decreasing globally by about 9% to 34% below present levels (approximately 8,000 Gg/yr) by 2030. However, these reductions differ by sector and by region. Although transportation in industrialized countries composes the major source of projected near-term emission reductions, there is the potential for growth in emissions in some sectors in some developing countries.

Four Representative Concentration Pathway (RCP) scenarios have been generated for use in the upcoming IPCC *Fifth Assessment Report* that project emissions into the future; these, too, show decreases in global emissions of 10% to 20% below present levels by 2030, with continued reductions after that date. On a sectoral level, the four RCP scenarios are divided as to whether open biomass burning (savannah and forest fires) will decrease or increase in the near term in all regions. Similarly, there is some disagreement about whether emissions in other sectors in Asia, the Middle East, and Africa will increase or decrease in the near term. Finally, there have been projections that emissions of BC from international shipping within the Arctic Circle will increase as a result of the retreat of Arctic sea ice, the opening of new shipping routes, and the increase of economic activity in that region (Corbett et al., 2010).

4.1 GAINS Projected Emissions for 2020 and 2030

Based on the GAINS model projections using current legislation and controls, total BC and OC emissions between 2005 and 2030 are expected to decrease in the entire Arctic region by 41% and 25%, respectively. The emissions reductions within each nation vary greatly within the GAINS projections, with the largest reductions in BC emissions expected from the Transport sector on both a mass and percentage basis. The Transport sector is particularly important in the United States and Canada while the Domestic sector dominates emissions reductions in the Kingdom of Denmark, Norway, and Finland. A discussion of the national-level policies and programs driving these reductions is presented in ***Section 5***.

Tables 4-1 and 4-2 present the total projected BC and OC emissions by Arctic Council nation, respectively, generated by IIASA using the GAINS model (Amman et al., 2010) for two scenarios. The 2005 national inventories and the GAINS inventory take into account country-specific regulations and policies that are currently in place. The Current Legislation (CLE) GAINS scenario estimates the emissions that would result as a consequence of the assumed economic activities, country- and sector-specific emission factors, and progressive implementation of the emission-control legislation that is currently laid down in national laws. The CLE GAINS scenario follows the 2009 reference scenario of the International Energy Agency (IEA, 2009).

In general, the GAINS emissions estimates track well with the available national emissions estimates by nation for the base year (2005), as discussed in ***Section 3*** of this report. There are, however, two countries where large differences exist for both BC and OC emissions projections for those countries that produced future emission projections for this report: Canada and the United States. The GAINS inventory does not include emissions estimates for international shipping, aviation, cruise ships, and open biomass burning (i.e., forest and savannah fires). There are also slight differences between the number and detail of emissions for source categories between the national and GAINS inventories that may also be a factor in the different emissions estimates for 2005.

The extent of emission reductions for both BC and OC vary by nation. Over the 2005 to 2030 time period, the range of future projected BC emission reductions are from minus 14% (Norway) to minus 52% (United States), with an average reduction over all Arctic Council nations of 41% (**Table 4-1** under the CLE GAINS scenario). Over the same time period, OC emissions are estimated to decrease by 25% on average (**Table 4-2**). The Transport and Domestic sectors are the main drivers for the decrease in emissions for both BC and OC in 2030 (**Tables 4-3 and 4-4** and **Figures 4-1 and 4-2**).

Table 4-1. Summary of GAINS BC Projected Emissions for 2020 and 2030*

	Black Carbon (Gg/yr)				% Reduction in BC Emissions	
	2005		2020	2030		
Country	**National**	**GAINS**	**CLE GAINS**	**CLE GAINS**	**GAINS 2005 and CLE 2020**	**GAINS 2005 and CLE 2030**
Canada	55.1	39.2	24.1	22.5	38.6%	42.7%
Denmark, Greenland and Faroe Islands	7.4	7.0	3.8	3.8	46.0%	45.4%
Finland	6.9	7.9	4.5	4.5	42.7%	42.7%
Iceland†	NA	0.2	0.1	0.1	31.6%	36.8%
Norway†	NA	6.4	5.4	5.6	16.6%	13.7%
Sweden	5.1	7.6	2.7	2.8	65.0%	63.8%
Russia†	NA	219.4	171.0	159.6	22.1%	27.2%
United States	481.7	261.0	136.8	125.3	47.6%	52.0%
Total	782.1	548.7	348.3	324.1	36.5%	40.9%

* Emissions from open biomass burning (wildfires and prescribed burns) are not included in this table. No estimates were provided by Bond for the Flaring and Other sectors.

† Iceland, Norway, and the Russian Federation did not provide national BC and OC emissions inventories. Norway did provide a $PM_{2.5}$ emissions inventory that is discussed in this report.

NA = not available.

Table 4-2. Summary of GAINS OC Projected Emissions for 2020 and 2030*

Country	Organic Carbon (Gg/yr)				% Reduction in OC Emissions	
	2005		2020	2030	GAINS 2005 and CLE 2020	GAINS 2005 and CLE 2030
	National	GAINS	CLE GAINS	CLE GAINS		
Canada	105.4	57.0	40.8	37.2	28.5%	34.9%
Denmark, Greenland, and Faroe Islands	8.1	14.0	8.0	7.6	42.8%	45.7%
Finland	5.6	7.2	4.5	4.8	37.1%	33.3%
Iceland†	NA	0.1	0.1	0.1	30.8%	30.8%
Norway†	NA	25.2	19.9	21.0	21.0%	16.6%
Sweden	6.5	7.0	4.0	4.4	42.6%	37.1%
Russia†	NA	254.1	230.4	231.0	9.3%	9.1%
United States	789.4	404.7	285.5	269.2	29.4%	33.5%
Total	1,194.3	769.3	593.2	575.2	22.9%	25.2%

* Emissions from open biomass burning (wildfires and prescribed burns) are not included in this table. No estimates were provided by Bond for the Flaring and Other sectors.

† Iceland, Norway, and the Russian Federation did not provide national BC and OC emissions inventories. Norway did provide a $PM_{2.5}$ emissions inventory that is discussed in this report.

NA = not available.

Table 4-3. Black Carbon Emissions for all AC Countries by Sector (Gg/yr)*

Source Category	Black Carbon (Gg/yr)				
	2000		2005	2020	2030
	Bond	GAINS	GAINS	CLE GAINS	CLE GAINS
Domestic	106.4	151.2	99.6	94.5	108.2
Transport	429.2	277.9	280.0	119.4	86.0
Energy & Industrial Production, Waste	36.9	26.2	23.8	21.3	20.0
Agricultural	24.1	38.9	38.7	37.3	36.6
Flaring	NE	73.0	101.1	69.8	67.1
Other	NE	5.4	5.6	6.0	6.3
Total	596.6	572.7	548.7	348.3	324.2

* Emissions from open biomass burning (wildfires and prescribed burns) are not included in this table.

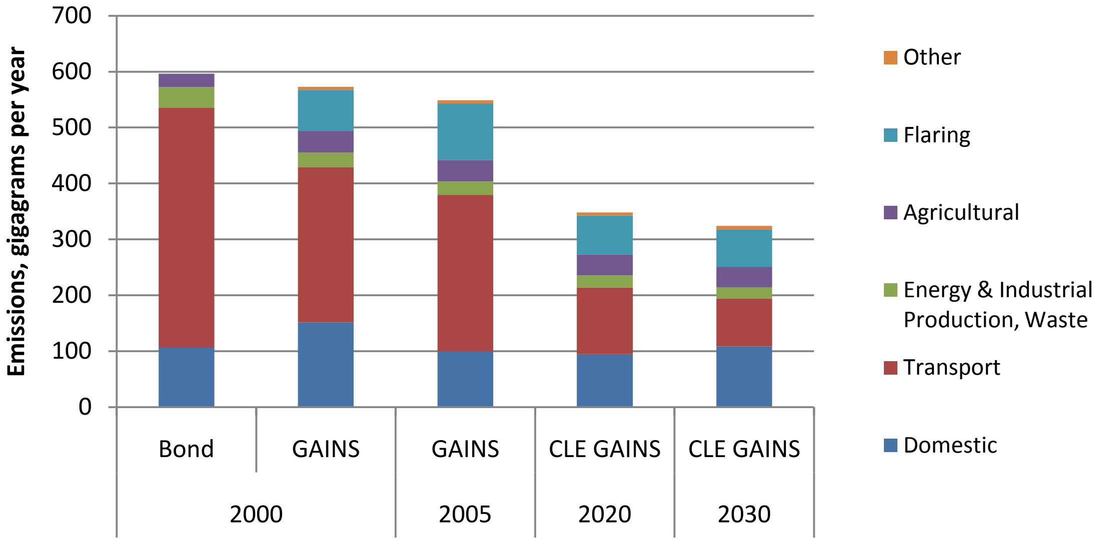
NE = not estimated

Table 4-4. Organic Carbon Emissions for AC Countries by Sector (Gg/yr)*

	Organic Carbon (Gg/yr)				
	2000		2005	2020	2030
Source Category	Bond	GAINS	GAINS	CLE GAINS	CLE GAINS
Domestic	432.2	323.5	276.7	217.2	216.1
Transport	270.7	256.2	257.1	154.6	143.8
Energy & Industrial Production, Waste	181.3	65.0	60.7	56.1	52.2
Agricultural	115.4	128.2	127.2	122.3	119.8
Flaring	NE	14.6	20.2	14.0	13.4
Other	NE	26.6	27.3	29.0	29.9
Total	999.6	814.1	769.3	593.2	575.2

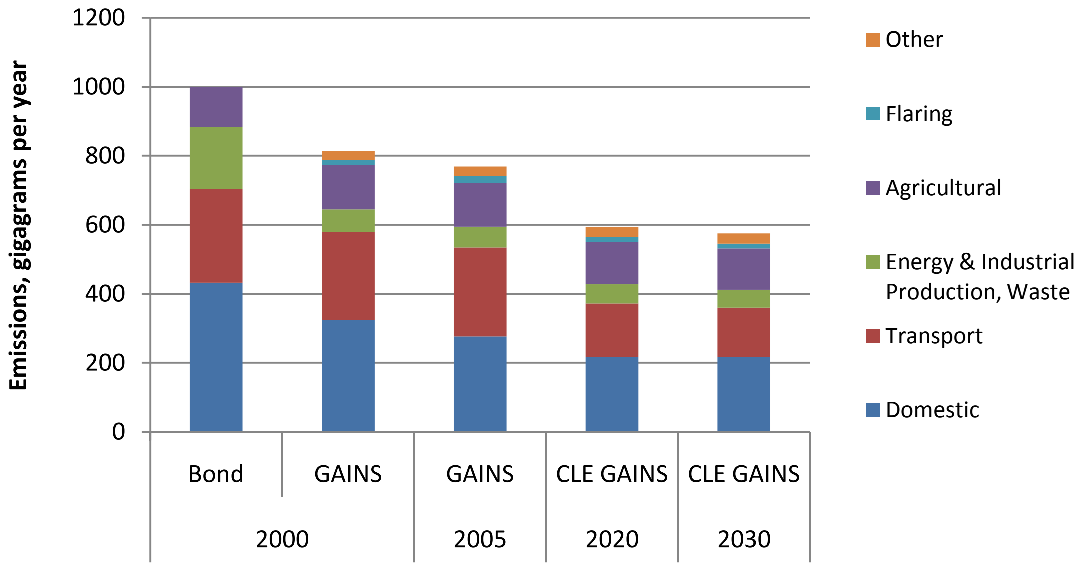
* Emissions from open biomass burning (wildfires and prescribed burns) are not included in this table.
NE = Not estimated

Figure 4-1. BC emissions for all Arctic Council nations by aggregated sector (Gg/yr).*



* Emissions from open biomass burning (wildfires and prescribed burns) are not included in the GAINS model and are not included in this figure.

Figure 4-2. OC Emissions for Arctic Council nationa by aggregated sector (Gg/yr).*

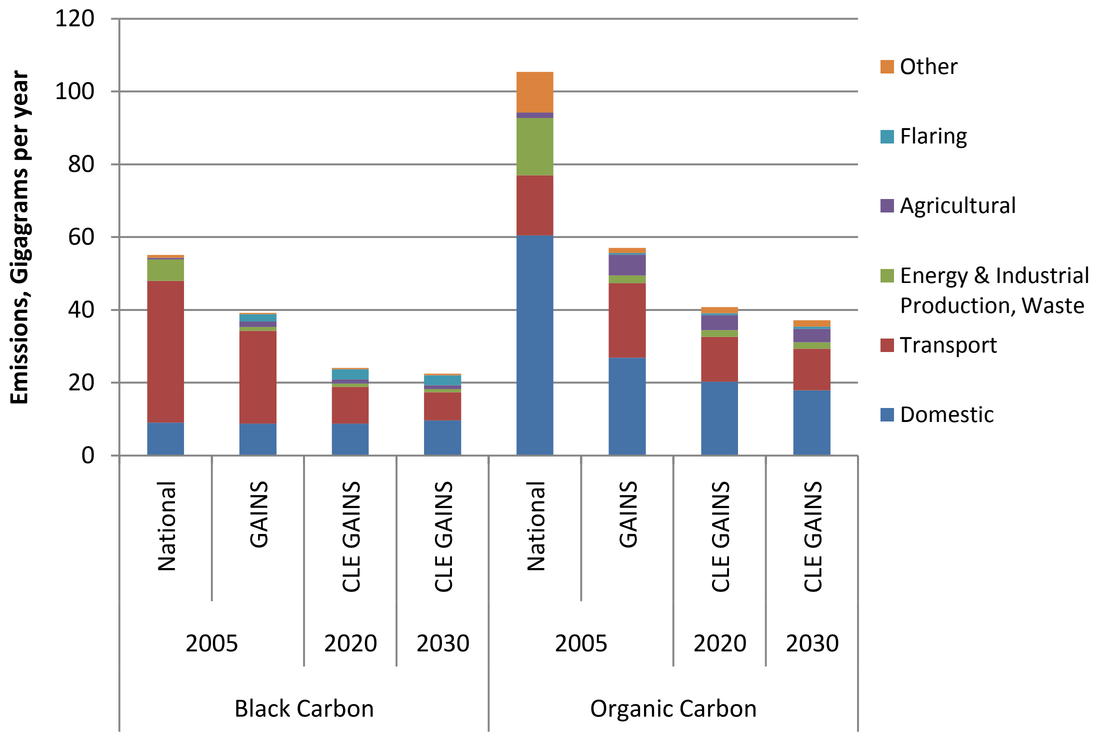


* Emissions from open biomass burning (wildfires and prescribed burns) are not included in the GAINS model and are not included in this figure.

Figures 4-3 through 4-10 present GAINS projections by Arctic Council nation. Baseline emissions for 2005 are included for reference. Additional data are provided in ***Appendix G***. Open biomass burning (wildfires and prescribed forest burning) emissions estimates are *not* included in these figures because the GAINS model did not estimate emissions from this source category.

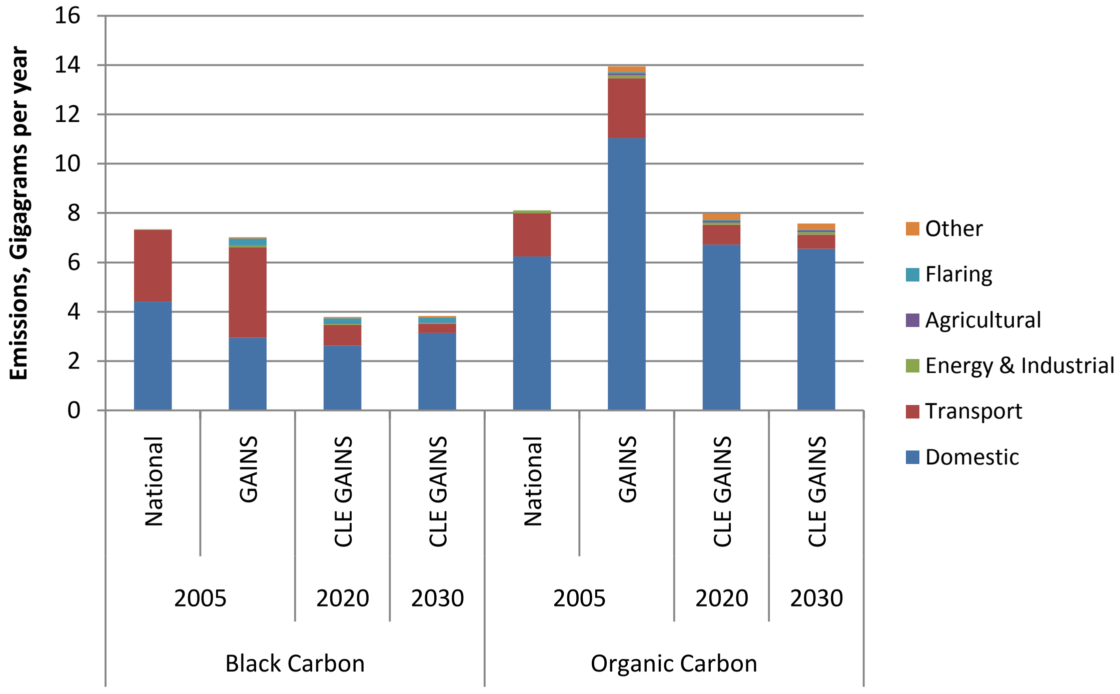
Overall, BC and OC emissions are projected to decrease for all Arctic Council nations, with significant decreases observed in the Transport sector; the impact of current legislation is projected to be not as effective in the Domestic sector. Iceland is the only country where emissions are not projected to decrease substantially and emissions in Finland are projected to be much lower than other Arctic Council nations.

Figure 4-3. GAINS projected BC and OC emissions for Canada (Gg/yr).*



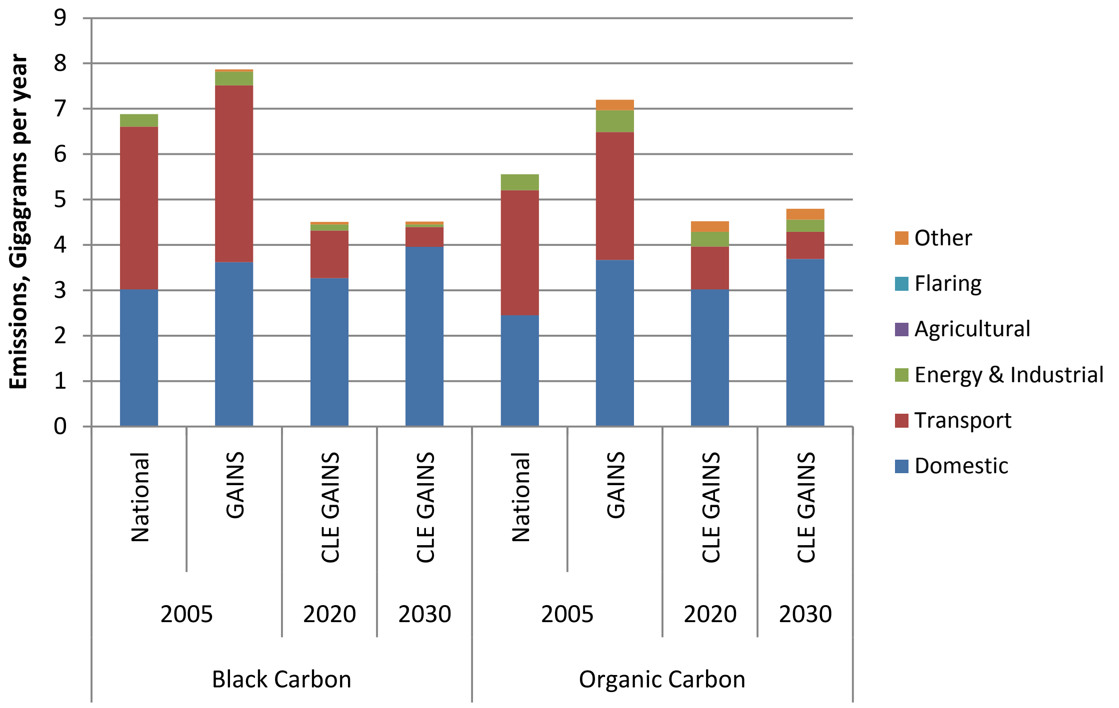
* Emissions from open biomass burning (prescribed burns and wildfires) are not included in this figure.

Figure 4-4. GAINS projected BC and OC emissions for Denmark, Greenland, and the Faroe Islands (Gg/yr).*



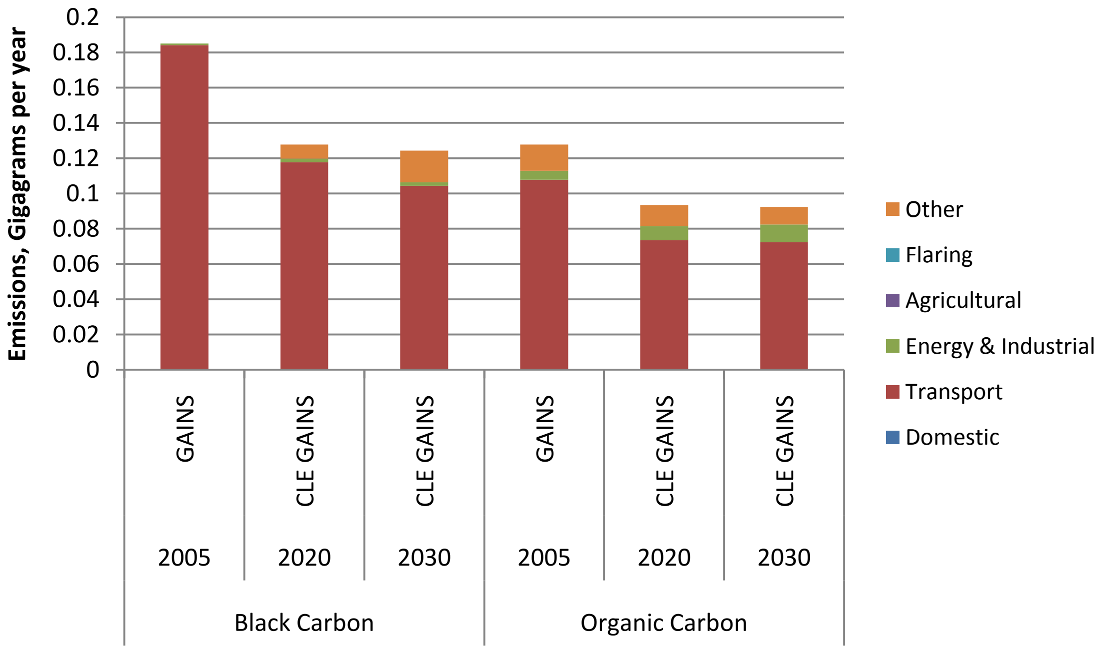
* Emissions from open biomass burning (prescribed burns and wildfires) are not included in this figure.

Figure 4-5. GAINS projected BC and OC emissions for Finland (Gg/yr).*



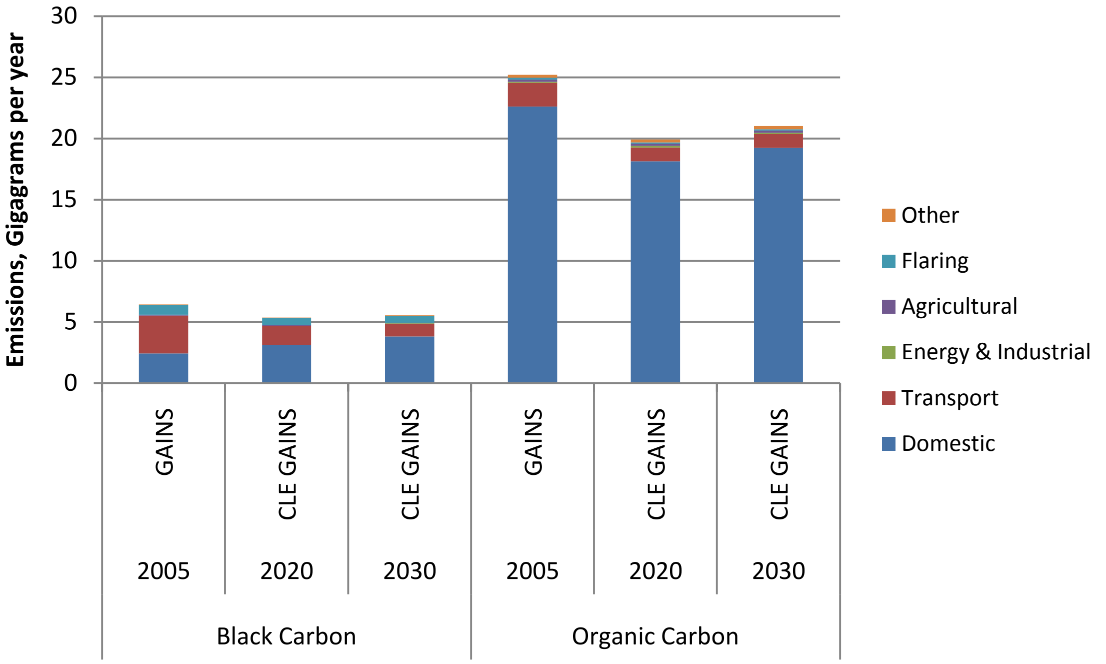
* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal for Finland and are not included in this figure.

Figure 4-6. GAINS projected BC and OC emissions for Iceland (Gg/yr).*



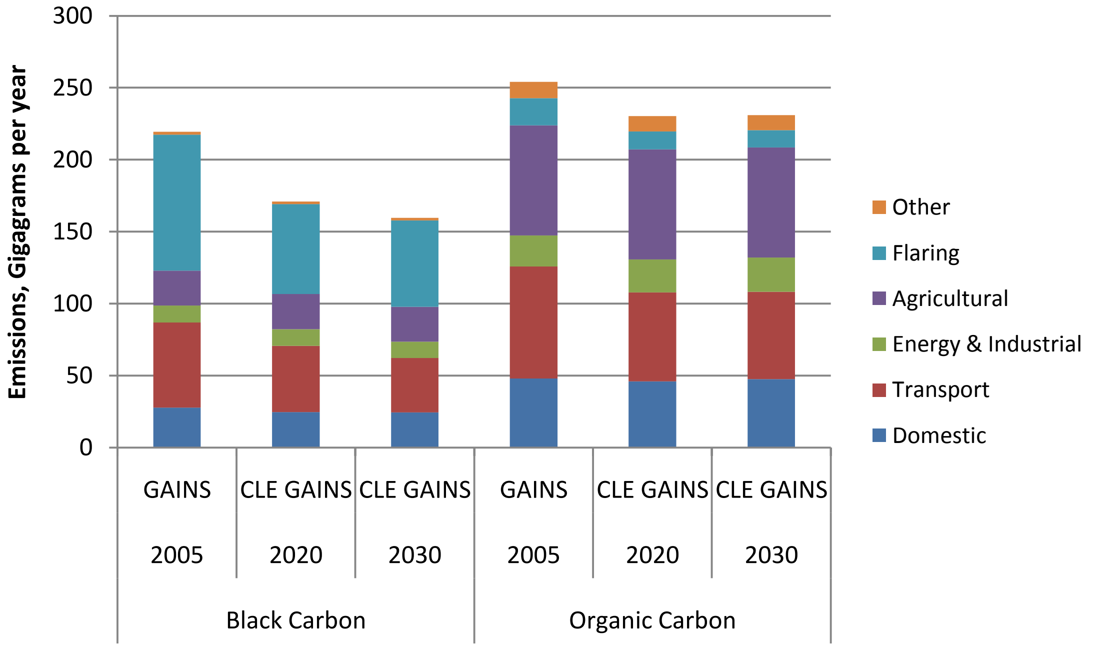
* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal and are not included in this figure. Iceland did not provide a national inventory; therefore, the 2005 estimates do not include national data for Iceland.

Figure 4-7. GAINS projected BC and OC emissions for Norway (Gg/yr).*



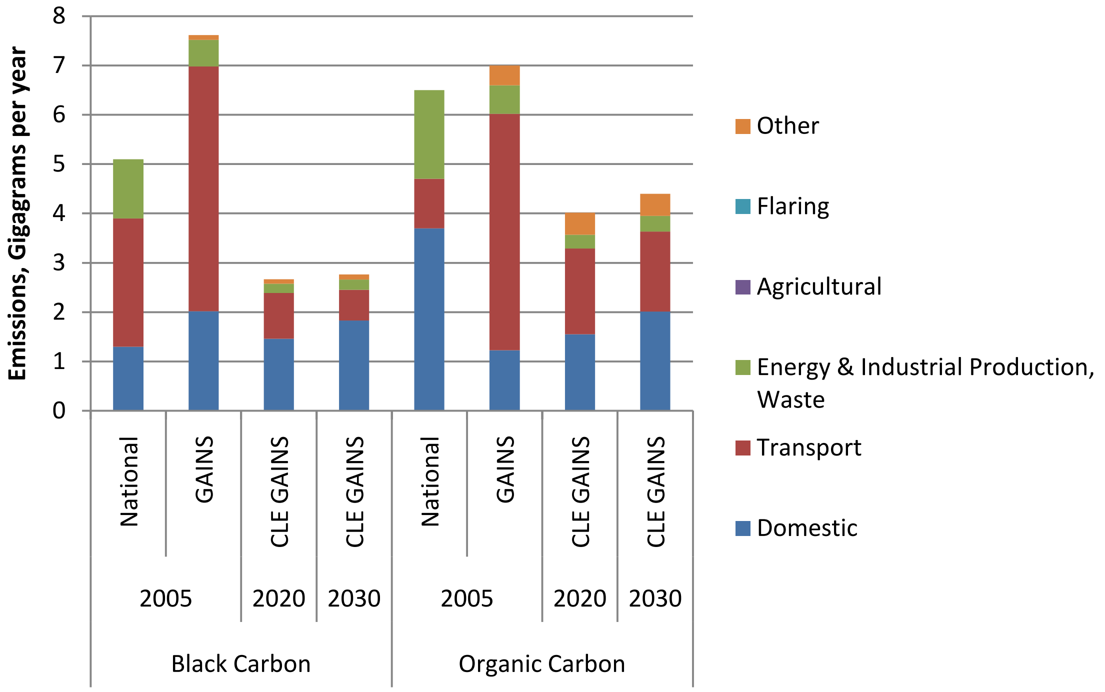
* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal for Norway and are not included in this figure. Norway did not provide a national inventory; therefore, the 2005 estimates do not include national data for Norway.

Figure 4-8. GAINS projected BC and OC emissions for the Russian Federation (Gg/yr).*



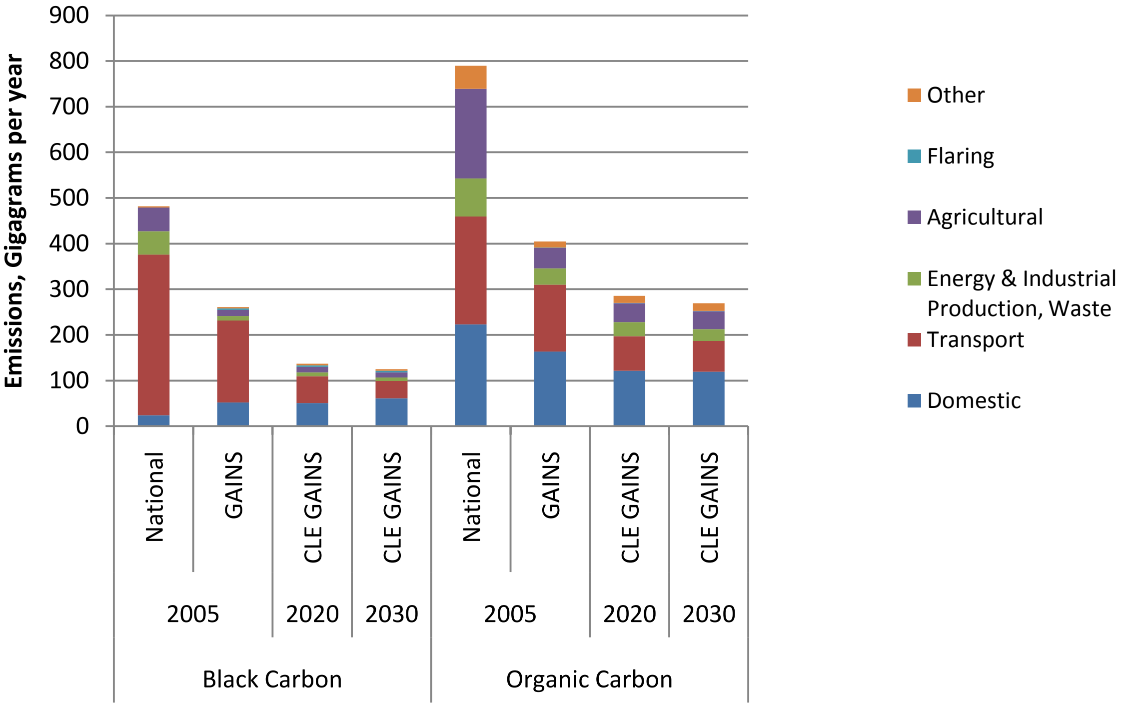
* Emissions from open biomass burning (prescribed burns and wildfires) are not included in this figure. The Russian Federation did not provide a national inventory; therefore, the 2005 estimates do not include national data for the Russian Federation.

Figure 4-9. GAINS projected BC and OC emissions for Sweden (Gg/yr).*



* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal for Sweden and are not included in this figure.

Figure 4-10. GAINS projected BC and OC emissions for the United States (Gg/yr).*



* Emissions from open biomass burning (prescribed burns and wildfires) are not included in this figure.

4.2 National Projections

The following sections provide information on the BC and OC emissions projections that were provided by most Arctic Council nations. In some cases, these emissions projections focus on PM rather than on BC and OC.

4.2.1 Canada

BC projections are estimated by applying sector-specific coefficients to a long-term projection of $PM_{2.5}$ emissions. The long-term $PM_{2.5}$ projection is developed using a simplified approach. First, coefficients that relate emissions and activity are estimated based on the latest historical $PM_{2.5}$ levels (i.e., 2007). Fuel-specific and process-specific coefficients are estimated by sector and province. This process results in average coefficients that are then applied to the appropriate activity levels.

Current policies and regulations are reflected in the $PM_{2.5}$ projections. These policies and regulations have the effect of modifying the average coefficient. Where no policies or regulations are in effect, the average coefficient is assumed to remain constant (i.e., reflects emission/activity ratio for 2007). Thus, *planned* regulations, such as Tier 4 regulations for on-road heavy-duty vehicles and rail are not included, and the impact of these regulations has not been calculated..

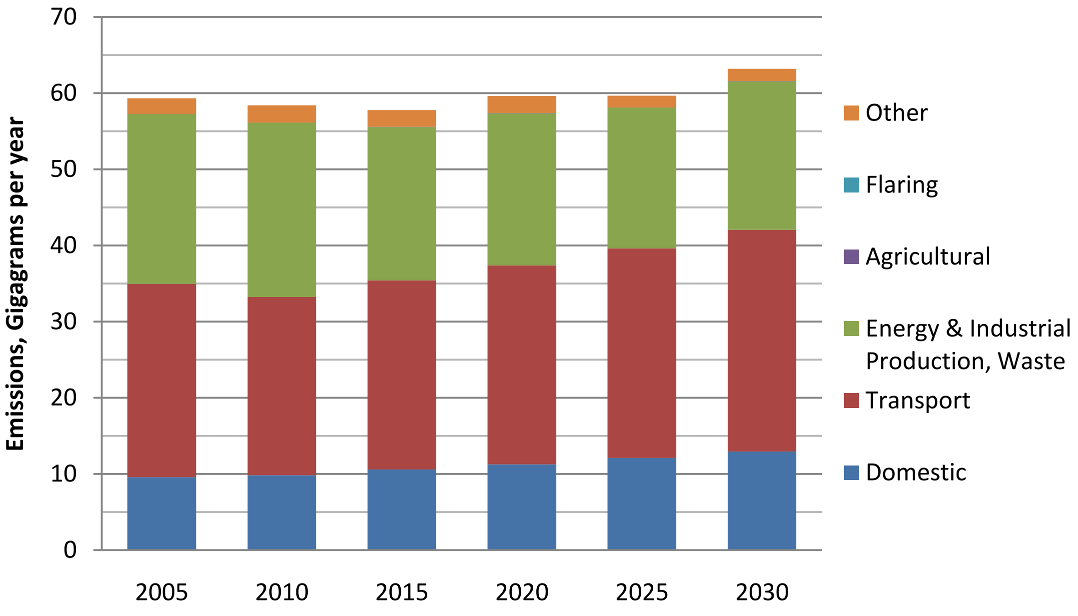
The estimation procedure currently used results in a high degree of uncertainty. The uncertainty stems from several areas, including the methodology for estimating $PM_{2.5}$ emissions and the coefficient applied to the $PM_{2.5}$ emissions to generate the BC emissions. Emissions from open biomass burning were not projected due to large uncertainties, as explained below:

- The activity data used in the baseline PM inventory are area burned exclusively. Biomass consumed per area burned is set as a constant value for all of Canada and does not reflect the great variability in pre-burn fuel load, nor the influence of burning conditions (e.g., temperature) on the quantity of biomass consumed.
- The PM and/or $PM_{2.5}$ emission factors (on a mass basis) are also constant values regardless of year, location, burning conditions, and completeness of the burn (i.e., combustion efficiency).
- The $PM_{2.5}$ EC profile in the U.S. EPA SPECIATE 4.2 database is derived from a small set of experimental data that are not representative of emissions from northern wildfires in Canada.
- The current PM-based BC inventory would suggest that controlling the area burned is the obvious mitigation activity. Simplistically, this is true (i.e., no fire equals no BC emissions), but because of methodological weaknesses, the inventory wrongly suggests that reducing the area burned anywhere at any time has the same mitigation effectiveness. An assessment of the mitigation potential should rely on an inventory that shows how BC emissions vary with fire location, types, and circumstances, all of which affect the amount of biomass burned.

Based on the current (2005) estimates, BC emissions (excluding open and natural sources) in Canada are projected to increase by approximately 26% above 2005 levels by 2030 (**Figures 4-11 and 4-12** and **Table A-7** in ***Appendix A***), with an increase from 57.3 Gg in 2005 to 72 Gg in 2030.

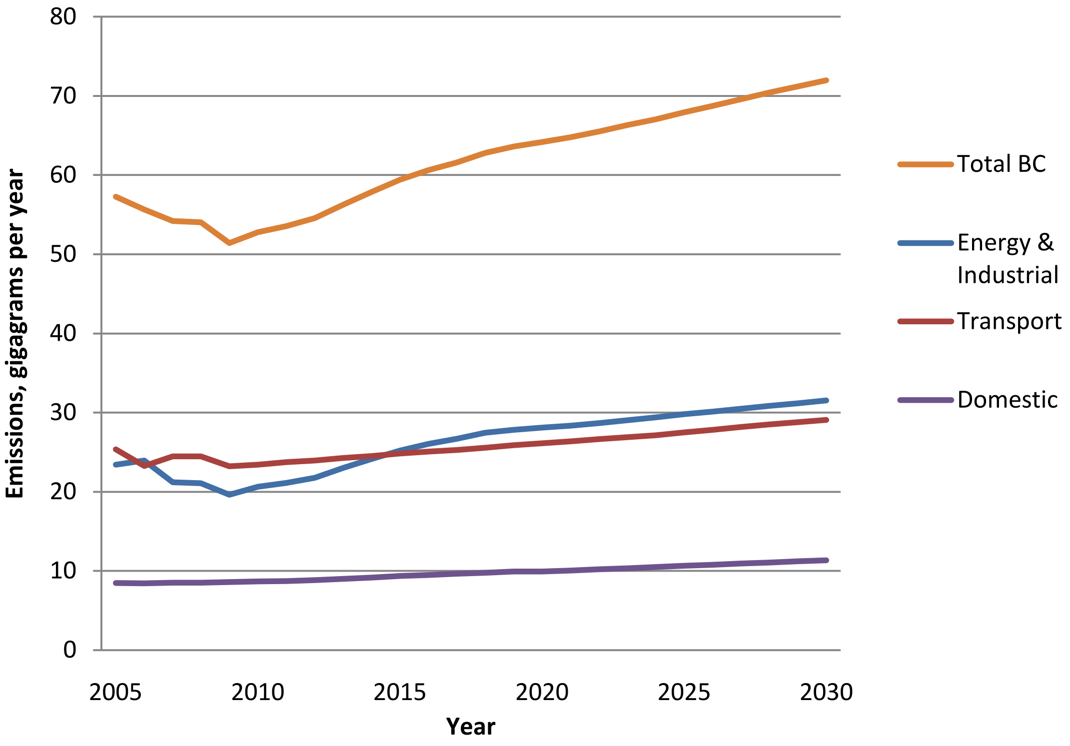
Key source categories for which a relatively greater increase in BC emissions is projected include transportation (from 25.3 Gg in 2005 to 29.1 Gg in 2030) and construction (projected to grow by 34%, from 15.9 Gg to 21.3 Gg), followed by activity in the fossil fuel and mining industries, which are projected to grow by 137% (from 2.4 Gg to 5.7 Gg). BC emissions from off-road activity and the residential sources are projected to grow by 2.9 Gg and 2.8 Gg, , respectively..

Figure 4-11. Total BC emissions trends 2005 through 2030, Canada.*



* Emissions from open biomass burning (prescribed burns and wildfires) were not projected due to large uncertainties associated with the emission factors and activity data and are not included in this table. Flaring emissions were not estimated.

Figure 4-12. BC emissions trends by major sector in Gg, 2005 through 2030, Canada.*

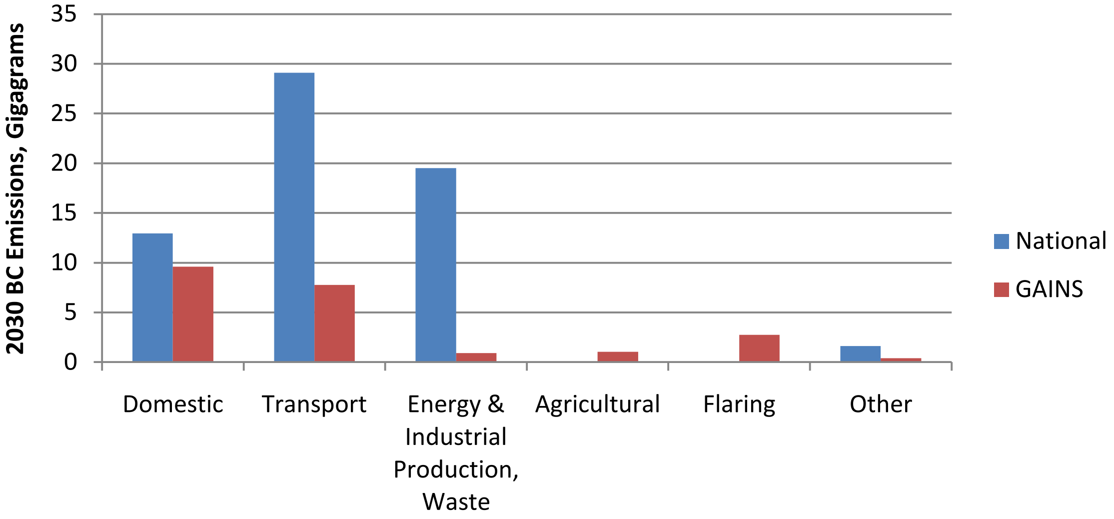


* Emissions from open biomass burning (prescribed burns and wildfires) were not projected. Flaring emissions were not estimated.

Comparison of Canadian Projected Emissions to GAINS

There are large differences between the GAINS estimates and the national estimates in projected BC emissions for the year 2030 in Canada for the Transport sector and the Energy & Industrial Production, Waste sector, as shown in **Figure 4-13**. As stated above, when projecting emissions, the national estimates did not take into account the expected emissions reduction due to the legislation not yet in effect, whereas the GAINS projections do assume declining emissions as result of the future policy. This difference in assumptions likely explains most of the difference in future estimated trends between the GAINS and Canadian national projections.

Figure 4-13. Comparison of national and GAINS CLE projected 2030 BC emissions estimates, Canada (Gg).*



* Canada did not project open biomass burning emissions due to the large uncertainties associated with available data and emission factors. GAINS does not model emissions from open biomass burning.

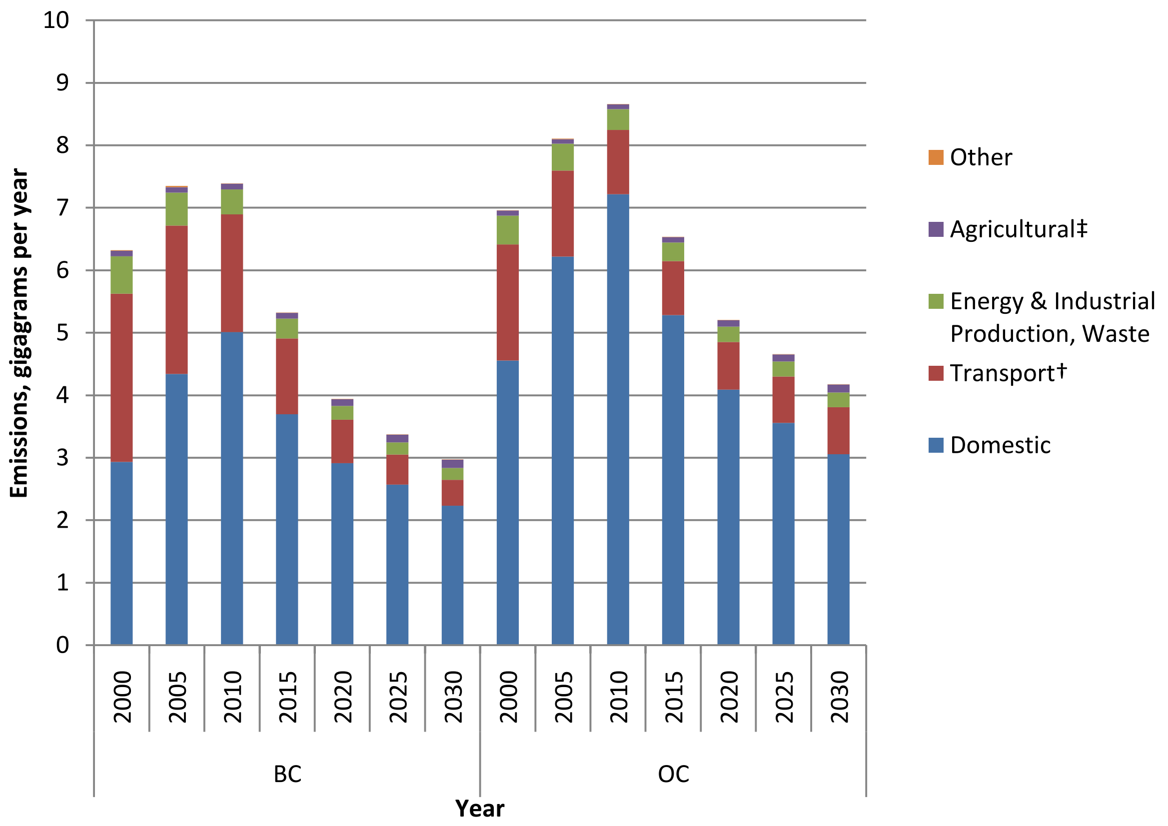
4.2.2 Denmark, Greenland, and the Faroe Islands

Denmark

Looking ahead to 2020 and 2030, key sectors in Denmark are expected to be the Domestic and Transport sectors (both on- and off-road sources). As shown in **Table B-4** in ***Appendix B*** and **Figure 4-14**, total BC emissions for Denmark are projected to decrease by 60% in the Domestic sector and 52% in the Transport sector by 2030 (based on 2010 emissions). Emissions in Denmark are projected to decrease substantially in all sectors, except the Agricultural sector. The largest decrease in BC and OC emissions is shown in the Transport sector, where BC and OC emissions are projected to decrease from 2010 emissions by up to 78% and 27%, respectively. The dramatic decrease in BC emissions out to 2030 in on-road mobile sources will make the Transport sector a much less significant source sector in the future. BC and OC emissions in the Domestic sector are projected to decrease by 55% and 58%, respectively, from 2010 to 2030. BC and OC emissions in the Agricultural sector are projected to increase by 54% and 64%, respectively, from 2010 to 2030.

Projections of future emissions from wood-burning activities show an expected decrease as a result of expected improvements in wood-burning technologies. Substantial BC and OC emissions reductions are also expected to occur as a result of stricter EURO-norms for mobile sources.

Figure 4-14. BC and OC emissions for 2000–2030, Denmark and the Faroe Islands.*



* Flaring emissions are not considered applicable. Emissions from open biomass burning were not projected and are expected to be minimal.

† The majority of emissions from the Forestry, Agriculture, and Fishery source category in Greenland (99%) were reported to come from the fishery industry due to fuel use. Due to this, these emissions were aggregated into the Transport sector.

‡ Emissions in the Agricultural sector consist of those facilities in the Agriculture, Forestry, and Fishery source category.

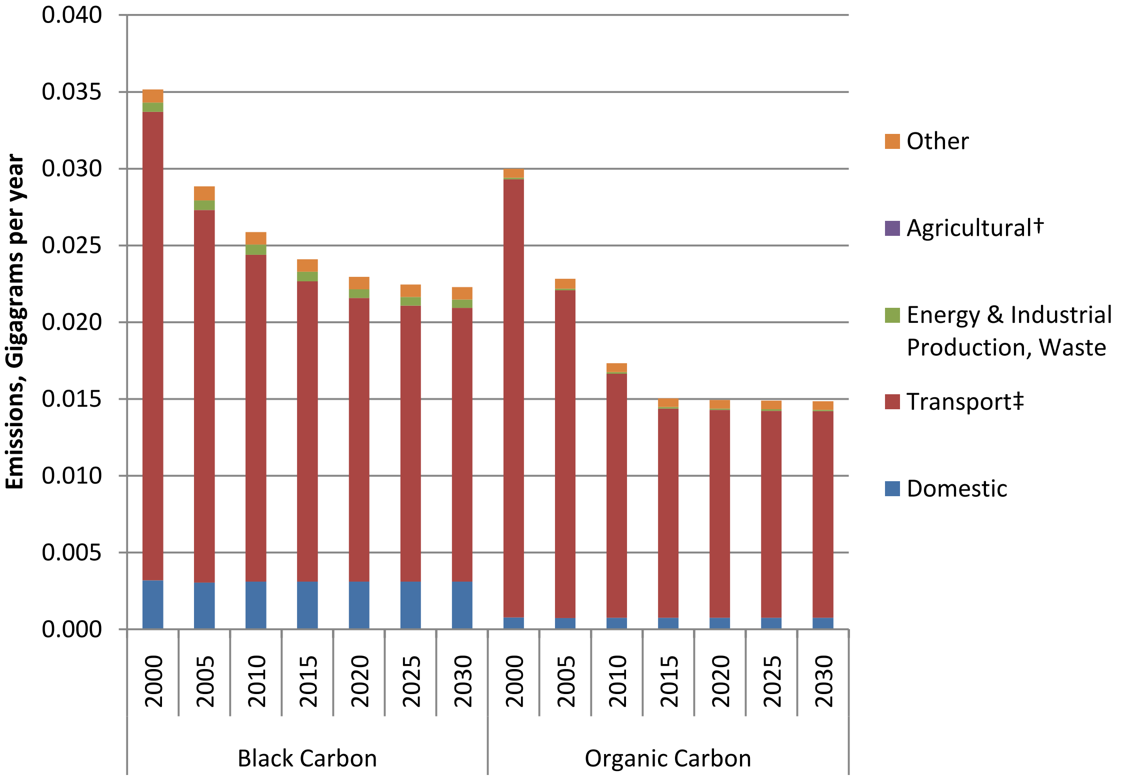
A steep increase in BC emissions in the Domestic sector over the 2000 to 2010 time period has occurred as a result of increased domestic wood combustion. OC emissions closely follow those of BC, and the same trends can be observed. While an improvement in the combustion efficiency of stoves has taken place, the number of stoves and their use has far outweighed the improvement over this time period. The increased domestic emissions have also outweighed a substantial reduction in emissions from mobile sources, (i.e., on- and off-road transport).

Greenland

In 2030, key sectors in Greenland are projected to be the Domestic and Transport sectors, as shown in **Figure 4-15** and **Table B-5** in ***Appendix B***. Greenland is expected to see a 14% reduction in both BC and OC emissions by 2030, compared to current emissions (2010), a trend carried by continually decreasing emissions, mainly from on-road transportation sources and somewhat from the public power and district heating and marine navigation. Both BC and OC emissions are projected to decrease by approximately 15% to 16% in the Transport sector and by 18% in the Energy & Industrial Production, Waste sector. No decrease is expected in the Domestic sector over the 2010 to 2030 time period, although emissions from this sector are minimal compared to those from the Transport sector.

There are several uncertainties related to estimating emissions from the fishery industry and the emergence of new industries (e.g. oil and gas production, mining and aluminium smelting). Structural reforms in the fishing industry will reduce the number of small-scale fishing activities likely to be introduced between 2010 and 2030, but the net effect of these reforms on BC emissions is uncertain. Exploratory off-shore drillings north of the Disco Island in 2010 detected the presence of oil and gas, and production may start before 2030, but the BC emissions from potential future oil and gas activities have not been included in these emissions projections.

Figure 4-15.BC and OC emissions projections for Greenland in Gg/yr, 2010–2030.*



* Emissions from open biomass burning were not estimated. Flaring emissions were not projected.

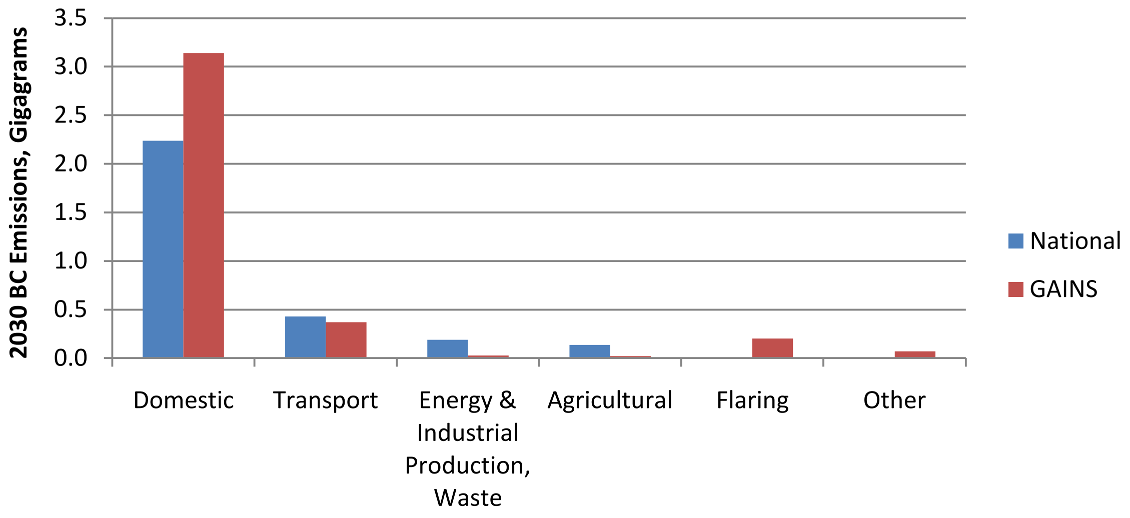
† Agricultural sector emissions consist of facilities in the Agriculture, Forestry, and Fishery source category.

‡ The majority of emissions from the Forestry, Agriculture, and Fishery source category in Greenland (99%) were reported to come mainly from the fishery industry due to fuel use. Because of this, these emissions were aggregated into the Transport sector.

Comparison of Denmark, Greenland and Faroe Islands Projected Emissions to GAINS

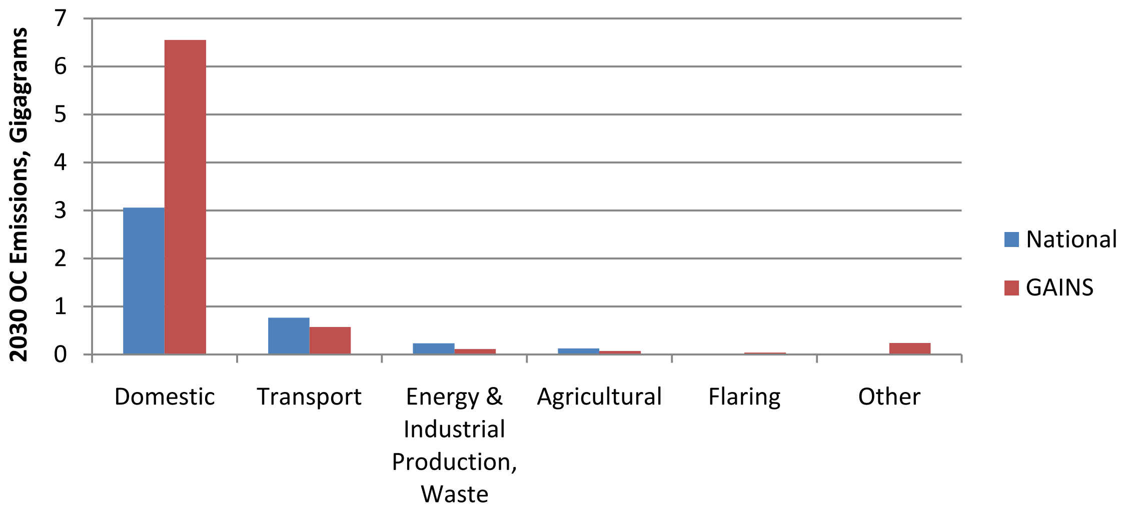
Figures 4-16 and 4-17 compare the projected BC and OC emissions for the combined Denmark, Greenland, and Faroe Islands emissions inventory with the GAINS CLE scenario for 2030. The emissions inventories agree well, and both project the Domestic sector as contributing the majority of emissions in 2030.

Figure 4-16. Comparison of national and GAINS projected 2030 BC emissions estimates, Denmark, Greenland, and the Faroe Islands (Gg).*



* Open biomass burning emissions are not considered applicable and are not included in this figure.

Figure 4-17. Comparison of national and GAINS projected 2030 OC emissions estimates, Denmark, Greenland, and the Faroe Islands (Gg).*



* Open biomass burning emissions are not considered applicable and are not included in this figure.

4.2.3 Finland

The Finnish national emission model (FRES) has been used to assess the potential future emission pathways of BC and OC emissions in two scenarios: the 2020 scenario and the 2020red scenario. These scenarios share the same sectoral categories as the Finnish government’s *2008 National Climate and Energy Strategy*.

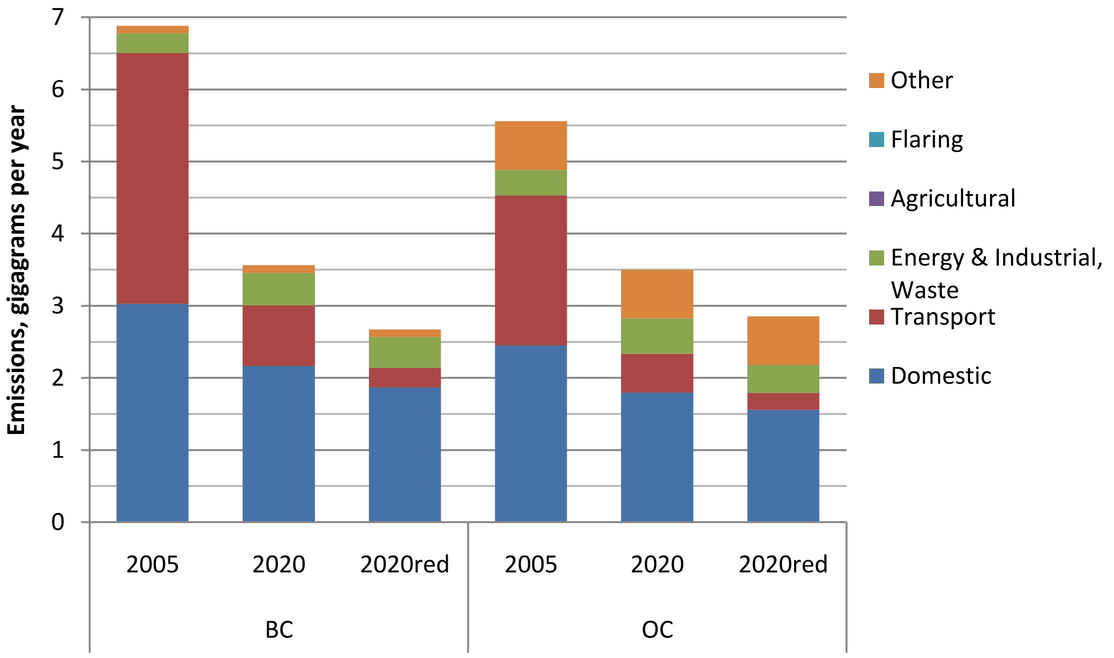
The 2020 scenario assumes a full implementation of current legislation to reduce air pollution and expected reductions in pollutant levels, and only moderate improvements in residential combustion technologies. Current legislation will mostly impact the Transport sector.

The 2020red scenario assumes ambitious additional reductions on top of the current legislation as used in the 2020 scenario. Under this scenario, all masonry ovens and 25% of traditional stoves are considered new and more efficient in the Domestic sector. In addition, all boilers, except for those in recreational buildings, are equipped with electrostatic precipitators to control PM emissions. In the Transport sector, all vehicles are modelled to comply with the EURO 5/6 emission requirements. In the power generation and industrial source categories, all large-scale combustion plants are equipped with fabric filters, while small combustion plants (< 50MW) use solid fuel with electrostatic precipitators.

Figure 4-18 and **Table C-3** in ***Appendix C*** show the Finnish BC and OC emissions in 2005 and the modelled 2020 and 2020red scenarios. Currently, the key sectors are the Transport (both on-road and off-road transportation) and Domestic (combustion from primary wood burning) sectors. The total BC and OC emissions are expected to decline by 48% and 19%, respectively, with current legislation (2020 scenario) that targets mostly on- and off-road transportation sources. Transportation emissions will decrease by almost 80% out to 2020. Emissions from wood combustion in the Domestic sector are estimated to decrease by 20% out to 2020, with more reductions occurring as more modern and efficient stoves and boilers are installed. Additionally, it is expected that the use of wood pellets will increase; thus, BC and OC emissions from the Domestic sector are expected to decrease by approximately 25 to 30%.

In the ambitious 2020red scenario, BC and OC emissions are further reduced by 25% and 19%, respectively, on top of the reductions from current legislation. Most of the additional BC reduction potential is still estimated to be in the Transport sector, but significant reductions also will occur in the Domestic sector due to accelerated modernization of equipment. The comparison of sectoral emissions in 2000 and 2020 indicates that while it is expected that Transport sector emissions will be reduced effectively, the impact of domestic combustion will increase.

Figure 4-18. BC and OC Emissions Projections for Finland, 2005 and 2020.*

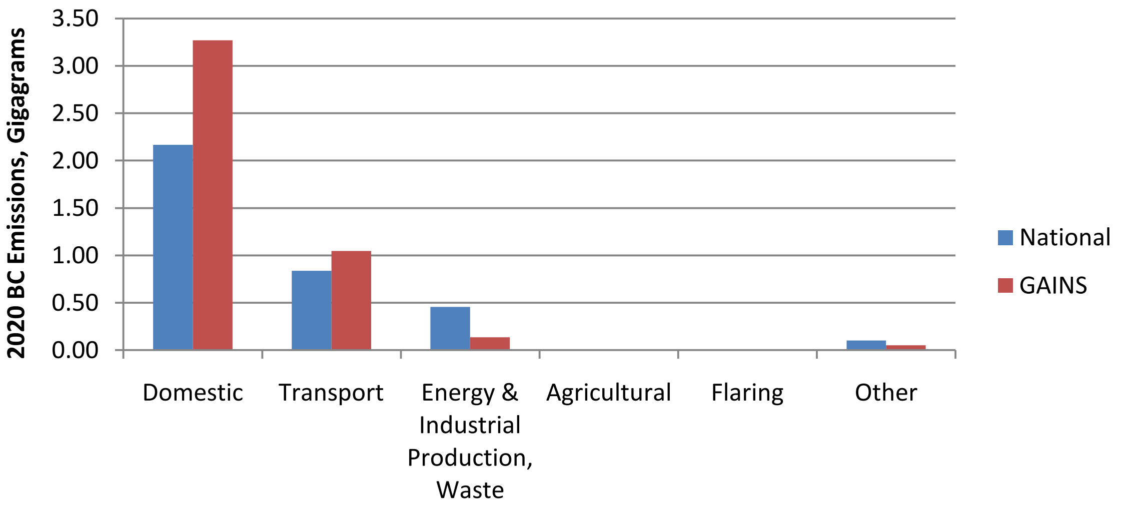


* Finland did not project emissions from open biomass burning, agriculture, and flaring; therefore, estimates for these sectors are not included in this figure.

Comparison of Finnish Projected Emissions to GAINS

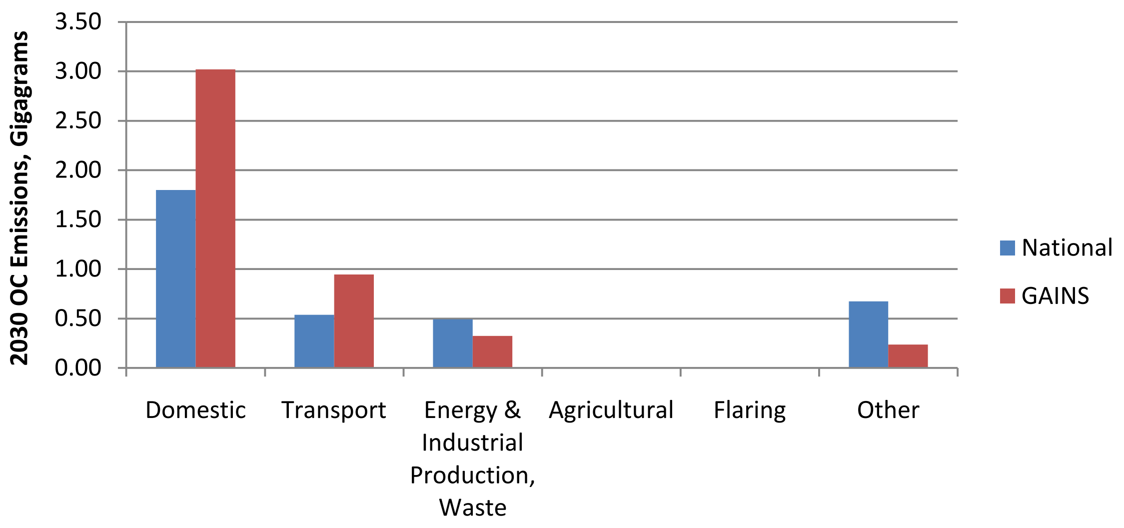
Figures 4-19 and 4-20 compare the projected BC and OC emissions estimates for the 2020 FRES scenario (national) and the 2020 GAIN CLE scenario. In general, the two inventories agree although there is more variability with respect to the OC emissions estimates.

Figure 4-19. Comparison of 2020 Projected BC Emissions, Finland (Gg).*



* The GAINS and Finnish inventories did not project emissions estimates for open biomass burning, agriculture, and flaring, so data for these sectors are not included in this figure.

Figure 4-20. Comparison of 2020 Projected OC Emissions, Finland (Gg).*



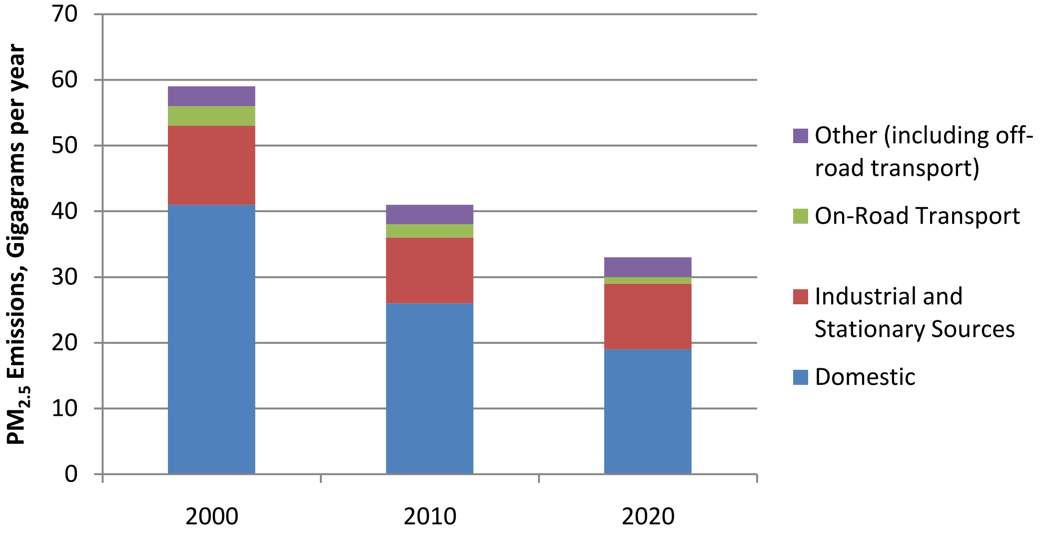
* The GAINS and Finnish inventories did not project emissions estimates for open biomass burning, agriculture, and flaring, so data for these sectors are not included in this figure.

4.2.4 Norway

Projections of $PM_{2.5}$ emissions in Norway for 2010 and 2020 have been developed by The Climate and Pollution Agency in Norway (SFT, 2006), as shown in **Figure 4-21** and **Table D-2** in ***Appendix D***. The Domestic sector is the largest generator of $PM_{2.5}$ emissions, and is therefore the focus of the model. Several Domestic sector–related assumptions have been made to develop the $PM_{2.5}$ projections, as discussed below.

The projections assume that 36% of residential wood-burning stoves in 2005 are new (i.e., modern and efficient) technology, and that this percent will increase at the same rate out to 2020 as observed from 2002 to 2005, resulting in approximately 50% of stoves with new technology in 2010. This assumption is fairly correct because 46% of stoves with new technology were in place in 2009. It is anticipated that the rate of stove replacement will decrease out to 2020, as households that still keep their old “antique” stoves seem to have strong personal reasons to do so. The share of new stoves is estimated in the model to be 70% in 2020. The rate of wood consumption per household is assumed constant.

Figure 4-21. Projections of $PM_{2.5}$ emissions for 2000, 2010, and 2020, Norway (SFT, 2006).*

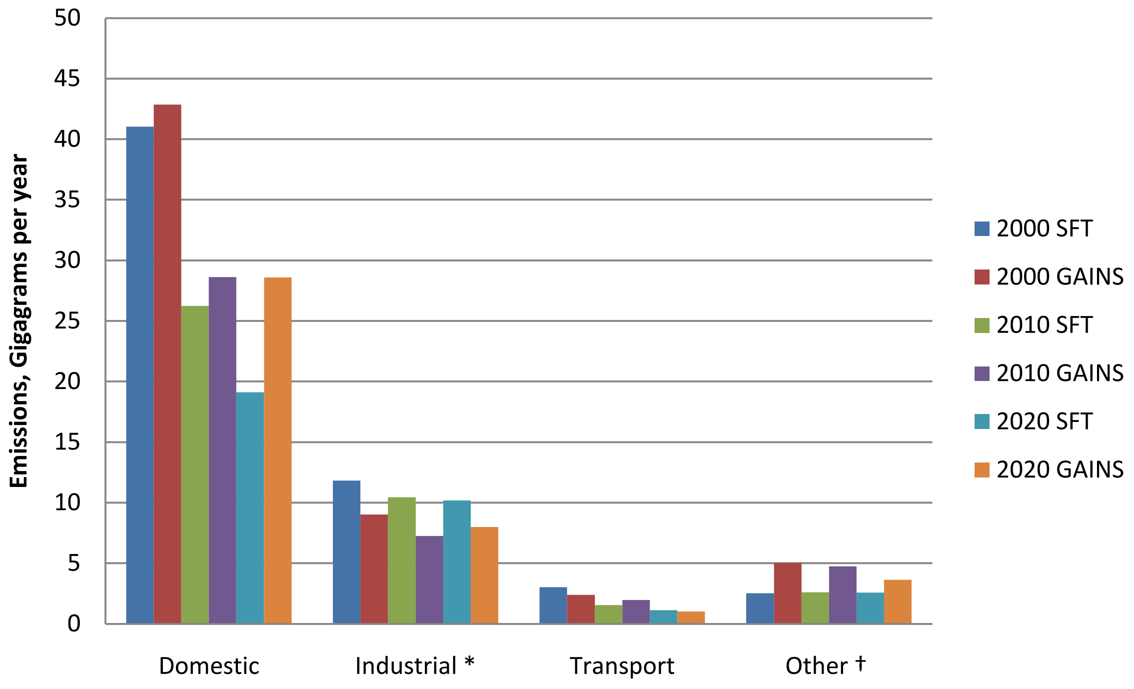


* Emissions from open biomass burning and agriculture are not considered applicable and were not projected. Flaring emissions were not projected.

Comparison of Norwegian Projected $PM_{2.5}$ Emissions to GAINS

When compared to the GAINS emissions for year 2000 and projected emissions for 2010 and 2020 (**Figure 4-22**), a relatively large difference is observed in the Domestic sector for 2020. This is most likely the result of different assumptions in the turnover from old to new technology heating stoves. Other differences could be attributed to differences in sector allocation between SFT (now the Climate and Pollution Agency [Klif]) and GAINS. In addition, the SFT projections are not official national projections, and discrepancies could arise from a less developed and fine-tuned methodology.

Figure 4-22. Comparison of $PM_{2.5}$ emissions from SFT and GAINS for 2000, 2010, and 2020 in Gg, Norway.



* The Industrial sector includes industrial combustion and industrial processes.
† Emissions from flaring are included in the Other sector.

4.2.5 Sweden

Emissions projections for Sweden out to 2030 for BC and OC were performed in accordance with the CLRTAP and the European National Emission Ceilings Directive (NEC) (Directive 2001/81/EC).[25]

Projected emission trends for $PM_{2.5}$ are presented in **Figure 4-23** using 2007 as the base year. Supporting data can be found in ***Appendix E***. **Table E-5** in ***Appendix E*** and **Figure 4-24** present projected BC and OC emissions for Sweden for the year 2020 using BC and OC mass fractions, as presented in **Table E-4**. Residential heating, electricity generation, and heat production are viewed as key source categories where national abatement initiatives may be most effective in further reducing emissions. Emissions from these sources are concentrated from November to April, when BC has its strongest climate impact in the Arctic. In addition, focusing on the use of biofuels in residential heating will have the co-benefit of also reducing methane emissions.

The $PM_{2.5}$ emissions from diesel-engine working machinery, lorries, and other vehicles are expected to decrease by 60% to 80% from 2007 to 2020 due to the impact of current EURO 3 and EURO 5 emission regulations and future EURO 6 tailpipe emission

---

[25] The aim of the NEC Directive is to establish national emission limit ceilings for acidifying and eutrophying pollutants and ozone precursors in order to improve the environment and public health. The EMEP/CORINAIR guidebook is used to establish emission limit ceilings and to prepare emission projections for SO_2, NO_x, VOCs, NH_3, CO, PM, various heavy metals, and POPs.

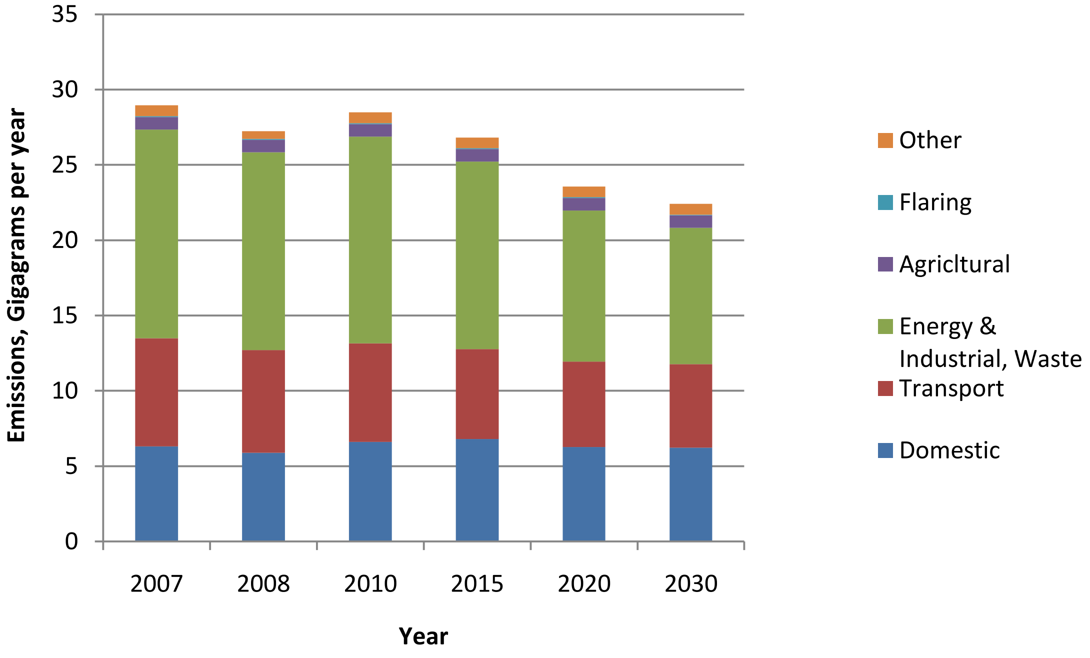
regulations for particulates. In 2014, new particulate exhaust emission regulations (EURO 6) for heavy-duty vehicles come into force that will require the use of particulate filters.

$PM_{2.5}$ emissions from industrial combustion; public electricity and heat production; and stationary, residential, and commercial heating boilers and stoves are projected to be similar to 2007 emissions.

Increasing trends of bioenergy use and a reduction of fossil fuel consumption in public electricity and heat production are expected to continue in the future. The use of fossil fuels for heat boilers in the residential and service source categories will almost have ended entirely by 2020. This fuel conversion is driven by an increased level of CO_2 tax on fossil fuels, an energy tax relief for bioenergy, and increasing market prices for fossil fuels.

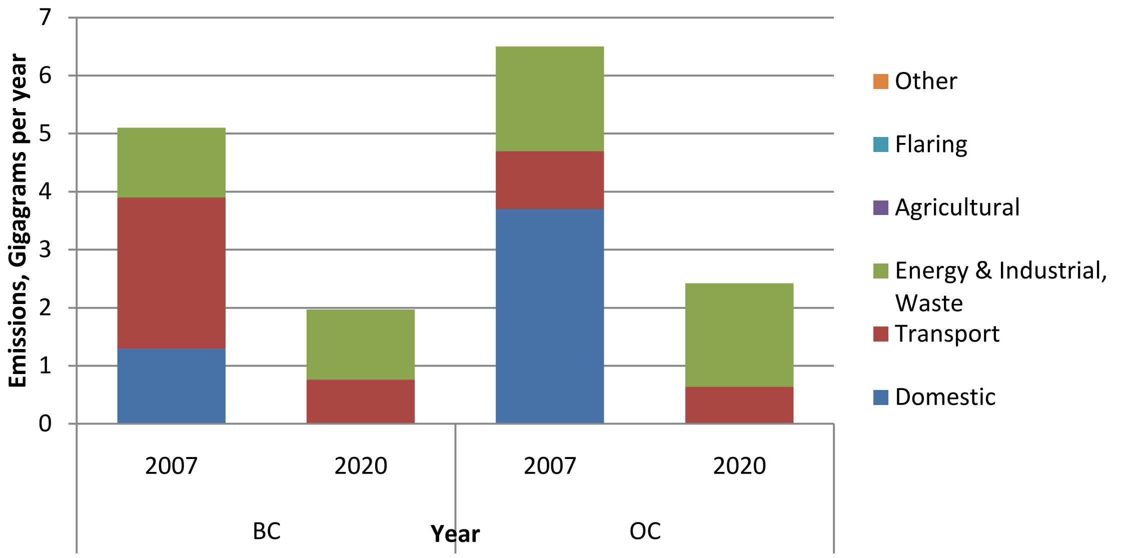
Future BC emissions are estimated to decrease by approximately 40% from 2007 to 2020, mainly from the introduction of more stringent PM emission requirements and particulate traps on cars, diesel-engine lorries, and working machinery. The penetration of particulate traps for diesel vehicles is expected to play a major role in decreasing BC and OC emissions, starting in 2007 for automobiles and 2014 for heavy-duty vehicles. More stringent emission requirements for working machinery will also force the use of particulate traps beginning around 2016/2017. The fraction of OC used in the emissions estimates for the combustion of biofuels for residential heating is expected to decrease from the current year (2007) mass fraction due to an assumed improvement in the efficiency of stoves and boilers.

Figure 4-23. $PM_{2.5}$ emissions projections in Gg with base year of 2007, Sweden.*



* Emissions from open biomass burning and flaring were not estimated for Sweden.

Figure 4-24. Projected BC and OC emissions for 2020 compared with base year 2007, Sweden.*

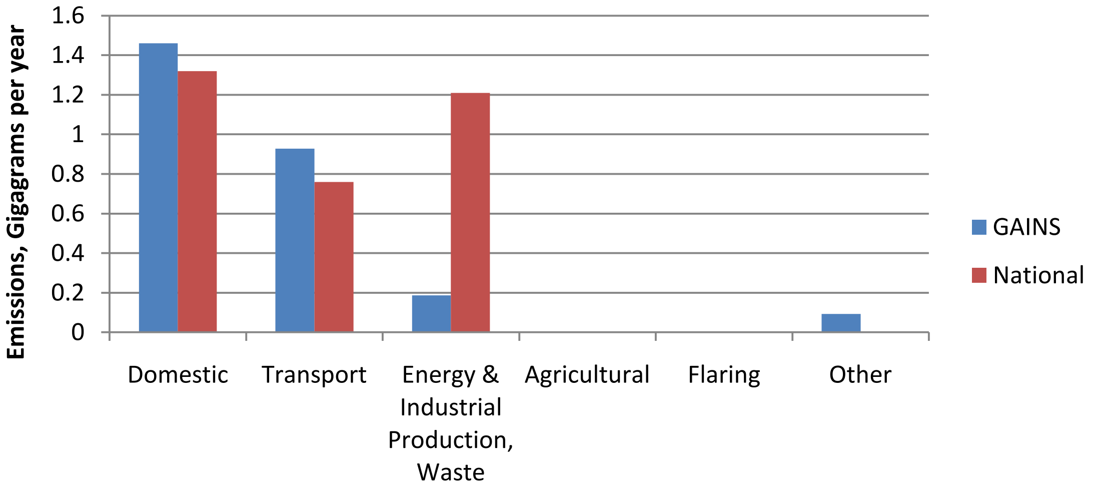


* Emissions from open biomass burning, agricultural, and flaring were not estimated for Sweden.

Comparison of Swedish Projected Emissions to GAINS

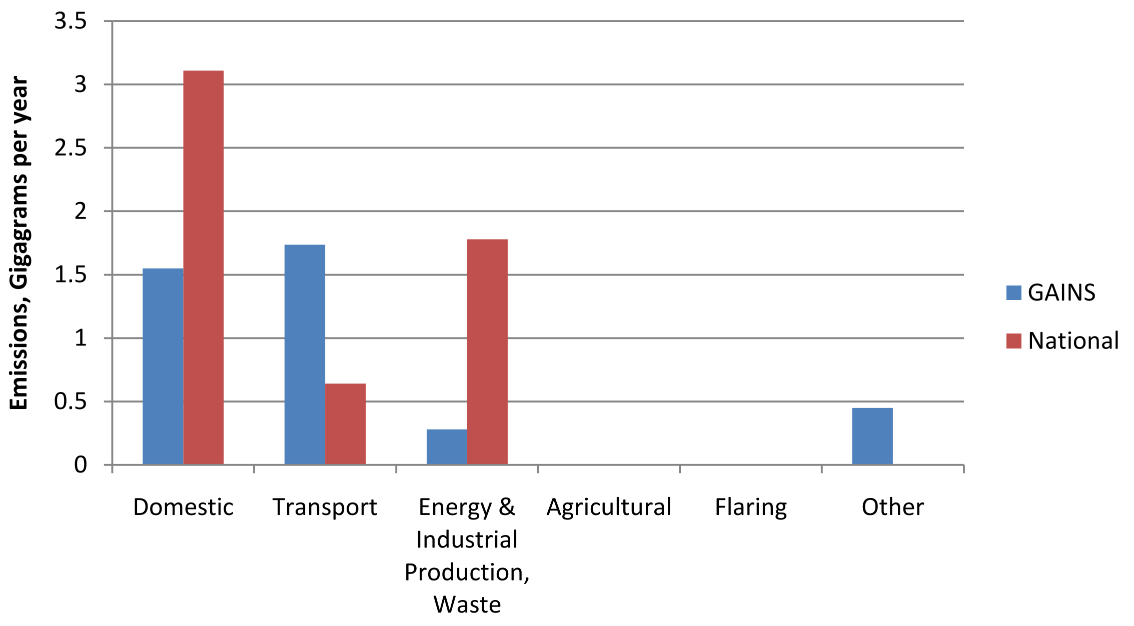
Figures 4-25 and 4-26 compare the BC and OC projected emissions between GAINS and the national estimates for Sweden for the year 2020. The national Energy & Industrial Production, Waste category comprises emissions from electricity and heat production and industrial combustion. It is unclear why there is such a large difference between the GAINS estimates and national estimates, but it can be assumed that the GAINS model is taking into account more or different legislation in their emissions forecasting.

Figure 4-25. Comparison of projected 2020 BC emissions to GAINS, Sweden (Gg).*



* Emissions from open biomass burning, agricultural, and flaring were not estimated.

Figure 4-26. Comparison of projected 2020 OC emissions to GAINS, Sweden (Gg).*



* Emissions from open biomass burning, agricultural, and flaring were not estimated for Sweden.

4.2.6 United States

Projected mobile source emissions out to 2020 are estimated by the $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS) modelling platform, which used 2005 as its base-year inventory. Since mobile source emissions are estimated via this model, the consistency in the methods used can be preserved over time (i.e., the best current model can be applied to both retrospective calendar years, as well as prospective calendar years). Emissions were projected for the United States using the most recent version of the mobile source models to be able to compare historic and future emission trends.

Table F-5 in ***Appendix F*** summarizes the mobile source BC, OC, and $PM_{2.5}$ emissions inventory numbers for various years from 1990 through 2030. ***Appendix F*** also provides details on how these emissions were calculated using U.S. EPA emissions models for on-road and off-road vehicles and/or engines. The control programs that are expected to result in these emissions reductions by 2030 are discussed in more detail in ***Section 5.2.6*** of this report.

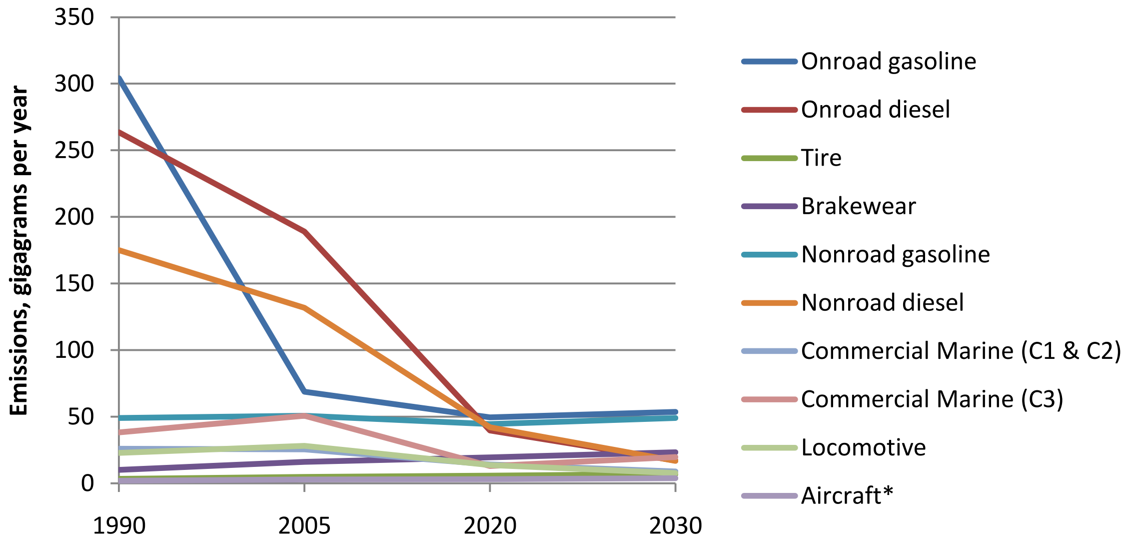
Details on domestic BC trends will be largely limited to mobile sources because they are estimated using consistent methods and because they are a large portion of the current BC emissions inventory. BC trends in the other source categories (open biomass burning, industry, and fossil fuel combustion) are not as easy to depict due to a lack of data and inconsistent methods over time. The methods used to actually estimate emissions from 1990 to 2005 have changed significantly, as has the way $PM_{2.5}$ is translated to BC. In addition, there are no BC estimates available for any non-mobile source categories, including fires (agricultural burning, prescribed burns, and wildfires), for the year 1990.

From 1990 to 2005, all mobile sources combined show about a 32% reduction in BC, a 51% reduction in OC, and a 36% reduction in $PM_{2.5}$ emissions. Then, from 2005 to 2030, major reductions are expected in mobile source BC (about 86%) and $PM_{2.5}$ (about 64%). **Figures 4-27 and 4-28** show how all mobile source categories, including the major mobile source BC categories (on-road gasoline, on-road diesel, and off-road diesel) sources, trend over time.

BC emissions decreased by 79%, 30%, and 25% for on-road gasoline, on-road diesel, and off-road diesel sources from 1990 to 2005. BC emissions, though extremely small, did not change from 1990 to 2005 for off-road gasoline sources. Then, by the year 2030, when much of the diesel controls would have taken effect, many of the smaller, current-year mobile source categories like on-road gasoline and off-road gasoline BC emissions will be top emitting categories (along with off-road diesel, even though heavy reductions from 2005 BC levels are expected to occur). It is also interesting to note that the total mobile source BC:$PM_{2.5}$ ratio is estimated to change from approximately 49% in 1990 to 21% in 2030. This is a clear indication that the amount of BC in $PM_{2.5}$ on-road and off-road mobile sources will have been reduced by the control programs discussed in ***Section 5*** of this report.

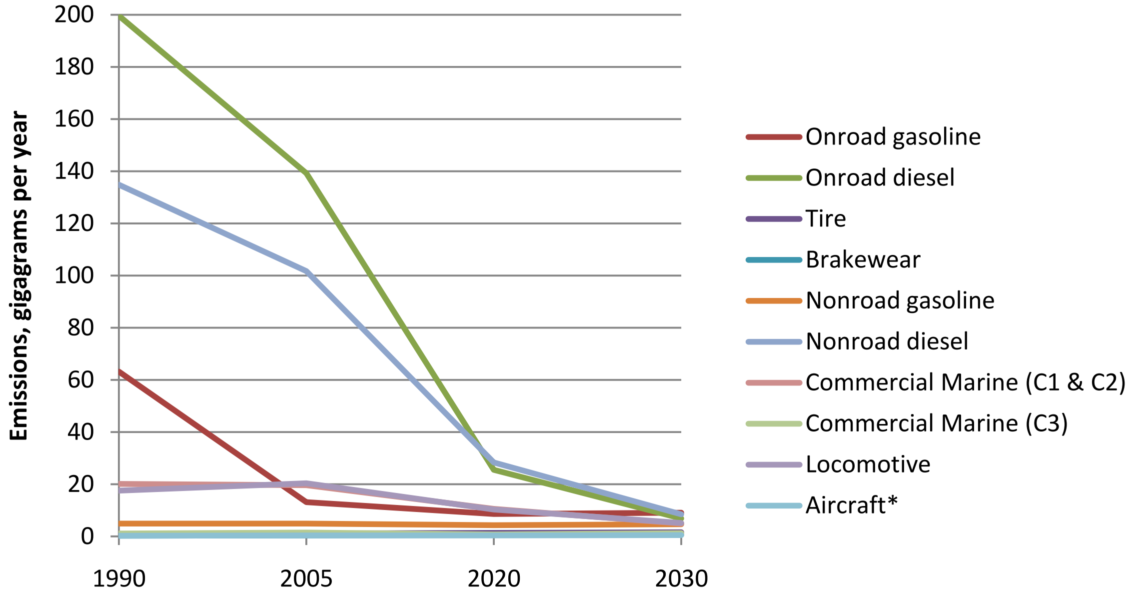
It is expected that minor reductions in direct $PM_{2.5}$ emissions will occur in the other source categories (biomass burning, industry, and fossil fuel combustion) out to the 2020 time period. A small decrease in the biomass burning sector is expected due to decreases in $PM_{2.5}$ emissions from the residential wood combustion category. Industrial direct $PM_{2.5}$ emissions are not expected to decline significantly, and a slight decrease (of about 20%) in $PM_{2.5}$ emissions from the fossil fuel combustion category, including electric generating units (EGUs), is expected (however, some of this could be due to inconsistent methods in estimating 1990 emissions versus 2005/2020 emissions). Since $PM_{2.5}$ emissions reductions are expected to be small for these categories over time, BC emission changes will also be small, and the total BC reductions in future years will be dominated by reductions in the major mobile source diesel sectors.

Figure 4-27. Mobile source direct $PM_{2.5}$ emission trends.*



* Non-landing and take-off (LTO) emissions and anticipated technology and operations improvements are not included in projected emissions for the United States.

Figure 4-28. Mobile source direct BC emission trends.*



* Non-landing and take-off (LTO) emissions and anticipated technology and operations improvements are not included in projected emissions for the United States.

Comparison of United States Projected Emissions to GAINS

The projected BC emissions for the Transport sector compare quite well with the GAINS estimates. The national OC projected emissions from Transport (122 Gg) for the United States, on the other hand, are projected to be twice as high as those from the GAINS model projected emissions (68 Gg).

Section 5

Current Regulations, Policies, and Programs Relevant for Emission Control

Introduction

This section discusses regulation, policies and programs that are already in place or those that are planned for implementation in the near future. There are several regulations that cover many Arctic Council nations, which are discussed in ***Section 5.1***, focusing on North America and Europe. Additional country-specific regulations, policies, and programs are discussed in ***Section 5.2***.

The most effective BC control strategies benefitting the Arctic climate will vary by location and season. Those measures that are going to prove the most effective in reducing BC emissions are specific to the transport, domestic, open biomass burning (including forest fires), and marine shipping source categories. On- and off-road diesel vehicles are a large source of BC emissions that are subject to regulation both in North America and Europe for PM emissions. Most Arctic Council nations have regulations for new on- and off-road diesel engines that are in effect or will become active by 2020; these regulations require these vehicles to implement technologies to reduce BC emissions by 90% or more compared to pre-regulation engines.

Table 5-1 shows key mitigation measures used in the GAINS model.

Table 5-1. BC-Specific Measures Used by the IIASA GAINS Model Emissions Estimates

GAINS Meta Category	Specific Measures that affect BC and other co-emitted compounds (not all of which will be applicable to Arctic Council nations)*
Transport	Diesel particle filters for road and off-road vehicles.
	Elimination of high-emitting vehicles in road and off-road transport.
Domestic	Replacing coal by coal briquettes in cooking and heating stoves.
	Pellet stoves and boilers, using fuel made from recycled wood waste or sawdust, to replace current wood-burning technologies in the Domestic sector in industrialized countries.
	Introduction of clean-burning biomass stoves for cooking and heating in developing countries.
	Substitution of clean-burning cookstoves using modern fuels for traditional biomass cookstoves in developing countries.
	Regular maintenance of oil-fired residential boilers.
Industry	Replacing traditional brick kilns with vertical shaft kilns and Hoffman kilns.
	Replacing traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures.
	Various end-of-pipe options for reducing PM emissions, including cyclones, wet scrubbers, electrostatic precipitators, and fabric filters.
	Regular maintenance of oil-fired industrial boilers.
Agriculture†	Ban of open field burning of agricultural waste.

Source: Modified from UNEP, 2011.

* There are measures other than those identified in the table that could be implemented. For example, electric cars would have a similar impact to diesel particulate filters, but these have not yet been widely introduced; forest fire controls also could be important, but are not included due to the difficulty in establishing the proportion of fires that are anthropogenic.

† The GAINS model does not include wildfires and forest fires.

5.1 Transnational Programs

5.1.1 North American Programs

In 1991, the United States and Canada entered into an agreement[26] to address transboundary air pollution. Transboundary air pollution occurs when pollutants released at one location travel long distances, affecting air quality at their source locations as well as many miles away. The 1991 agreement led to reductions in acid rain in the 1990s and was expanded in 2000 to reduce transboundary smog emissions under the Ozone Annex. Under the Ozone Annex obligations, Canada has implemented a series of regulations to align its emission standards for vehicles and engines with corresponding standards in the United States.

5.1.2 European Programs

Cross-Sectoral Instruments: Environmental Quality Standards

Environmental quality standards (EQS) are cross-sectoral instruments being used to reach national air quality objectives and those set forth by the European Directive on Clean Air (2008/50/EC). EQS were introduced in 1999 (although the EQS for $PM_{2.5}$ was not introduced until 2010) and are legally binding in different Arctic Council nations (for example, by the Swedish Environmental Code). National authorities within the nations (often the municipalities) are responsible for surveying air quality and preparing action programmes to achieve air quality objectives.

Transport

On-Road Vehicles

Emission requirements for on-road vehicles are set by the EU (i.e., the EURO exhaust emission standards). The particulate standard for new diesel cars and other light-duty vehicles were strengthened in 1996 (EURO 2), 2000 (EURO 3), and 2005 (EURO 4). The EURO 5 norms for light-duty diesel vehicles and particulate emissions, in force from 2009/2010, are set at such a strict level that all new cars will be equipped with particulate filters. The EURO 5 particulate standard also covers direct-injected petrol vehicles. See **Tables 5-2 and 5-3** for more details on particulate exhaust emission EURO limits for passenger cars and light commercial vehicles.

Table 5-2. European Emission Standards for Diesel Passenger Cars and Light Commercial Vehicles ≤1305 Kg

Emission Standard	Date of Entry*	PM Emission Standard (g/km)
EURO 1	1991/1992†	0.14
EURO 2	1995/1996†	0.08

---

[26] U.S. – Canada Air Quality Agreement, http://www.epa.gov/airmarkt/progsregs/usca/index.htm, U.S. EPA, October 2010.

EURO 3	1999/2000	0.05
EURO 4	2004/2005	0.025
EURO 5	2008/2009	0.005‡
EURO 6	2013/2014	0.005‡

* First date concerns new type approvals. Second date concerns all new vehicles.

† Date of entry for light commercial vehicles is 2 years later.

‡ Applies also to petrol driven vehicles with direct injected engines

Table 5-3. European Emission Standards for Diesel Light Commercial Vehicles 1305–3500 kg

Emission Standard	Date of Entry*	PM† Emission Standard (g/km)
EURO 1	1993/1994	0.19/0.25
EURO 2	1997/1998	0.12/0.17
EURO 3	2000/2001	0.07/0.10
EURO 4	2005/2006	0.04/0.06
EURO 5	2009/2010	0.005‡
EURO 6	2014/2015	0.005‡

* First date concerns new type approvals. Second date concerns all new vehicles.

† First figure concerns LCV of 1305–1760 kg vehicle reference weight. Second figure concerns LCV of 1760–3500 kg.

‡ Applies also to petrol driven vehicles with direct injected engines.

The emission standards for new heavy-duty vehicles have regulated particulate emissions with approximately the same time table as light-duty vehicles. Particulate standards were introduced in 1991 (EURO 1), with more stringent requirements concerning particulates introduced in 1996 (EURO 2), 2000 (EURO 3), and 2005 (EURO 4). The EURO 4 standard will significantly reduce PM emissions in the time period to 2020, but will be fulfilled by vehicle manufacturers through engine modifications and not result in the use of particulate filters. It is anticipated that particulate filters will be necessary to comply with the strengthened EURO 6 standard for PM that will become mandatory in 2013. See **Table 5-4** for more details on particulate exhaust emission EURO limits for diesel engines in heavy-duty vehicles.

After the vehicles have been put on the market, no interference with engines and exhaust emission equipment is allowed that can affect the emission performance. Retrofits with particulate filters mounted on the tailpipe are accepted by national authorities to ensure that vehicles comply with the emission requirements in low emission zones.

Table 5-4. European Emission Standards for Heavy-duty Diesel Engines

Emission Standard	Date of Entry*	Test Cycle†	PM‡ Emission Standard (g/kWh)
EURO 1	1991/1992; ≤85 kW	ESC	0.612
	1991/1992; >85 kW		0.36
EURO 2	1995/1996		0.15
EURO 3	2000/2001	ESC/ETC	0.16/0.10
EURO 4	2005/2006		0.03/0.02
EURO 5	2008/2009		0.03/0.02
EURO 6	2013/2014		0.01

* First date concerns new type approvals. Second date concerns all new engines.
† ESC=European Steady-state Cycle; ETC=European Transient Cycle.
‡ First figure concerns ESC, and second concerns ETC.

Off-Road Vehicles and Working Machinery

Common European emission standards for new off-road vehicles and working machinery were introduced in 1998/1999 and for agricultural and forestry tractors in 2001. The current standard for particulate emissions (Stage II) was introduced stepwise, depending on the engine power, from 2001 to 2003. Stage IIIA (19 to 560 kW) was implemented in 2006/2007 and requires a slightly stricter PM standard for the smallest diesel engines. Significantly stricter standards for PM emissions (90% reduction), in line with the EURO 4 norm for heavy-duty vehicles, will be implemented in the 2011/2112 timeframe. PM standards for Stage IV (56 to 560 kW), which will be effective in 2014, are the same as those for Stage IIIB (37 to 560 kW), which were recently implemented (2011). Options for further developments of PM standards are in preparation for Stage V. See **Table 5-5** for more details on particulate exhaust emission EURO standards for diesel engines in off-road mobile machinery and agricultural/forestry tractors.

Table 5-5. European Emission Standards for Off-road Diesel Mobile Machinery and Agricultural/Forestry Tractors

Steps	Date of Entry†	PM Emission Standard (g/kWh)
Step I		
37 ≤ P* < 75	1999/2001	0.85
75 ≤ P < 130	1999/2001	0.7
130 ≤ P < 560	1999/2001	0.54
Step II		
18 ≤ P < 37	2001/2001	0.8
37 ≤ P < 75	2004/2004	0.4
75 ≤ P < 130	2003	0.3
130 ≤ P < 560	2002	0.2
Step III A		
19 ≤ P < 37	2007	0.6
37 ≤ P < 75	2008	0.4
75 ≤ P < 130	2007	0.3
130 ≤ P < 560	2006	0.2
Step III B		
37 ≤ P < 56	2013	0.025
56 ≤ P < 75	2012	0.025
75 ≤ P < 130	2012	0.025
130 ≤ P < 560	2011	0.025

* P = Power (kW)

† First date concerns date of entry for new engines, second date concerns tractors.

Energy and Industrial Production (Stationary Sources)

Emission standards for large combustion plants, waste incineration plants, and other large industrial combustion plants are regulated in three common European directives: the Large Combustion Plants Directive (2001/80/EC), Directive 2000/76/EC on the Incineration of Waste, and the Directive on Integrated Pollution Prevention and Control (2008/1/EC). These requirements are implemented in national legislation. An environmental permit with specific PM emission standards is required to construct or operate a combustion plant greater than 50 MW or burn more than 50 metric tons/year of waste. Smaller combustion plants will be notified and regional or local environmental authorities may submit requirements on emission prevention to reduce public health and environmental impacts.

Stricter emission standards are set for large combustion plants and waste incineration plants constructed after 2003. Limits for particulate emissions from waste incineration are lower than for other combustion plants, which demand the use of very efficient flue gas cleaning.

Directive 2010/75/EC on industrial emissions came into force in July 2011 and includes new particulate emission standards for combustion plants and waste incineration in connection with the aim to merge six separate directives (among these, the large combustion plants, waste incineration, and IPPC directives). The particulate standards were halved compared to the existing directives.

5.1.3 International Shipping Regulations

An increased focus on the impacts of air emissions from the shipping source category has resulted in several regulations to control these sources on both the international and regional levels. The International Maritime Organization (IMO), the United Nations agency responsible for preventing maritime pollution from ships, issued rules to control SO_x and NO_x emissions through Annex VI of the MARPOL Convention. These rules include a progressive reduction in SO_x emissions from ships, with the global sulphur cap reduced initially from 4.5% to 3.5% sulphur in fuel oil, effective 1 January 2012, then progressively to 0.5% by 2020, subject to feasibility review. For SO_x Emission Control Areas (ECAs), including the Baltic Sea, North Sea, and North America, fuel sulphur contents were reduced from 1.5% to 1.0% in July 2010 and will be reduced to 0.1% in 2015. Similar regional fuel sulphur requirements are currently enforced in Europe through the EU Sulphur Directive, Directive 1999/32/EC, as amended by Directive 2005/33/EC.[27] This regulation, effective 1 January 2010, requires all ships at berth in European ports to use fuel with a sulphur content of 0.1% or less. Through these fuel limits, associated PM, and therefore BC emissions, are to some extent, expected to be achieved.

5.2 Arctic Council Nations’ Specific Initiatives

5.2.1 Canada

In line with other countries, Canada does not have any regulations explicitly oriented to mitigate BC; however, it does have various measures that set limits on other pollutants that in turn affect BC emissions. Environmental regulation is a shared responsibility in Canada, with many of the legislative and regulatory instruments under both federal and provincial jurisdictions. ***Appendix A-8*** presents a catalogue of federal measures that may potentially impact BC, ozone, and/or methane emissions nationwide. In addition, some provincial-level measures of regulations, policies, and initiatives are provided in ***Appendix A***.

---

[27] Directive 2005/33/EC of the European Parliament and of the Council of 6 July 2005 amending Directive 1999/32/EC as regards the sulphur content of marine fuels, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2005:191:0059:0069:EN:PDF.

Nationally, Canada-wide Standards (CWS) for PM and ozone have been in place since 2000, as part of a joint agreement signed by the country's federal, provincial, and territorial governments (except Quebec) under the Canadian Council of Ministers of the Environment (CCME). These non-binding standards were aimed at reducing PM and ground-level ozone by 2010. The standards (for jurisdictions in areas with a population of over 100,000) were the following:

- CWS for PM: $PM_{2.5}$ of 30 $\mu g/m^3$, 24-hour averaging time, by year 2010
- CWS for ground-level O_3: 65 parts per billion (ppb), 8-hour averaging time, by 2010.

CWS was implemented to varying degrees, with mixed results, as it was not an enforceable standard.

Federal, provincial, and territorial Ministers in Canada have announced that they are moving forward with a new collaborative air management approach based on the multi-stakeholder Comprehensive Air Management System (CAMS) framework proposal. It is anticipated that the new system will include new Canadian Ambient Air Quality Standards (CAAQS) and sector-specific, base-level industrial requirements to limit air pollutants. Implementation of the system is intended to begin in 2013.

Transport

At the federal level, some of the most significant measures with potential impacts on SLCFs have been taken in the transporation sector. Canada has developed and will continue to develop a series of regulations to reduce smog-forming air pollutant emissions from vehicles and engines in alignment with the standards of the U.S. EPA.

Currently, there are regulations in place to reduce air pollutant emissions from passenger cars and light-duty trucks, heavy-duty vehicles, motorcycles, marine engines, recreational vehicles as well as construction and agricultural equipment, and garden equipment such as lawnmowers and chainsaws.

Canada will continue to amend and update existing regulations to maintain alignment with the U.S.

On-Road Vehicles

Beginning in 2004, the On-Road Vehicle and Engine Emission Regulations became effective in Canada, aligning with U.S. standards for new 2004 and later model–year light-duty vehicles and trucks, heavy-duty vehicles, and motorcycles to limit NO_x and VOC emissions. In 2006, these regulations were amended to introduce new requirements for 2006 and later model year on-road motorcycles to align with the more stringent standards adopted by the U.S. EPA.

For heavy-duty diesel vehicles, since 2007, new engines must meet a strict performance standard for diesel particulate, which results in a reduction of BC by about 95%. The technology used is typically diesel particulate filters. Ozone precursors (NO_x and VOCs) are also included in the Government of Canada's on-road vehicle and engine emission regulations for heavy-duty and light-duty vehicles.

Off-Road Vehicles

On February 12, 2011, the proposed Regulations Amending the Off-Road Compression-Ignition Engine Emissions Regulations were published in the Canada Gazette Part I. These amendments will result in further reductions of smog-forming emissions from the off-road diesel engine sector which includes engines typically found in construction, farming, forestry and some mining machines.

New locomotive emissions regulations are being developed by Transport Canada under the Railway Safety Act that will be aligned with United States locomotive emission standards. Emission performance standards will be specified for a number of air pollutants, including carbon monoxide; hydrocarbons; NO_x; and PM. The standards will be set according to Tier levels becoming increasingly more stringent to 2015. Tier 4 locomotive standards would be expected to significantly reduce NO_x and PM emissions from locomotives manufactured in 2015 or later.

Fuels

Regulatory initiatives for fuels include the Sulphur in Gasoline Regulations, which limit the level of sulphur in gasoline to 30 milligrams (mg)/kg (equivalent to 30 parts per million [ppm]) as of January 1, 2005; and the Sulphur in Diesel Fuel Regulations, which reduce the level of sulphur in diesel fuel used in on-road vehicles to 15 mg/kg (15 ppm) as of June 1, 2006 and reduce the level of sulfur in diesel fuel used in off-road, rail, and marine engines to 500 mg/kg (500 ppm) as of 2007. Levels were further limited to 15 mg/kg (15 ppm) in 2010 for off-road and 2012 for rail and marine engines.

The federal Renewable Fuels Regulations which came into effect in December 2010 requires an average of 5% renewable fuel content, based on the volumes of gasoline produced and imported. A second requirement for 2% biodiesel content in the diesel pool has been proposed to start July 1, 2011. Regulations setting this start date are expected to be finalized in summer 2011.

In addition to these regulations, various federal policies and programs have some impact on BC emissions, including support for pilot-scale diesel emissions retrofit programs to reduce diesel PM. Other federal policies and programs include ecoFREIGHT and Fleetsmart, which focus on improving fuel efficiency and demonstrating and verifying new technologies.

Many Canadian provinces also have put in place programs and policies that likely have an impact on BC emissions, including legislated annual motor vehicle inspections for exhaust systems; vehicle anti-idling campaigns; and scrappage or retrofitting programs for older, higher-polluting vehicles. For example, in British Columbia, as of 1 October 2010, heavy-duty diesel on-road vehicles of model years 1989–1993 will be required to be retrofitted with emissions-reduction devices, with the goal of reducing PM from older, heavy-duty diesel vehicles by 20%. The most common device used for this reduction is a diesel oxidation catalyst (DOC) filter.

Industrial Production

Industrial air pollutants in Canada have traditionally been regulated by provinces and/or territories. The main mechanism in Canada for control of industrial air emissions is through permitting requirements (approvals) for specific industries (with the exception of the Northwest Territories and Nunavut). Permits are issued by the provincial, territorial, regional, or municipal government. In some cases, industries are governed through separate legislation or codes of practice established by provinces.

The federal government, in collaboration with Carleton University, is also supporting research to better measure BC to develop diagnostics to quantify soot mass flux from gas flaring and BC mass fraction of soot flux from flares. Some Canadian provinces currently have regulations on flaring that impact BC emissions. Notably, Alberta's Directive 060 on Upstream Petroleum Industry Flaring, Incinerating, and Venting provides regulatory requirements and guidelines for flaring, incinerating, and venting in the province, as well as procedural information for flare permit requests, dispersion modelling, and the measuring and reporting of flared, incinerated, and vented gas. In addition to upstream petroleum industry facilities, the directive also applies to gas transmission facilities. Other provinces (e.g., British Columbia, Saskatchewan) have, or are in the process of developing, similar regulations and guidelines.

Domestic

Measures to regulate wood-burning appliances in Canada are generally applied at the provincial and municipal levels. Some provinces have regulations on the sale of wood-burning appliances, requiring conformity with particulate emission standards, as defined under U.S. EPA or Canadian Standards Association (CSA) codes . Some also have regulated codes of practice and/or wood stove changeout programs. For example, British Columbia established a wood stove changeout program in 2007, with the long-term goal of changing out 50,000 stoves and reducing $PM_{2.5}$ emissions by 3,100 tonnes per year.[28]

While wood combustion is not federally regulated, Canada's federal government does have educational programs on wood burning and has provided incentives for Canadians to buy cleaner residential wood-burning appliances. Also, a federal model bylaw was developed in 2006, in collaboration with stakeholders, for use by municipalities to assist in regulating the use of wood-burning appliances, with the objective of reducing $PM_{2.5}$ emissions from residential wood combustion. This bylaw includes strategies that specify limits on total emissions, strategies that provide incentives or impose disincentives to limit emissions (e.g., financial assistance to encourage changeout of non-certified wood-burning appliances), and public education and information strategies.

Agricultural Burning

Many provinces have regulations on agricultural burning; for example, British Columbia has an agricultural waste control regulation that establishes practices for

---

[28] They also have a broader wood residue burner and incinerator regulation that establishes phase-out dates and operating conditions for specified burners and sets emission limits and fees for the discharge of associated particulate matter for all burner facilities in the province.

using, storing, and managing agricultural waste. Many have regulations governing the burning of crop residue and non-crop herbage, including seasonal restrictions and limiting impacts on visibility.

Most provinces also have educational and incentive programs to promote improvements in crop residue management and to reduce burning. For example, Quebec provides financial support for manure processing and energy from agricultural, forest, and municipal biomass through a $650 million program to support municipalities and private industry to establish infrastructure to process organic matter through biomethanization or composting.

Open Biomass Burning

Most provinces/territories have forest protection and fire management legislation and regulations, as well as municipal bylaws regulating solid waste and open burning.

5.2.2 Denmark, Greenland, and the Faroe Islands

Like most other countries, Denmark has no regulations focusing specifically on emissions of BC, but a range of regulations limit the emissions of $PM_{2.5}$ and thereby BC. If $PM_{2.5}$ is included in the revised Gothenburg Protocol, the CLRTAP will require Arctic Council nations to reduce total emissions of $PM_{2.5}$. This section discusses current and planned regulations that target $PM_{2.5}$ emissions. Various regulations and other initiatives focused on reducing emissions of CO_2 also have a significant effect on BC emissions, since reducing fossil fuel combustion will, to a large extent, also reduce BC emissions accordingly.

Greenland is a self-governing island within the Kingdom of Denmark. Since 1988, the Greenland Parliament has instituted environmental and climate policies and regulations for Greenland. Unlike Denmark, Greenland is not a member of the EU. As a consequence, policy commitments and regulations undertaken by Denmark, as a member of the EU, do not apply in Greenland.

Greenland has no comprehensive regulation focused on reducing BC emissions. However, a series of sector-specific policies and initiatives addressing energy efficiency and emission reduction have already been implemented, with more planned for the future.

Denmark and the Faroe Islands

Transport (On-Road and Off-Road)

European Air Quality Standards have led to the appointment of Environmental Zones[29] that target PM emissions from heavy traffic in the four largest cities in Denmark. In addition, the country has introduced economic incentives promoting particle filter retrofit, more energy efficient vehicles, and enhanced car fleet exchange, further reducing emissions of BC. As a result of current and planned future regulation, BC

---

[29] DK Environmental Zones - Economic incentive for particle filter equipped vehicles - Lower registration fee for EURO 5.

emissions in Denmark from road transport are expected to decrease by approximately 65% by 2020, relative to 2010, and BC emissions from off-road mobile sources are expected to be reduced by approximately 55% by 2020, relative to 2010.

Domestic (Residential Heating)

Denmark has requirements[30] for wood stoves and boilers, targeting PM emissions. Currently, a maximum emission of 10 g PM per kilogram of wood is allowed for new stoves.

Agricultural and Open Biomass Burning

Agricultural burning has been prohibited in Denmark since 1992, and many municipalities have a ban on open biomass burning.

Greenland

Transport (On-Road)

The Transport sector is considered a key sector despite the fact that Greenland has no roads connecting towns and settlements. Oftentimes, road transport is not considered to be fuel efficient due to extreme winter temperatures. In addition, idling is common and often necessary under such extreme weather conditions.

In October, the 2011 Greenland Parliament passed three acts that create economic incentives for fuel-efficient behaviour:

- The Act on Environmental Taxes for Products used in Energy Production - [31] Greenland’s first environmental tax on fossil fuels came into force in January 2011. This is a direct tax of DKK 0.10 per litre of the retail price on most fossil fuels, regardless of end-use, creating an economic incentive to both reduce fossil fuel consumption and to invest in new and cleaner technologies within the private and public sectors.
- An increase in motor vehicle taxes of 10% to 50%, primarily focusing on heavy (diesel) vehicles
- A general tax exemption for hydrogen and electric vehicle (EV) cars.

Two EV cars were tested in Nuuk during the 2010/2011 winter as part of the Nordic El-Mobility project, and a third EV car is being tested by private entrepreneurs. Due to the extreme Arctic climate (i.e., low temperatures and snowfall), testing will focus on operational reliability. If successful, EV cars may prove a means to better exploit the current energy-producing potential of the existing hydropower plants.

---

[30] BEK nr 1432 af 11/12/2007 (in Danish)

[31] Inatsisartut lov nr. 21 af 18. november 2010 om miljøafgift på produkter til energifremstilling (in Greenlandic and Danish). Translates into Greenland Act no. 21 of 18 November 2010 on Environmental taxes on products used for energy production. http://www.lovgivning.gl/gh.gl-love/dk/2010/ltl/L_21-2010_energiafgift/L_nr_21-2010_dk.htm

Marine Shipping and Civil Aviation

In the shipping and civil aviation source categories, industry leaders are committed to fuel-efficient management of their operations. Both Air Greenland and Royal Arctic Line have invested in new fleets, reducing the environmental footprint of their operations.

Cruise ship tourism in Greenland has seen a marked increase over the past decade. Cruise ships operate in accordance with national and international standards when travelling through Greenland's waters. Most cruise ships operate within the environmental guidelines created by the Association of Arctic Expedition Cruise Operators.

There are no emission standards for the fishery industry in Greenland, but the Greenland government is pursuing economic incentives for fuel efficiency. In 2009, a Government commission published a report with recommendations for the future of the fishing industry. The Ministry of Fisheries, Hunting, and Agriculture, together with the fishing industry, has been working on adopting these recommendations into legislation by fall 2011. The government is also considering the possibility of replacing the current small-scale fishing fleet with a newer, more efficient fleet. At the moment, a large part of the functioning fleet will need to be replaced within the next 10 to 15 years. A government scheme to allocate funding for the replacement of operational small-scale fishing vessels older than 25 years of age was introduced in 2010. Further funding has been set aside for the 2011 to 2013 timeframe to replace a total of 100 vessels.

Current regulations also give the owner of fishing vessels access to funding for modern equipment (e.g. through favourable state loans). Some of these investments will target fuel efficiency and thereby reduce emissions of BC and OC.

Domestic (Residential Heating)

Greenland is currently experiencing a large increase in construction of residential buildings. BC emissions from residential plants account for 11% of total emissions today. Greenland's government has invested in renewable energy solutions and in energy recovery from incineration, but many homes still use oil-fired boilers that emit more PM/BC. The government also is promoting energy efficiency in new construction and restoration of existing homes. An assessment of the energy efficiency in new housing[32] proved that a new housing development of 210 homes in Nuuk has resulted in a marked reduction in the energy used for heating compared to the housing development replaced.[33]

Energy Production

The most effective initiative to replace the use of fossil fuels in Greenland has been long-term government investments in hydropower plants. Since the early 1990s, Greenland has invested 1% of its annual Gross Domestic Product into the development and construction of hydropower plants, resulting in an increase of renewable energy

---

[32] Greenland Government (2009): Assessment: potential instruments in GHG mitigation 2008–2012. Annex 3: Cost-assessment for selected instruments within the heating sector, INUPLAN, August 2009.

[33] Report: Cost assessment for selected instruments within the heating sector, August 2009. Annual energy use for heating in new Tuapannguit development is 235 MJ/m2/year compared to 538 MJ/m2/year for the old Q, R and S development.

from 0% in 1992 to 50% of total energy production in 2010. Greenland is committed to increasing the percentage of renewable energy to total energy production to 60% by 2020.

Other small-scale renewable energy solutions being developed and tested include solar panels constructed to optimize the energy production in snow- and ice-covered areas in Sisimiut and a pilot-scale windmill in the Sarfannguaq settlement.

Industrial Production

Environmental permits for industrial activities are issued in accordance with the Greenland Environmental Protection Act and specific regulations on environmental permits for polluting activities. Generally, environmental permits are not based directly on standards for emission, but instead on immission, which is the direct pollution that humans in an area are exposed to due to a certain polluting source. Immission is calculated from the emission of the source and an operational meteorological model for air quality. It is a Danish model that can be adjusted to also apply for conditions in Greenland. The Government sets permit requirements for pollution abatement measures (e.g., the use of air filters), as well as industry-specific requirements (e.g., low-sulphur fuel is generally required).

Mineral and Hydrocarbon Activities

Currently, all aspects of mineral and hydrocarbon activities are regulated in accordance with the 2009 Greenland Parliament Act No. 7 (the Mineral Resources Act). Sections 50–62 of the Mineral Resources Act states that mineral resource activities must be developed on a sustainable basis and in accordance with international standards, including Best Environmental Practices (BEP) and Best Available Technologies (BAT).

Provisions laid down by the Bureau of Minerals and Petroleum within the Greenland Government require mining and oil exploration companies to deliver a GHG budget as part of their EIA.[34] The budget must consider sustainable energy sources as alternatives to fuel combustion to reduce GHG (specifically CO_2), BC, and OC emissions. Companies are also required to use BEP/BAT for oil test drillings to reduce emissions from flaring and combustion, as stipulated in the EIA Guidelines (January 2011) issued by the Bureau of Minerals and Petroleum.

Agricultural and Open Biomass Burning

In Greenland, a limited number of small-scale hydropower plants (with an average effect of 50 kW or less) have been established by local entrepreneurs to supply sheep stations with renewable energy, thereby reducing BC and OC emissions from fossil-fuel generators locally.

5.2.3 Finland

There are no existing laws that specifically target BC and OC in Finland, although BC and OC are considered by a number of policy initiatives (e.g., Arctic Council, UNECE).

---

[34] Greenland Government, BMP guidelines for preparing an Environmental Impact Assessment (EIA), January 2011.http://www.bmp.gl/images/stories/minerals/EIA_guidelines_mining.pdf

Because BC is co-emitted with pollutants that are controlled by current legislation (i.e., $PM_{2.5}$), a reduction in emissions in several sectors is expected in Finland.

Currently, a major part of air pollution control legislation in Finland is EU legislation, and only minor parts are decided nationally. The emission limit values for on-road vehicle engines and off-road mobile machinery are fully harmonized in EU legislation (see ***Section 4.1***). For fuels, it has been possible to use economic instruments and other voluntary measures. Finland has introduced low sulphur (10 parts per million [ppm]) fuels for on-road and off-road vehicles earlier than required by the EU Directives. Preparations of emission-limit values for stoves, ovens, and other fireplaces are under way in the EU, as well as nationally.

5.2.4 Norway

PM regulations currently in place in Norway are summarized in **Table D-3** in ***Appendix D***. Low sulphur content in fuels is included because it contributes to the reduction of secondary particulates in the country, if not specifically BC. Some NO_x measures are also included in the summary table for the same reason.

Domestic

The most efficient national measure to reduce emissions in Norway is the 1998 regulation for new wood stoves, which promotes upgrading old stoves in Oslo through a reimbursement of 366 Euros in the city centre for each old stove replaced. If a stove is replaced outside of the city centre, the reimbursement is cut in half (i.e., 188 Euros). The emission limit values for new (replacement) stoves are listed in **Table 5-6**.

Table 5-6. Emission Limit Values for Wood Stoves in Norway (NS3059)

Type of Stove	Max Limit for One Sample	Max Average Value
Stove with catalyst	10 g/kg	5 g/kg
Stove without catalyst	20 g/kg	10 g/kg

Transport

Transport emissions are mainly regulated through EURO standards, which are applicable in Norway. In addition, Oslo County has introduced speed limits, which may reduce BC and PM emissions. Other PM-specific regulations include a tire wheel tax to reduce road abrasion emissions; mandatory road cleaning to remove dust; and application of salt to roadways instead of sand to increase road friction during winter. Attempts to increase the scrapping of super emitters were tried with little success in 2008 when the deposit was more than tripled (from 180 to 600 Euros). The failure of success is most likely because the price of an old super emitter is so low (about 3000 Euros) compared to a state-of-the-art vehicle. The deposit was later unified to about 180 Euros for all vehicles.

Industrial Production

Norwegian industries are regulated through facility-specific emissions permits. In order to make the regulations clear and more manageable, new “bulk” regulations for dust and other emissions from small combustion installations were introduced in 2010. The regulation is applicable for combustion plants and combustion units fired with clean fuels and with a rated thermal input of 1–50 MW (see **Tables D-4 and D-5** in ***Appendix D***).

5.2.5 Sweden

Policies and measures aimed at abating PM emissions have been part of the Swedish environmental policy for a long time, but BC has not specifically been addressed. National clean air objectives define the desirable air quality in urban areas that should be fulfilled within one generation. The $PM_{2.5}$ objectives to be fulfilled by 2010 consist of a diurnal average value of 20 $\mu g/m^3$ and a yearly average of 12 $\mu g\ /m^3$. There are currently no international agreements that set a ceiling on total particulate emissions, though the Government has declared its support for such an agreement since reduced emissions of $PM_{2.5}$ in Europe are imperative to reducing $PM_{2.5}$ levels in Swedish urban areas.

Sweden’s national clean air policy and measures to reduce $PM_{2.5}$ emissions are based on a strategy for more efficient use of energy and transportation (e.g., the EET-strategy). This strategy aims to achieve several environmental objectives, including clean air and reduced climate impact. Analyses have indicated that policies and measures that reduce GHG emissions often have a positive effect on the reduction of $PM_{2.5}$. In addition to GHG reduction measures, Sweden has focused on common and coordinated measures in Europe to reduce tailpipe emissions from road traffic, other mobile sources, and working machinery.

The main policy instruments affecting $PM_{2.5}$ emissions from combustion sources are discussed below.

Transport

Environmental Classification of Vehicles and Reduced Annual Vehicle Tax

To stimulate the early introduction of vehicles with improved emissions performance, both light- and heavy-duty vehicles in Sweden have been classified according to EURO standards. The environmental classification system informs consumers of new vehicles that they can choose a new vehicle in compliance with the current EURO standard, or a vehicle in compliance with an upcoming EURO standard. Economic incentives through reduced annual vehicle tax have normally accompanied the environmental classification to stimulate a faster introduction of vehicles that are approved according to new, stricter standards. These incentives end when the standards become mandatory.

In 2006, light-duty diesel vehicles equipped with particulate filters fulfilling the EURO 5 particulate standard were incentivised by an annual vehicle tax discount, resulting in almost every new diesel car being equipped with particulate filter from July 2006. The tax incentive ended in December 2007, when practically all new diesel cars put on the market in Sweden complied with the EURO 5 standard.

Congestion Taxes in City Centres

Vehicles entering or leaving Stockholm on weekdays between 6:30 am to 6:30 pm must pay a congestion tax. The objectives of the tax are to reduce the traffic in the most congested areas and improve air quality. The tax amounts to 10, 15, or 20 Swedish kronor (~ 0.1-0.2 €), depending on the time of day. The tax was introduced as a trial in 2006 and became permanent in 2007. During the first year, a 15% reduction in traffic (measured in vehicle kilometres) and a10% reduction in PM_{10} emissions were observed. Gothenburg, the second largest city in Sweden, will introduce a congestion tax in 2013.

Environmental Zones for Heavy-duty Vehicles

Municipalities may introduce environmental zones in parts of urban areas where the air quality is inadequate. In these zones, only heavy-duty diesel vehicles fulfilling certain emission requirements are allowed. Currently five cities—among these the three largest cities (Stockholm, Gothenburg, and Malmoe)—have declared parts of their city area an environmental zone. Several other municipalities are planning to introduce environmental zones. The main motive for the introduction of an environmental zone is the exceedance or risk of exceeding environmental quality standards (EQS) for air pollution. The emission requirements for environmental zones are nationally regulated and stipulate that the EURO 4 norms must be fulfilled at a minimum. In the cities that implemented environmental zones, PM reductions from 15% to 30% have been estimated in 2007.

Off-Road Transport

Governmental agencies are urged to set environmental requirements when they procure products and services. The Swedish Transport Administration has to meet emission requirements when they procure contracts for building and maintaining infrastructure. To stimulate the use of off-road mobile machinery by contractors, the administration has diversified the payment scheme. Contractors with lorries that do not fulfil the EURO 2 requirements or better, are paid reduced amounts by the Government. In areas that are at risk of exceeding environmental air quality standards, contractors using unregulated off-road machinery are paid at reduced amounts while contractors using machinery with particulate filters are paid above the standard amount.

Stockholm, Gothenburg, and Malmoe have common environmental requirements when contracting vehicles, tractors, and off-road mobile machinery. These requirements stipulate that mobile machinery shall not be older than 8 years and must fulfil the EURO 2 standard, or be equipped with a particulate filter.

Domestic

Energy Efficiency

Energy efficiency is a key area in the EU’s combined energy and climate strategy. Improving energy efficiency and building insulation will demand less energy and will reduce air pollution from individual combustion in houses, from district heating, and from electricity production. The Energy Performance of Buildings Directive and the

Swedish building regulations set maximum energy consumption levels for new buildings. The same requirements are in force for major renovations and extension of houses.

Single House Boilers and Stoves

During the past decade, significant changes to single home domestic heating have occurred in Sweden. Old oil-boilers have been replaced by district heating, heat-pumps, or biofuelled boilers and stoves, and new oil-boilers are no longer being installed. New installations of biofuelled single house boilers and stoves have to meet the air pollution standards in the building regulations set by The National Board of Housing. Currently, there is a high percentage of old biofuelled boilers and stoves with high rates of particulate emissions. To minimize air pollution from biofuelled boilers and stoves, information campaigns on the proper use of wood fuel have been performed both nationally and locally. However, the replacement of old boilers is a slow process, and it is expected that boilers will still be a significant contributor to total $PM_{2.5}$ emissions in 2020.

5.2.6 United States

Transport

Diesel and Gasoline Vehicle Engines

While mobile sources currently dominate the U.S. inventory currently, significant reductions in emissions of both BC and OC have been achieved since 1990. As existing vehicle regulations on $PM_{2.5}$ are implemented over the coming years, they are expected to produce further reductions. Most of these reductions will be a direct result of U.S. EPA’s regulations on diesel PM, but some will also be due to regulations on emissions from gasoline vehicles. Due to these regulations, the mobile source contribution to BC compared to other sources has declined on both an absolute basis and a fractional basis since 1990. In the United States, new engine requirements were responsible for a 30% reduction in BC emissions from mobile sources between 1990 and 2005. As vehicles and engines meeting new regulations are phased into the fleet, there will be a further 82% reduction in BC emissions from mobile sources from 2005 to 2030, leading to a total decline of 90% in BC emissions between 1990 and 2030.

Regulations on exhaust PM for diesel trucks, one of the most important emission source categories, were initiated in 1988. As a result, from 1990 to 2005, there was a 30% decline in BC emissions from diesel trucks, and a further 95% decline in BC emissions is projected from 2005 to 2030 (97% total decline since 1990). Other categories of diesel engines, such as off-road diesels (e.g., agricultural, construction equipment), commercial marine diesels, and locomotives, will also have major declines of 75% to 90% in BC emissions from 2005 to 2030 in the United States. U.S. EPA will evaluate the effectiveness of these programs as they are implemented to determine what additional control is appropriate.

Gasoline vehicles and off-road gasoline engines are another, but smaller, source of BC. A reduction in BC from gasoline vehicles of 86% is projected to occur from 1990 to 2030, with a 31% reduction occurring from 2005 to 2030. Unlike the reductions for diesels, the reductions in BC from gasoline engines occurred due to regulation of other pollutants (such as hydrocarbons, carbon monoxide, and NO_x), which resulted in use of catalysts and better air:fuel ratio control, rather than regulation of PM itself. In general, BC emissions from gasoline vehicles and engines have been less studied than those from diesel engines.

In the United States, the regulations on new engines have been accompanied by mandated reductions in sulphur levels in both gasoline and diesel fuels starting in 1995. Furthermore, these regulations on new engines are supplemented by control of BC from in-use vehicles/engines. In the United States, opportunities to control BC emissions from in-use vehicles focus almost exclusively on diesel engines. As used by U.S. EPA, the term *diesel retrofit* includes any technology or system that achieves emission reductions beyond those required by U.S. EPA regulations at the time of new engine certification. Diesel retrofit projects include the replacement of high-emitting vehicles/equipment with cleaner vehicles/equipment; repowering or engine replacement; rebuilding the engine to a cleaner standard; installation of advanced emissions control after-treatment technologies such as diesel particulate filters (DPFs); or the use of a cleaner fuel. The BC mitigation potential of diesel retrofits applied to existing engines depends on several factors, including engine application (vehicle or equipment type), engine age, engine size, engine condition (maintenance), and remaining engine life. One or more of these factors will dictate the mitigation strategy. Some engines, whether because of old age or poor maintenance, are not able to be retrofitted with DPFs. Engines with limited remaining life or low usage rates are not good candidates for retrofits when cost-effectiveness is considered. It is possible for 10% to 15% of the vehicles in a typical fleet to emit 50% or more of each major exhaust pollutant due to malfunctioning engine parts (National Academies Press, 2001). This is an important consideration in developing mitigation strategies. It can also be prohibitive to replace an old engine with a new one in many cases because of insufficient space in the original vehicle or piece of equipment.

The National Clean Diesel Campaign and the SmartWay Transport Partnership Program are U.S. EPA’s two primary programs responsible for reducing emissions from in-use diesel vehicles and equipment. These programs support the testing and deployment of numerous technologies and strategies to reduce BC from in-use diesel engines and can provide immediate reductions. The National Clean Diesel Campaign is an innovative partnership program that aims to accelerate the implementation of emission-control strategies in the existing fleet through approaches such as retrofitting, repairing, replacing, repowering, and scrappage of diesel vehicles and equipment; reducing idling; and switching to cleaner fuels. The SmartWay Program is an innovative collaboration between U.S. EPA and the freight sector to promote a number of technologies that directly reduce emissions of PM and BC, including idle reduction, accelerated vehicle replacement, and emission control retrofits. SmartWay also includes programs to test and verify fuel-saving equipment and vehicles; develop innovative finance strategies to promote retrofitting or accelerated replacement of older vehicles and equipment; and develop tools and methods to assess and track emissions from SmartWay partners. SmartWay tracks fuel savings, reductions in GHG emissions, reductions in smog-forming NO_x emissions, and reductions in PM, including BC.

Other Mobile Sources – Locomotives and Commercial Marine Vessels

Locomotives have used diesel (diesel electric) engines predominantly since the 1950s. U.S. EPA has implemented several tiers of emission standards for PM for these engines, with the most recent set of standards to be effective in 2015. These newest standards will result in the use of DPFs on new locomotives, which, again, preferentially reduce BC. In addition, national emission standards require that older locomotives that are remanufactured must be certified to more stringent emission standards than their prior certification level.

Commercial marine vessels are classified as C1, C2, and C3 based on engine size. C1 marine engines are similar in size (less than 5 litres/cylinder) to those used in construction/farm equipment. C2 marine engines (between 5–30 l/cylinder) are similar to locomotive diesels. The C3 engines (greater than 30 l/cylinder vessels) are similar to those used in some power plants and are used in ocean-going vessels. The most recent set of emission standards for these engines will result in the newest C1 and C2 commercial marine engines having DPFs starting in 2014. For these engines, there will be a dramatic drop in PM emissions and an even more dramatic drop in BC emissions. Like locomotives, older marine diesel engines must be certified to more stringent emission standards upon remanufacturing, compared to their previous certification level. The level of the standards to which these remanufactured engines must be certified varies depending on engine type and year of manufacture for the original engine.

For C3 vessels, the PM consists largely (about 75%) of sulphate and relatively little (less than 1%) of BC. Recent work with the IMO seeks to reduce the higher sulphur level of the fuel (largely bunker diesel fuel composed of especially high molecular weight, even solid, hydrocarbon compounds) used in these engines. Although sulphur and PM levels will be reduced, BC levels are expected to stay the same on a per-vessel basis and will constitute a larger percentage of the PM emissions. There is some increase in BC emissions from 2005 due to an increase in usage of these vessels. Still, C3 marine vessels are responsible for less than 1,000 tons of BC emissions. Additional BC emissions data are needed for C3 marine vessels.

Industrial Production and Stationary Sources

In the United States, stationary sources comprise both fossil fuel combustion units, such as power plants and industrial boilers, and other types of industrial sources, such as cement plants and stationary diesel engines. Stationary source emissions of BC have been reduced substantially from historical levels through technologies and strategies to limit direct $PM_{2.5}$ emissions for air quality purposes. Although some uncertainty remains regarding the control efficiency of these techniques for the BC fraction, that uncertainty does not change the conclusion that the mass emissions of BC from stationary sources are relatively low in comparison to mobile and area sources.

The stationary source controls that have been established under the Clean Air Act over decades have effectively reduced direct PM emissions, such that BC emissions from this sector are now only about 9% of total U.S. BC emissions. The longer-term emissions trend for $PM_{2.5}$ (and therefore, BC) from the overall industrial sector is expected to continue to decline as more areas of the United States comply with the current annual and 24-hour $PM_{2.5}$ NAAQS and any future revisions to those standards, and as sources are required to comply with more stringent industrial sector emissions standards for new and existing sources (both New Source Performance Standard [NSPS] and Maximum Achievable Control Technology [MACT] standards). Compliance with these standards will lead to control of those sources that do not now have $PM_{2.5}$ controls and improved control of sources that currently have some level of $PM_{2.5}$ control. Because BC is a component of $PM_{2.5}$, BC emissions will also be reduced.

In the United States, coal combustion is the largest sub-category of BC emissions from stationary sources. Most large coal combustion sources, such as EGUs, are likely to be well controlled to comply with prior PM emission standards. Nearly all large coal-fired EGUs have electrostatic precipitators (ESPs) or fabric filters for PM control. In contrast, smaller and older coal combustion units that have not been subject to similar emission standards may demonstrate greater control cost effectiveness because installation of a given control technology will remove a greater mass of PM (including $PM_{2.5}$ and BC) compared to a well-controlled EGU on a ton-per-Btu basis. Therefore, some sources that have heretofore been completely exempt from PM control because of their age, small size, or limited operation (such as certain distillate oil or coal combustion systems) may present favourable mitigation opportunities.

The next largest stationary combustion source category is stationary diesel engines, which are similar to mobile diesel engines and use mostly the same fuels, but are used to perform different tasks (such as pumping water or oil through pipelines, operating equipment in remote locations, or providing backup power generation). Stationary diesel engines can also operate using natural gas or heavier fuel oil grades than mobile diesel engines. U.S. EPA's stationary diesel engine and fuel standards taking effect over the next decade for new engines will significantly reduce PM emissions from new sources; however, over a million stationary diesel engines already in use will continue to emit large amounts of PM and NO_x.

Another stationary source category of note is large industrial, commercial, and institutional boilers, commonly referred to as ICI boilers. These sources are regulated by new stringent standards for PM, mercury, and many other pollutants, some of which are classified as hazardous. U.S. EPA recently promulgated new rules to limit emissions from many boilers, effectively lowering their potential to emit BC.[35]

Domestic

The key emitting source categories that comprise residential wood combustion are wood stoves, manufactured and masonry fireplaces, hydronic heaters, and indoor furnaces. Mitigation strategies for residential wood combustion sources have generally focused on either replacing inefficient units (such as wood stoves and hydronic heaters) with newer, cleaner units through voluntary or subsidized changeout programs, or retrofitting existing units to enable use of alternative fuels such as natural gas (fireplaces).

---

[35] U.S. EPA Industrial/Commercial/Institutional Boilers and Process Heaters Maximum Achievable Control Technology (MACT) Rule for Major Sources (Subpart DDDDD) and Area Sources (Subpart JJJJJ). The final rule was signed on 21 February 2011. More information is available at: http://www.epa.gov/ttn/atw/boiler/boilerpg.html.

Since 1990, U.S. EPA has regulated $PM_{2.5}$ emissions from new residential wood stoves, and the Agency is currently reviewing the Residential Wood Heaters Standard. This review is considering tightening the air pollution emission limits, adding limits for all pellet stoves, reducing the exemptions, and adding regulations for hydronic heaters, furnaces, and fireplaces. U.S. EPA expects to propose appropriate revisions by June 2011, and finalize revisions in 2012. The tightening of the wood heater NSPS has the potential to help reduce future residential wood-burning emissions throughout the United States. However, a fundamental limitation of the current NSPS standards is that they cannot influence emissions from units that were purchased prior to establishment of the NSPS. In many cases, existing units can remain in service for decades. The majority of BC and other potentially harmful fine particles, toxic air pollutants, and chemicals come from old, inefficient wood stoves built before 1990. Wood burning appliances with lower combustion efficiencies tend to have higher emissions of most pollutants than do those with higher efficiencies.

In 2005, U.S. EPA developed the Great American Wood Stove Changeout Program to support state, local, and tribal communities in reducing $PM_{2.5}$ and toxic air pollutants. These same initiatives can also be employed to help reduce BC and other GHGs (e.g., methane and CO_2) from residential wood combustion. The program supports local campaigns that are typically led by local government or non-profit organizations at the county or regional level. Residents of participating communities generally receive incentives such as cash rebates, low/no interest loans, and discounts to replace their old, conventional wood stoves and fireplace inserts with cleaner-burning, more efficient U.S. EPA-certified gas, pellet, electric, wood stoves, and fireplaces or even geothermal heat pumps. The local agency leading the changeout will sometimes involve weatherization programs and insulate homes to help reduce heat loss that results in less fuel burned. Households that participate in changeouts must surrender their old wood stoves to be recycled. Programs vary from one community to another, with some areas focusing on changing out old wood stoves and others on retrofitting open fireplaces with cleaner burning options (e.g., gas stoves). Some areas have provided cash incentives to low-income participants only, while others have provided incentives to everyone in the community.

In 2007, U.S. EPA established the Outdoor Wood-Fired Hydronic Heater Program to reduce $PM_{2.5}$ emissions from new outdoor wood-fired hydronic heaters. U.S. EPA has worked with industry to reach agreement on voluntary performance levels for new heaters to bring them to market faster than feasible under regulation. The program is structured in two phases: under Phase 1, qualified new units are 70 % cleaner than existing units, and under Phase 2, new units are 90 % cleaner than existing units. In October 2008, U.S. EPA terminated Phase 1 program agreements and started Phase 2 agreements, which entail tighter performance levels. The Agency also expanded the program to include indoor models and hydronic heaters that are fuelled by other kinds of solid biomass (e.g., wood pellets). Manufacturers may not use Phase 1 labels after 31 March 2010. As of 2009, nearly 7,400 U.S. EPA-qualified units have been sold; 24 manufacturing partners have agreed to produce units 70% to 90% cleaner; and 22 models have been placed on the market, reducing an estimated annual 4,123 tons of $PM_{2.5}$ emissions.

In 2009, U.S. EPA created the Wood-burning Fireplace Program, which is modelled after the Hydronic Heater Program to work closely with the hearth products industry to develop voluntary performance levels. The two-phase program covers new installation of low mass (i.e., pre-manufactured) and masonry fireplaces and is expected to drive technology improvements much sooner than possible through regulation. The program qualifies models achieving a Phase 1 (34% reduction) or a Phase 2 (54% reduction) $PM_{2.5}$ emission level.

U.S. EPA also launched an educational campaign called Burn Wise in October 2009 to complement the programs listed above. For example, changing out wood stoves is a very important part of the solution to many area's wood smoke problems; how wood stoves are operated and what is burned is equally as important. The campaign is designed to promote responsible wood burning and to educate users on the connection between what they burn, how they burn, and the impacts on their health and the environment. The campaign provides a Web site (www.epa.gov/burnwise), fact sheets, posters, and public service announcements. U.S. EPA has coordinated with the hearth products industry and other partners on the development and implementation of the campaign.

Agricultural and Open Biomass Burning

Fire emissions can impact air quality and contribute to an exceedance of the NAAQS for ozone and PM and may also impair visibility and contribute to regional haze. Where fire causes or contributes to violations of the NAAQS or impairs visibility in mandatory Class I federal areas (i.e., areas where the EPA Administrator, in consultation with the Secretary of the Interior and Secretary of the Department of Agriculture, has determined visibility to be an important value), states and tribes are required to address fire emissions through their implementation plans. The Exceptional Event Rule (EER) notes that wildfires are natural events and can be addressed so that they do not impact an area's ability to meet the NAAQS. If wildfire is contributing to the nonattainment status of an area, the EER has failed its intent. Prescribed fires that impact an area's ability to meet the NAAQS may also be addressed through a specific process and provisions in the EER.

The Interim Air Quality Policy on Wildland and Prescribed Fires (U.S. EPA, May 1998) addresses wildland and prescribed burning managed for resource benefits on public, tribal, and privately owned wildlands.[36] The policy integrates two public policy goals: (1) to allow fire to function, as nearly as possible, in its natural role in maintaining healthy wildland ecosystems and, (2) to protect public health and welfare by mitigating the impacts of fire emissions on air quality and visibility. The policy encourages state and tribal authorities to adopt and implement smoke management programs to mitigate the public health and welfare impacts from prescribed fires and promote communication and coordination of prescribed burning among land owners.

A smoke management program establishes a basic framework of procedures and requirements for planning and managing smoke from prescribed fires. It is typically developed by a state/tribal agency with cooperation and participation by various stakeholders (e.g., public/private land owners/managers, the public). If a state/tribe determines that a smoke management program is needed, they may choose to develop a

---

[36] The U.S. EPA is currently updating this policy. The updated version will include agricultural field burning and will be used in conjunction with the U.S. EPA's Exceptional Event Rule (http://www.epa.gov/EPA-AIR/2007/March/Day-22/a5156.htm.

program using an array of smoke management practices and/or basic smoke management practices that they believe will prevent air quality violations and address visibility impairment. Emission-reduction techniques are a subset of basic smoke management practices; they are not verified for BC reduction and need assessment for use on a site-by-site basis due to potential environmental effects. A smoke management program can range from a purely voluntary program to a program where prescribed fires are regulated by a permitting authority that analyzes meteorological conditions and air quality considerations and authorizes burning by time of day, fire location/size, and anticipated duration. The more-structured program may include enforceable requirements on who may burn and when burning may occur.

Section 6

Additional Mitigation Opportunities

Introduction

A variety of initiatives may lead to substantial reductions in $PM_{2.5}$ emissions, and therefore, reductions in BC and OC emissions. Analysis suggests that BC emissions from the Transport sector will decrease significantly, while emissions in other sectors may remain roughly constant or even increase in the future. New measures implemented by Arctic Council nations could yield additional BC emission reductions, particularly from residential combustion, off-road vehicles, agricultural or prescribed forest burning, and marine shipping.

This section discusses additional sector-specific abatement measures, implementation feasibility, and cost of implementation (where available), with country-specific examples provided where applicable. This report does not quantify the benefit of a reduction in climate impacts (i.e., avoided temperature increase or avoided sea ice loss) associated with a given emission-reduction measure. Instead, we refer readers to the 2011 AMAP report, *The Impact of Black Carbon on Arctic Climates,* to provide some insights into this issue (AMAP, 2011). The potential health benefits of the mitigation opportunities identified in this section are also not quantified here.

This section is divided into two parts. ***Section 6.1*** provides the results from the GAINS analysis that shows further BC and OC mitigation potential for Arctic Council nations by the year 2030. ***Section 6.2*** provides further detail by sector with a variety of information provided by Arctic Council nations.

6.1 Additional Mitigation Potential Estimated by the GAINS Model

Tables 6-1 and 6-2 present the percent change in BC and OC emissions as a result of the CLE scenario discussed in ***Section 4*** and further emissions reduction potential as a result of the Low GAINS scenario, using 2005 as the baseline. As described in ***Section 4***, the CLE GAINS scenario projects emissions based on current and future proposed legislation. The Low GAINS scenario uses the same activity level data as CLE GAINS scenario, but assumes an ambitious mix of technical and non-technical measures specifically targeting BC and minimizing the net radiative forcing effect of co-emitted species (e.g., OC). The Low GAINS scenario explores reductions in key sectors via measures that could be realized by 2030, provided strong additional incentives are introduced, either as legislation, or as economic incentives accelerating certain processes, specifically in the Transport, Domestic, and Agricultural sectors. The Low GAINS scenario also introduces measures to key sectors that are not affected by current legislation, or where enforcement of existing legislation is lacking or has not been effective (e.g., agricultural burning and open biomass burning).

The Low GAINS scenario specifically accelerates the introduction of effective technologies in the Transport, Domestic, and Agricultural sectors. Technologies introduced in the Transport sector assure full penetration of particulate standards (e.g., EURO 6) for on-road and off-road diesel vehicles and successfully eliminate high-emitting vehicles. Within the Domestic sector, widespread replacement of all domestic stoves and small-scale biomass boilers with pellet installations, and the transfer from raw coal usage to coal briquettes, is projected to occur. Incentives to reduce open burning of agricultural waste are also incorporated into the Low GAINS scenario. Other potential sectors and measures that were not included in the Low GAINS scenario include shifting the timing of agricultural burning and non-burning techniques, which would be most applicable to the Russian Federation, the United States, and Canada, and incentives targeting within- and near-Arctic shipping and oil and gas flaring.

The 2005 GAINS inventory shows that the Transport sector generates the largest amount of BC emissions in seven of the eight Arctic Council nations, as discussed in ***Section 4*** and presented in **Table G-9** in ***Appendix G***. The Russian Federation is the only nation that is the exception to this estimate, with emissions from gas flaring projected to be larger than those in the Transport sector. The Domestic sector is shown as the largest source of OC emissions in six of the eight Arctic Council nations (see **Table G-10** in ***Appendix G***). The Domestic and Transport sectors are still projected to be the largest sources of BC and OC emissions in the 2030 CLE GAINS and 2030 Low GAINS scenarios, as shown in **Tables G-23 and G-24** in ***Appendix G***.

The 2030 Low GAINS scenario projections show an overall decrease of BC and OC emissions, from the baseline up to 56% and 51%, respectively. The Low GAINS 2030 scenario projects an additional emissions decrease from the CLE GAINS 2030 scenario of 45% and 39% for total BC and OC, respectively; that is, these percentage reductions show the mitigation potential above and beyond the reductions that are already expected to occur. The Low GAINS scenario is projected to be most effective in the Agricultural and Domestic sectors for both BC and OC emissions. Large emissions decreases are also projected in the Transport and Energy and Industrial Production, Waste sectors. Additional decreases in BC and OC emissions are not projected from gas flaring however. Further initiatives to decrease emissions beyond current regulatory programs will achieve the greatest long-term emissions reductions within these key sectors.

Source categories that are currently not well regulated in national or EU legislation (e.g., domestic heating) will be of greater relative importance in the future and will have a large potential for additional mitigation. BC emissions from domestic heating are expected to increase within the 2020 to 2030 timeframe in Canada, the United States, Finland, and Norway. In addition, there are few policies or regulations targeting emissions from agricultural burning, open biomass burning (wildfires and prescribed burns), fishing, and off-road sources in all of the Arctic Council nations. To maximise both environmental and public health benefits, additional mitigation opportunities targeting these sources may be effective in further reducing emissions.

Table 6-1. Total BC Emissions and Further Mitigation Potential (Gg/yr) by Sector (GAINS data)

	2005	2020	2030		% Change		
Sector	**GAINS**	**CLE GAINS**	**CLE GAINS**	**Low GAINS**	**GAINS 2005 and CLE 2030**	**GAINS 2005 and Low 2030**	**GAINS CLE 2030 and Low 2030**
Domestic	99.6	94.5	108.2	33.8	8.6%	-66.1%	-68.8%
Transport	280	119.4	86	41.7	-69.3%	-85.1%	-51.5%
Energy & Industrial Production, Waste	23.8	21.3	20	11.9	-16.0%	-50.0%	-40.5%
Agricultural*	38.7	37.3	36.6	0	-5.4%	-100.0%	-100.0%
Flaring	101.1	69.8	67.1	67.1	-33.6%	-33.6%	0.0%
Other	5.6	6	6.3	5.6	12.5%	0.0%	-11.1%
Total	548.7	348.3	324.2	160.2	-17.2%	-55.8%	-45.3%

* The GAINS scenario emissions estimates for the Agricultural sector do not include emissions from open biomass burning.

Table 6-2. Total OC Emissions and Further Mitigation Potential (Gg/yr) by Sector (GAINS data)

	2005	2020	2030		% Change		
Sector	**GAINS**	**CLE GAINS**	**CLE GAINS**	**Low GAINS**	**GAINS 2005 and CLE 2030**	**GAINS 2005 and Low 2030**	**GAINS CLE 2030 and Low 2030**
Domestic	276.7	217.2	216.1	86.3	-21.9%	-68.8%	-60.1%
Transport	257.1	154.6	143.8	79.4	-44.1%	-69.1%	-44.8%
Energy & Industrial Production, Waste	60.7	56.1	52.2	46.8	-14.0%	-22.9%	-10.3%
Agricultural	127.2	122.3	119.8	0	-5.8%	-100.0%	-100.0%
Flaring	20.2	14	13.4	13.4	-33.7%	-33.7%	0.0%
Other	27.3	29	29.9	25	9.5%	-8.4%	-16.4%
Total	769.3	593.2	575.2	251	-18.3%	-50.5%	-38.6%

* The GAINS scenario emissions estimates for the Agricultural sector do not include emissions from open biomass burning.

Table 6-3. Summary of GAINS BC Projected Emissions for 2020 and 2030*

Country	Black Carbon (Gg/yr)					% Reduction in BC Emissions	
	2005		2020	2030		GAINS 2005 and CLE 2030	GAINS CLE 2030 and Low 2030
	National	GAINS	CLE GAINS	CLE GAINS	Low GAINS		
Canada	55.1	39.2	24.1	22.5	12.2	-42.6%	-45.6%
Denmark, Greenland and Faroe Islands	7.4	7	3.8	3.8	1.6	-45.7%	-56.9%
Finland	6.9	7.9	4.5	4.5	1.1	-43.0%	-76.5%
Iceland†	NA	0.2	0.1	0.1	0.1	-50.0%	10.1%
Norway†	NA	6.4	5.4	5.6	2.1	-12.5%	-61.9%
Sweden	5.1	7.6	2.7	2.8	1.6	-63.2%	-41.1%
Russia†	NA	219.4	171	159.6	84.5	-27.3%	-47.0%
United States	481.7	261	136.8	125.3	56.8	-52.0%	-54.7%
Total	782.1	548.7	348.3	324.1	160.2	-40.9%	-50.6%

* Emissions from open biomass burning (wildfires and prescribed burns) are not included in this table. No estimates were provided by Bond for the Flaring and Other sectors.

† Iceland, Norway, and the Russian Federation did not provide national BC and OC emissions inventories. Norway did provide a $PM_{2.5}$ emissions inventory that is discussed in this report.

NA = not available.

Table 6-4. Summary of GAINS OC Projected Emissions for 2020 and 2030*

Country	Organic Carbon (Gg/yr)					% Reduction in OC Emissions	
	2005		2020	2030		GAINS 2005 and CLE 2030	GAINS CLE 2030 and Low 2030
	National	GAINS	CLE GAINS	CLE GAINS	Low GAINS		
Canada	105.4	57	40.8	37.2	19.0	-34.7%	-49.0%
Denmark, Greenland, and Faroe Islands	8.1	14	8	7.6	3.4	-45.7%	-54.6%
Finland	5.6	7.2	4.5	4.8	2.9	-33.3%	-39.6%
Iceland†	NA	0.1	0.1	0.1	0.1	0.0%	0.0%
Norway†	NA	25.2	19.9	21	5.8	-16.7%	-72.4%
Sweden	6.5	7	4	4.4	2.8	-37.1%	-36.4%
Russia†	NA	254.1	230.4	231	66	-9.1%	-71.4%
United States	789.4	404.7	285.5	269.2	151.1	-33.5%	-43.9%
Total	1,194.30	769.3	593.2	575.2	251	-25.2%	-56.4%

* Emissions from open biomass burning (wildfires and prescribed burns) are not included in this table. No estimates were provided by Bond for the Flaring and Other sectors.

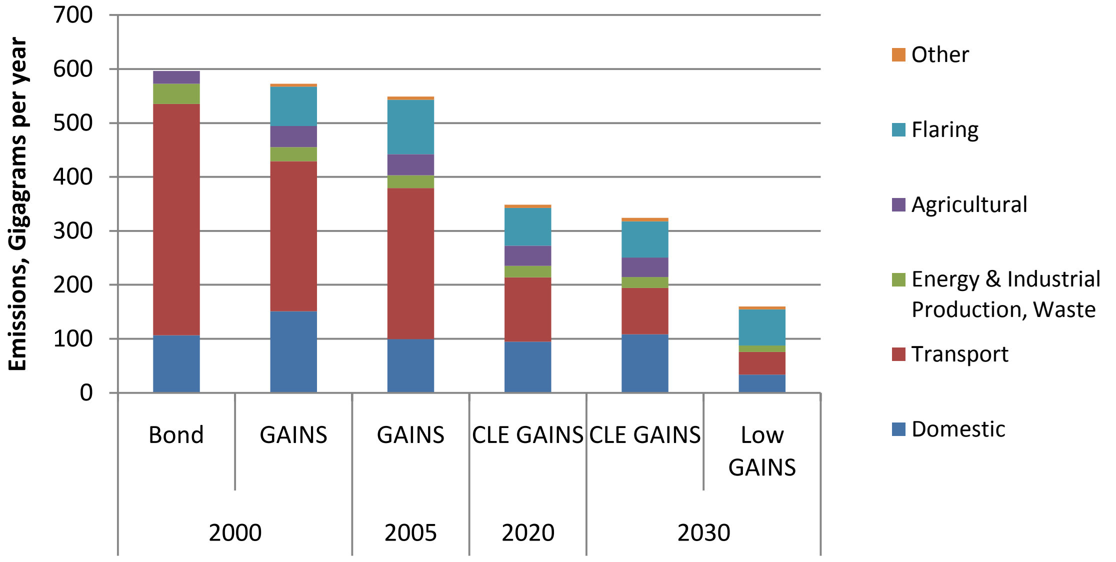
† Iceland, Norway, and the Russian Federation did not provide national BC and OC emissions inventories. Norway did provide a $PM_{2.5}$ emissions inventory that is discussed in this report.

NA = not available.

Figures 6-1 and 6-2 present the impact of the Low GAINS scenario projections for all Arctic Council nations while **Figures 6-3 through 6-10** present additional mitigation opportunities for each Arctic Council nation. Baseline emissions for 2005 are included for reference (labelled as *National*). Additional data are provided in ***Appendix G***. Open biomass burning (wildfires and prescribed forest burning) emissions estimates are *not* included in these figures because the GAINS model did not estimate emissions from this source category.

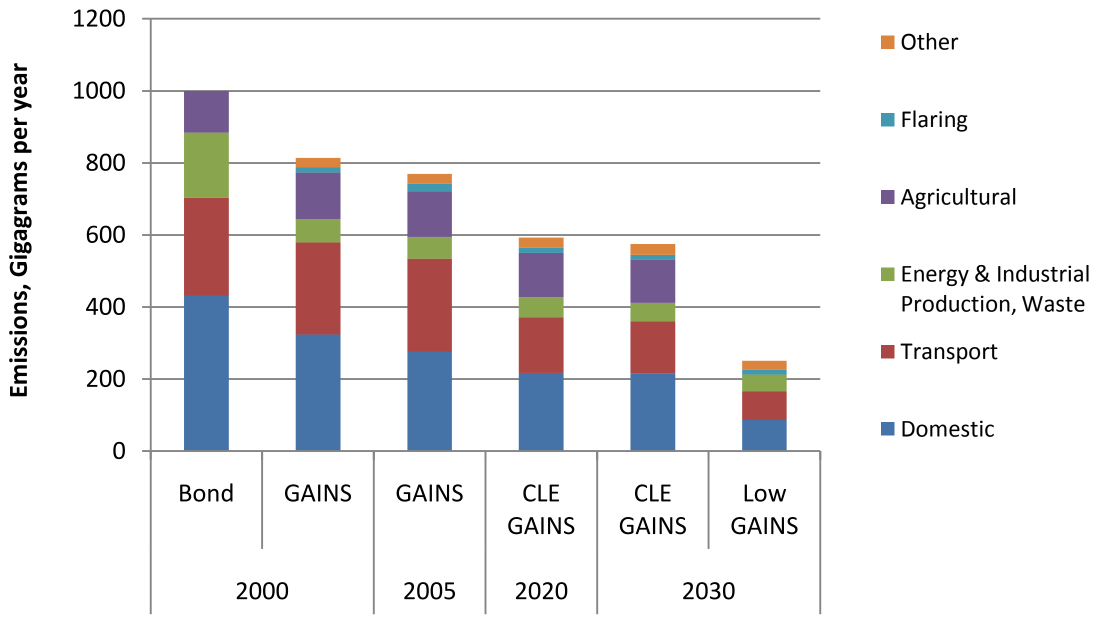
The Low GAINS scenario projects significant reductions in both BC and OC emissions for the year 2030 in all Arctic Council countries. The most significant regional reductions are observed in the Transport and Domestic sectors. Iceland is the only country where emissions are not projected to decrease substantially, but the total emissions are minimal compared to other Arctic Council nations. Emissions from the Kingdom of Denmark for the Domestic sector are projected to be minimal by the Low GAINS scenario.

Figure 6-1. BC emissions for all Arctic Council nations by aggregated sector (Gg/yr).*



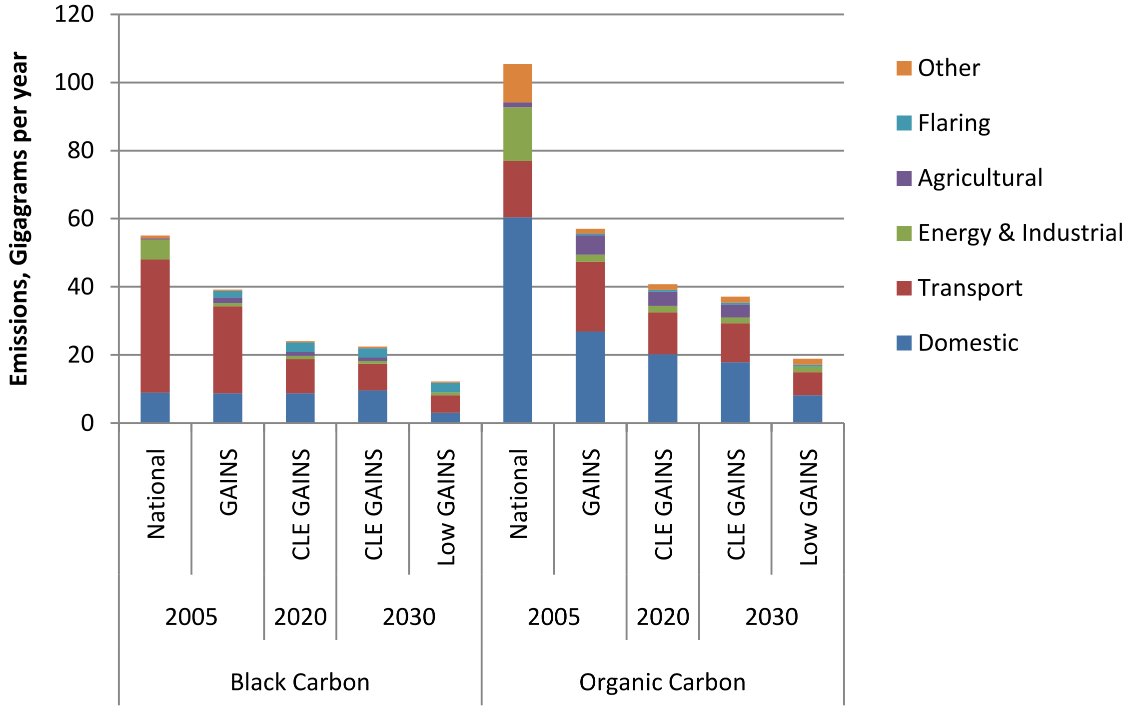
* Emissions from open biomass burning (wildfires and prescribed burns) are not included in the GAINS model and are not included in this figure.

Figure 6-2. OC Emissions for Arctic Council nations by aggregated sector (Gg/yr).*



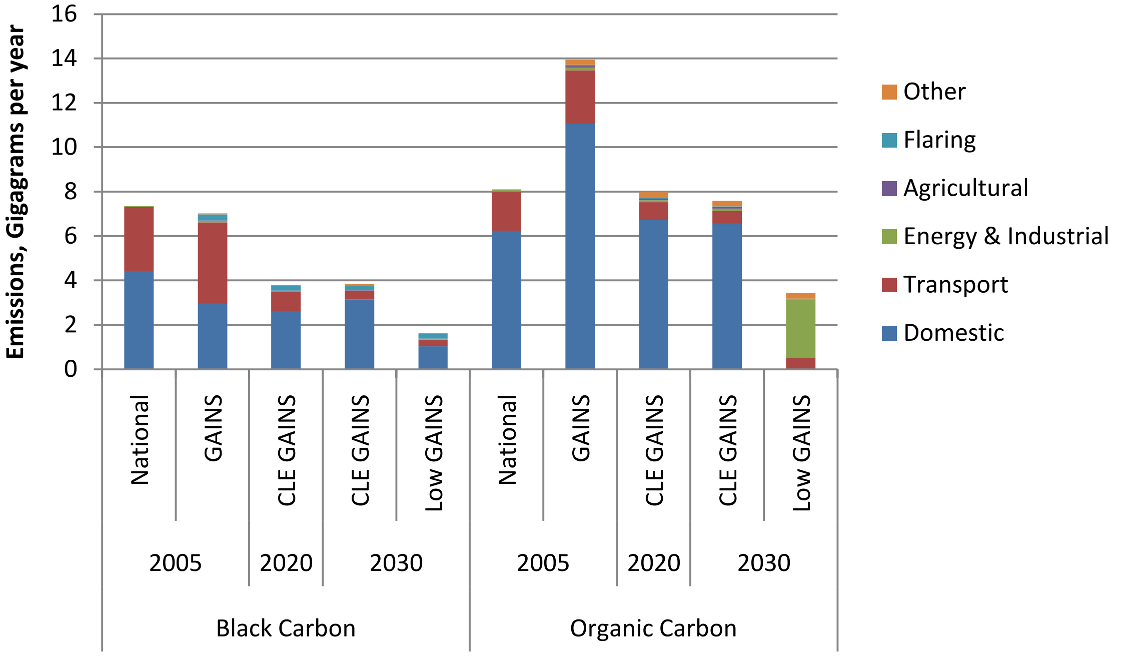
* Emissions from open biomass burning (wildfires and prescribed burns) are not included in the GAINS model and are not included in this figure.

Figure 6-3. GAINS projected BC and OC emissions for Canada (Gg/yr).*



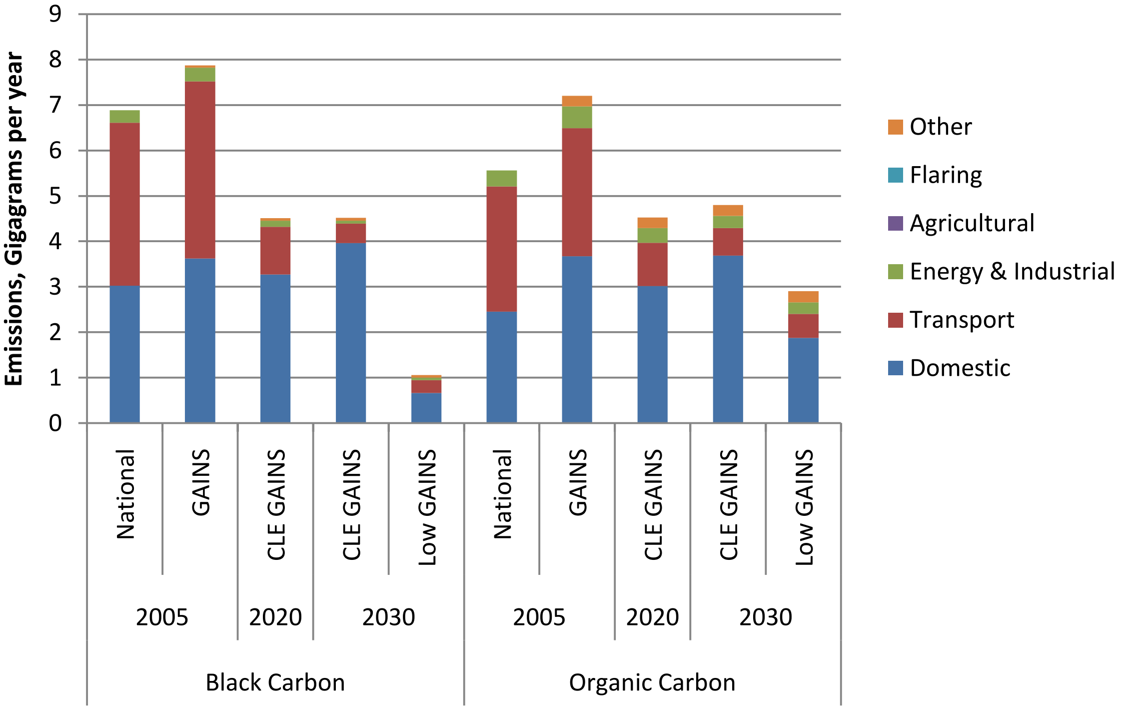
* Emissions from open biomass burning (prescribed burns and wildfires) are not included in this figure.

Figure 6-4. GAINS projected BC and OC emissions for Denmark, Greenland, and the Faroe Islands (Gg/yr).*



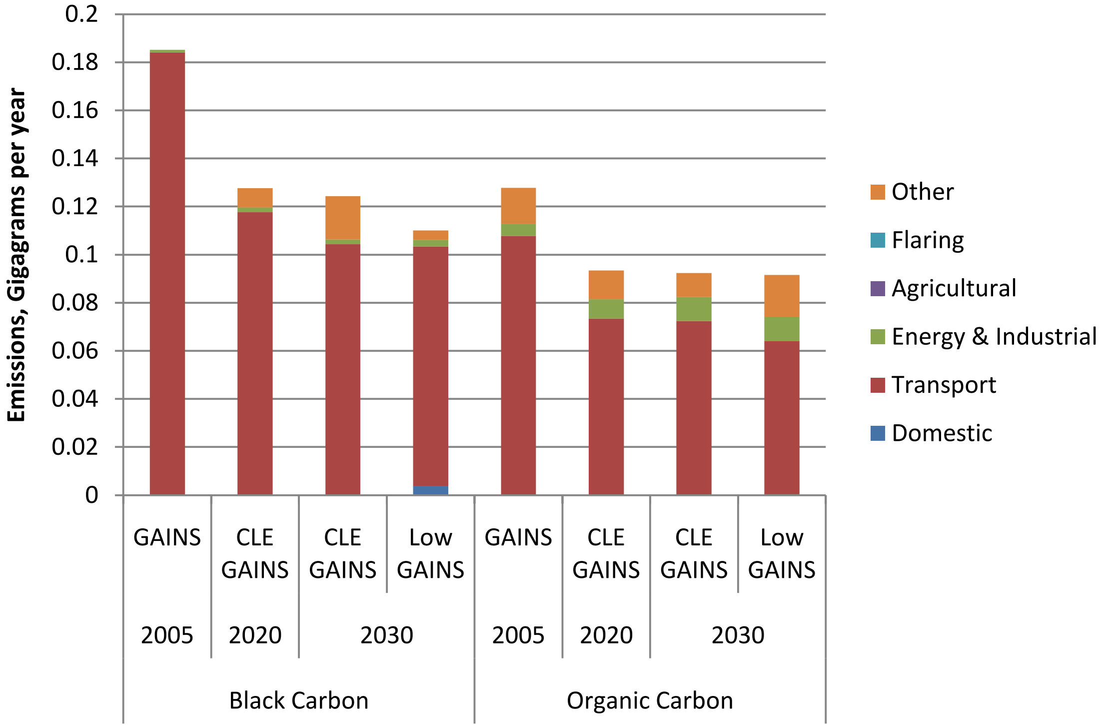
* Emissions from open biomass burning (prescribed burns and wildfires) are not included in this figure.

Figure 6-5. GAINS projected BC and OC emissions for Finland (Gg/yr).*



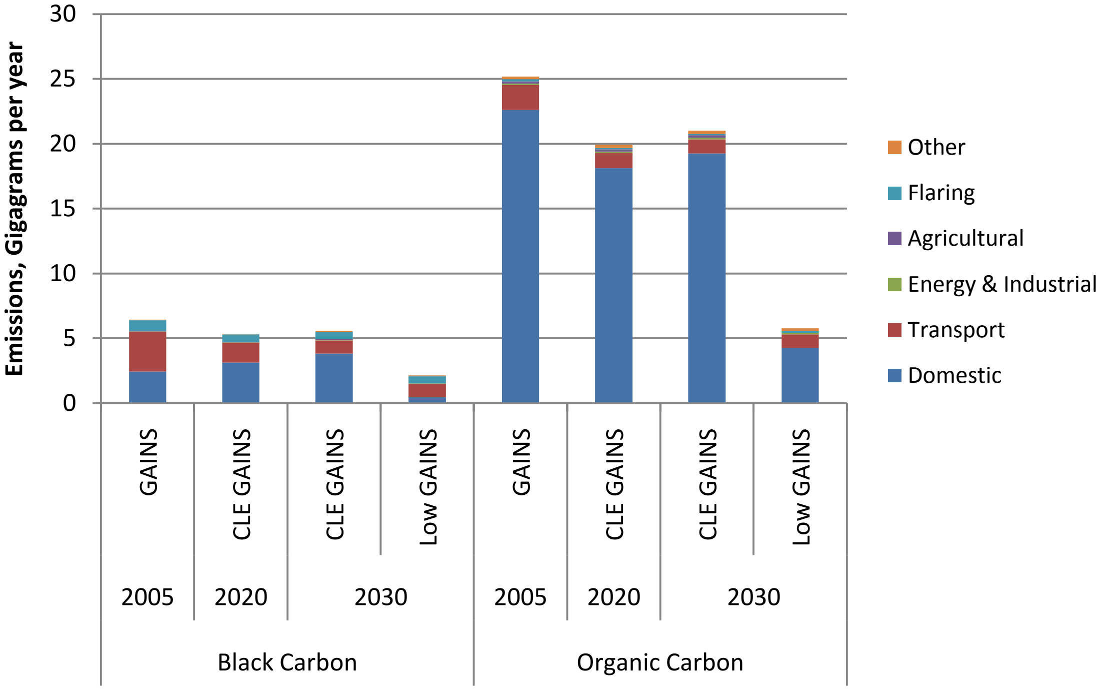
* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal for Finland and are not included in this figure.

Figure 6-6. GAINS projected BC and OC emissions for Iceland (Gg/yr).*



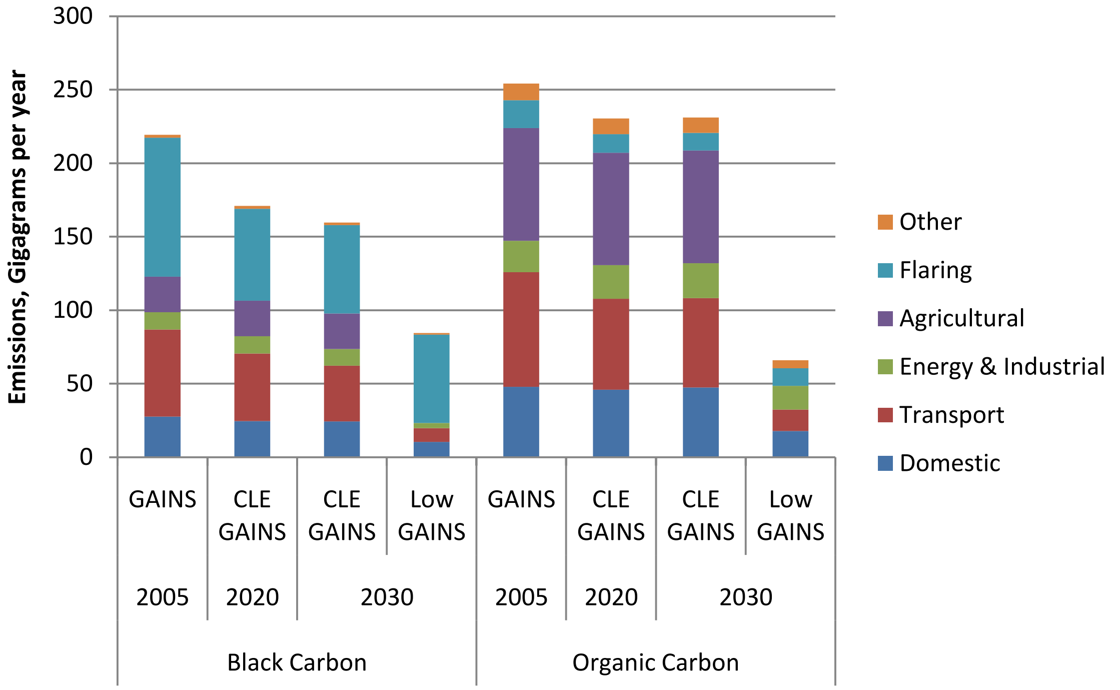
* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal and are not included in this figure. A national inventory was not provided by Iceland; therefore, no national data are presented for 2005.

Figure 6-7. GAINS projected BC and OC emissions for Norway (Gg/yr).*



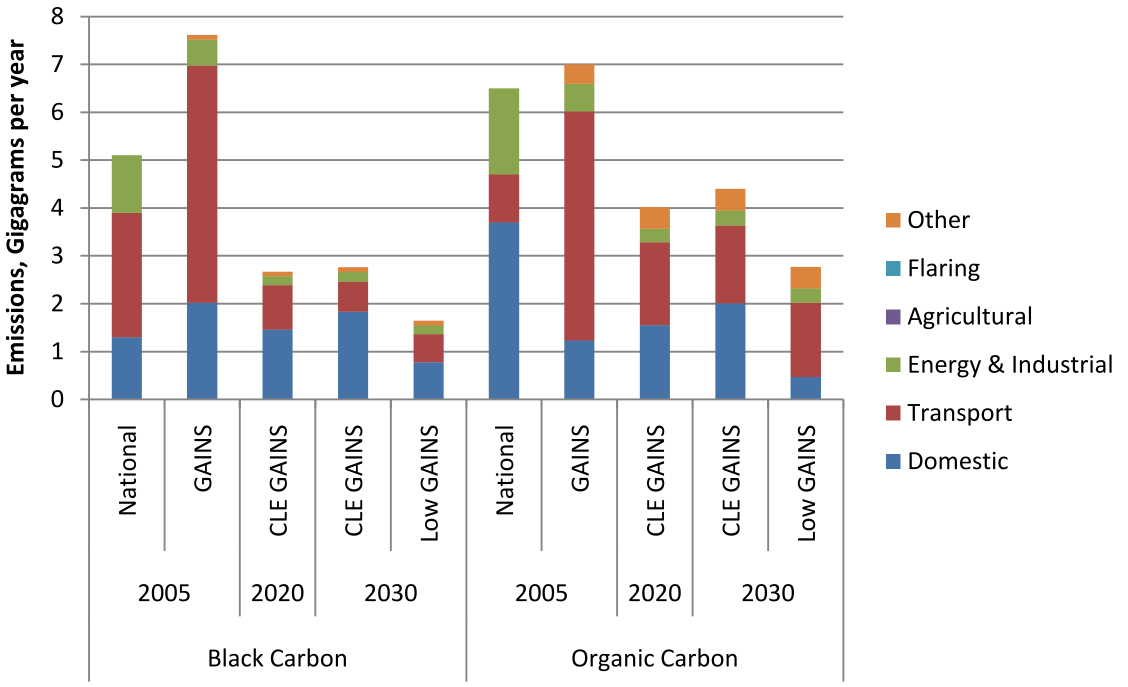
* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal and are not included in this figure. A national inventory was not provided by Norway; therefore, no national data are presented for 2005.

Figure 6-8. GAINS projected BC and OC emissions for the Russian Federation (Gg/yr).*



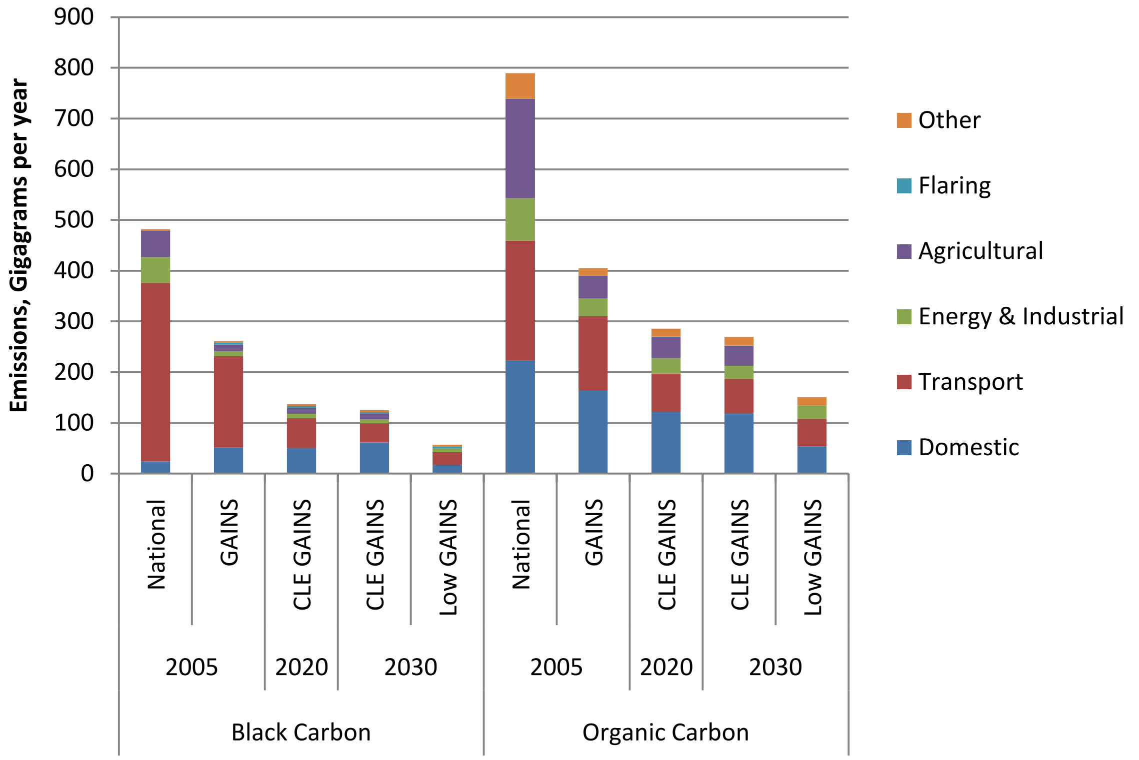
* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal and are not included in this figure. A national inventory was not provided by the Russian Federation; therefore, no national data are presented for 2005.

Figure 6-9. GAINS projected BC and OC emissions for Sweden (Gg/yr).*



* Emissions from open biomass burning (prescribed burns and wildfires) are considered minimal for Sweden and are not included in this figure.

Figure 6-10. GAINS projected BC and OC emissions for the United States (Gg/yr).*



* Emissions from open biomass burning (prescribed burns and wildfires) are not included in this figure.

6.2 Sectoral Information Provided By Arctic Council Nations

The following sections describe additional mitigation opportunities by sector. This information was submitted by Arctic Council nations and varies in the level of detail and quantification.

6.2.1 Domestic (Residential Heating)

Wood stoves and boilers have emerged as a leading target for BC emission mitigation strategies because they are a major source of BC emissions in the Arctic. Wood-burning is frequent in the Arctic region nations, particularly during the winter and early spring when the climate impact of BC in the Arctic region is most severe. The contribution of BC emissions from wood-burning stoves and boilers in the Domestic sector varies among the Arctic regions. Although some countries do regulate PM emissions from wood-fired stoves and boilers, these control measures do not specifically target BC emissions. Planned stove replacement campaigns and PM emissions controls may reduce BC emissions in some areas, but without new measures, overall emissions from these sources are projected to remain steady or even increase by 2030 in some countries. Additional opportunities to decrease BC emissions include switching to cleaner-burning fuels, a faster replacement of older stoves, implementing inspection and maintenance schemes, and the introduction of more efficient stove technologies.

Fuel switching from wood and coal to cleaner fuels (such as natural gas) can dramatically reduce emissions, specifically for the Domestic sector, and is entirely feasible (Rypdal et al., 2009). Many homes in the Arctic Council region have transitioned from oil to wood over the past decade, a trend expected to continue out to 2020 and 2030. Emissions from the Domestic sector are projected to decrease out to 2030, but will still remain a dominant source of BC emissions in most Arctic region nations.

New stove technologies and cleaner fuels may enable highly effective mitigation measures to improve both health and climate. Sweden and Norway have investigated the cost-effectiveness of several scenarios that upgrade stoves to more efficient technologies using cleaner-burning fuels, as discussed below.

According to estimations made by the Swedish Energy Agency in 2003 (Swedish EPA, 2007), the majority of installations used for domestic heating are low-performance stoves and boilers without accumulation tanks (see **Table 6-5**), indicating that the opportunity for stove replacement is large. Low-performance in this context means that the stoves are not in accordance with the approved current environmental standard in the Swedish National Board of Housing, Building, and Planning building regulations (BBR; Boverkets, 1994).

Table 6-5. Number of various residential heating installations in 2003, Sweden

Type	Number	Percent
BBR Approved with Accumulation Tank	70,000	27
Non-BBR Approved Without Accumulation Tank	150,000	57
Non-BBR Approved with Accumulation Tank	10,000	4
Pellet Stoves	30,000	12
Total	260,000	100

BBR = Boverkets Byggregler (The Swedish National Board of Housing, Building and Planning).

The Swedish EPA conducted a 2007 analysis that included five different abatement scenarios for all small-scale residential heating units in the country. The different scenarios were as follows:

1. Early scrapping of old non-BBR installations; estimated shorter lifetime for old installation by 5 years; by 2020, there will be 100% of BBR-installations (instead of 80%).
2. Increase the number of BBR+-installations; exchange old installations by natural turn-over time with BBR+-installations; BBR+-installations have lower emissions than required in the BBR.
3. Exchange wood-installations for pellet boilers by natural turnover time; emissions from pellet boilers are lower than BBR+-installations using wood except for particles where emissions are approximately the same.
4. Early scrapping of old stoves, replacing them with BBR+ installations.
5. Information on good burning practice (including recommendations to install accumulation tanks).

Scenario results presented in **Table 6-6** show that the most cost-efficient scenario is found by replacing old boilers and stoves with new, low-emitting stoves (BBR+). In the business as usual scenario, which is based on current legislation (i.e., the BBR regulations), it is estimated that 20% of the installations are non-BBR installations. Non-BBR installations alone amount to roughly 40% of the total emissions from the Domestic sector, as is indicated by the relatively large reduction of PM emissions in Scenario 1 with early scrapping of these installations. The lower result in Scenario 2 is due to a slow turnover time for these installations, which means that this measure will not have any major effect until 2020. The largest reduction in PM emissions results from Scenario 4, which is a combination of Scenarios 1 and 2. Emission factors used in the analysis are presented in **Table E-7** in ***Appendix E***.

When looking at associated costs to reduce PM, the picture looks slightly different (see cost/tonne of reduced PM in **Table 6-6**): Scenario 2 is the most cost-efficient, while Scenario 4 is more expensive. However, Scenario 4 has three times higher reduction potential, with 3,240 tonne/year at a cost of approximately 0.254 Swedish kronor (~0.029 €) per metric ton PM. The Swedish analyses show the highest cost-efficiency (emission reduction per Swedish kronor) for replacement of old boilers and stoves for new ones with very low (BBR+) air pollutant emissions. Combined with early scrapping of old boilers, the emission reduction would triple.

Table 6-6. Analysis Results for Various Scenarios, Emission Reductions, and Costs (2020)

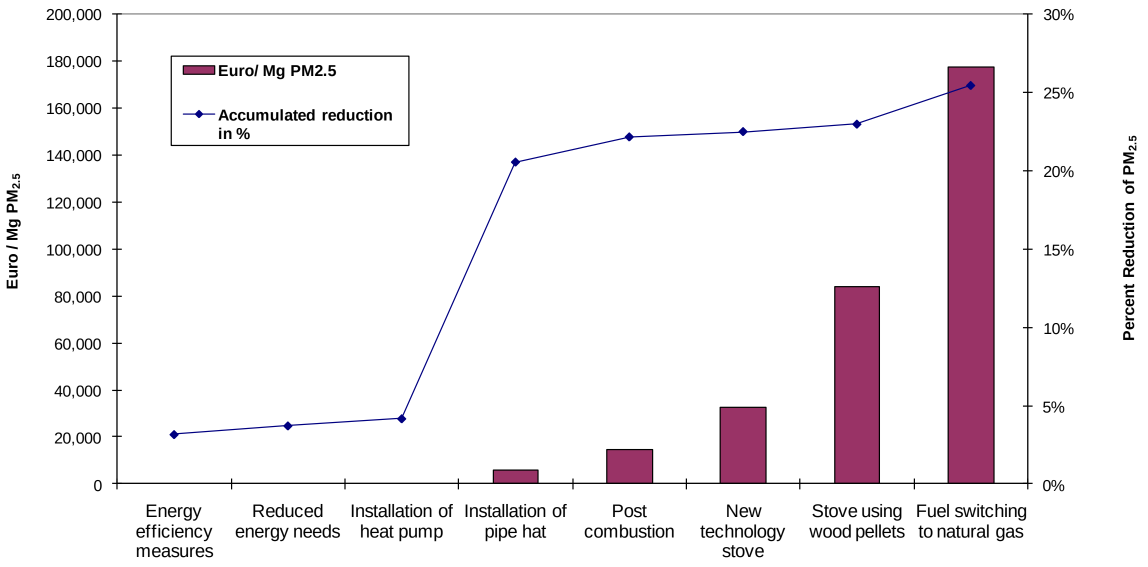
Scenario Number	Reduction of PM in tonnes (%)	Reduction of NMVOC in tonnes	Reduction of CH_4 in tonnes	Societal Costs/year	Private Costs/year	Cost/tonne of reduced PM
				(Million SEK and Euros)	(Million SEK and Euros)	
1	1,014 (16.3%)	1,178	415	738 SEK	1,487 SEK	0.728 SEK
				83.5 Euros	168.3 Euros	0.082 Euros
2	941	1,345	2,131	50 SEK	72 SEK	0.053 SEK
	-15.2%			5.6 Euros	8.2 Euros	0.006 Euros
3	934	2,315	2,251	611 SEK	764 SEK	0.654 SEK
	-15.0%			69.2 Euros	86.5 Euros	0.074 Euros
4	3,240 (52.3%)	4,358	4,622	824 SEK	1,599 SEK	0.254 SEK
				93.3 Euros	181.0 Euros	0.029 Euros
5	1,134 (18.3%)	1,828	1,768	NA	NA	NA

NMVOC = non-CH_4 volatile organic compounds
NA = not applicable.

An analysis conducted by Norway found many low-cost measures in the Domestic sector, including energy-efficiency measures and installation of heat pumps, as shown in **Figure 6-11**. Norway used the RAINS model to compare the cost efficiency of various additional mitigation measures out to 2020, relative to baseline projections discussed in ***Section 5*** (SFT, 2006). Upgrading to new technology stoves were estimated to cost 250,000 NOK (32,500 Euro). The highest costs are associated with switching from other modes of energy to natural gas in residential homes, which is estimated to be 1.36 million NOK/Mg $PM_{2.5}$ reduction (177,213 Euros/Mg $PM_{2.5}$ reduction) and yields a maximum reduction potential (25%) from the baseline projection. A more detailed description of this analysis is available in the 2006

Norwegian report *Assessments of Measures to Reduce Particulate Emissions* (SFT, 2006).[37]

Figure 6-1. Cost efficiency of additional measures in the Domestic sector in 2020, Norway.



Unit: Euro/Mg $PM_{2.5}$

Note: Additional information on mitigation measures and the cost efficiency study is presented in ***Appendix D***.

Other potential policy instruments that could force additional reductions in BC emissions include stricter emission limits for new stoves and boilers, scrapping premiums or investment grants, educational/informational campaigns, and environmental fees.

The present air emission regulations for new wood-fuelled stoves and boilers in the EU can be considered lenient by some. For example, the Swedish BBR emission standards are set at a level that even older non-approved boilers might meet if they are properly fuelled and maintained. The abatement analysis presented in **Table 6-6** shows that significant emission reductions could be achieved with modern, efficient stoves (e.g., BBR+) at a very low cost. The regional climate impacts of BC and OC from domestic heating, as well as the cost-efficiency of replacing old boilers with modern, efficient stoves and boilers, motivate the implementation of stricter emission regulations.

A scrapping premium or investment grant could be awarded if an old stove is scrapped and replaced with a more efficient one. Sweden estimated that early scrapping of old stoves would cost 1,500 million Swedish kronor (169.8 million Euros). The greatest environmental benefit would be reached if old stoves were replaced with new low-emitting boilers. The extra cost of replacing an old boiler with a low-emitting boiler (BBR+) instead of just a BBR-approved boiler is less than 200 million Swedish kronor. This requires that a new BBR+-classification be introduced. Disadvantages to this include market fluctuations and the costs associated with scrapping and investment grants.

---

[37] Tiltaksanalyse for Partikkelutslipp (in Norwegian)

The costs for an educational campaign are comparatively low, and although the effect on emission reduction is difficult to estimate, it is considered relatively low. A number of campaigns in Sweden, the United States and elsewhere have focused on homeowner education about how single-house boilers and stoves should be fuelled. The environmental effect and cost-efficiency of educational/informational campaigns have not been evaluated, but might be an important supplement to support and improve the effects of other policy instruments to reduce PM emissions from small-scale residential heating units.

A differentiated environmental fee on single-house boilers and stoves could be introduced in Arctic nations according to the environmental performance of the boiler. Such a fee requires an environmental classification scheme and a centralised register, which currently does not exist in any Arctic Council nation. An alternative is a combination of a fee and investment grant, commonly called a “feebate” scheme.

6.3 Transport

Planned implementation of North American emission standards, EURO-norms, and EU’s AQS will significantly reduce emissions from mobile sources (both on- and off-road) by 2020. Additional transport-related emission-reduction measures that may have additional significant health co-benefits include:

- Introduction of an environmental classification system of vehicles and fuels, combined with economic incentives, used to stimulate faster introduction of on-road and off-road vehicles complying with adopted future regulations (e.g., EURO 6).
- Introduction of general motor vehicle tests and inspections that focus on environmental standards may be relevant in countries where these programs are absent. A general test and inspection for off-road vehicles, including snowmobiles may be relevant, in addition to policies that target vehicle idling.
- Accelerated implementation of ultra low sulphur diesel requirements for both on- and off-road diesel fuels, accompanied by emission controls to reduce diesel PM.
- Development and implementation of particulate emission standards, enforcing the use of particulate traps for new engines in on- and off-road vehicles, mobile machinery, locomotives, and certain marine vessels where such standards may not be in place.
- An early introduction of heavy-duty vehicles that fulfil the EURO 6, stimulated by requirements and a differentiated annual vehicle tax with environmental classification for these vehicles.
- Retrofitting existing older and high-emitting vehicles and equipment with particle filters through regulation or voluntary subsidy programs.
- Retirement or replacement of the most polluting existing sources, especially those not easily fitted with filters, through regulation or financial incentives. Guidelines for early retirement or scrappage programs should ensure that the original engine is either destroyed or, when possible, returned to the manufacturer to be remanufactured to cleaner emission standards.

- Coordinated campaigns for better enforcement of new standards, more stringent inspection requirements, and encouragement of better maintenance practices.
- Introduction or expansion of "green zones" that ban or require special fees for vehicles with high particulate emissions.
- Reduction of truck and off-road idling through regulation, education, or rest stop electrification; additional vehicle efficiency programs; addition of auxiliary power units on off-road equipment; and use of smart transport algorithms.

Stricter emission standards for new vehicles may be possible in some cases over the next couple of decades. It is more efficient and often cheaper to reduce air pollutants from new vehicles than to reduce emissions from vehicles currently in use. Bond and Sun (2005) found that the capital cost to install a particulate trap on an existing truck ranges from $5,000 to $10,000 (3,644 to 7,270 Euros) and yields a lifetime (20 years) avoidance of 200 kg of BC emissions. Installing a particle trap into an existing light vehicle costs $250 to $500 (182 to 364 Euros), resulting in a lifetime (10 years) avoidance of 14 kg of BC emissions. Installing particle traps and retrofitting existing diesel-powered vehicles are relatively expensive measures to reduce BC emissions in the existing fleet. However, no cost-benefit analyses have been conducted for retrofitting the existing heavy-duty vehicle fleet. A fast introduction of new vehicles with very low particulate emitting performance in the coming years is seen as the most cost-effective measure to further reduce emissions in the 2020–2030 timeframe.

6.3.1 Off-Road Vehicles and Working Machinery

European emission requirements for off-road diesel machinery and tractors have been more lenient than for heavy-duty vehicles. In practice, the same type of engine is used in all diesel engine mobile sources so there are no performance-based reasons why diesel engines used in working machinery have more lenient air pollution emission requirements compared to their use in heavy-duty vehicles. Countries should be engaged in the introduction of stricter particulate emissions for off-road mobile machinery and tractors, in line with EURO 6 for heavy-duty vehicles.

Very few cost–benefit analyses have been conducted to date on off-road vehicles and working machinery. The results from one such study conducted by the Swedish Environmental Research Institute (IVL) for off-road vehicles and working machinery in various scenarios is presented in **Table 6-7** (IVL, 2009). The B-scenarios consist of various measures to increase replacement of old machinery for that with lower particulate emissions. Scenarios 1Biii and 1Biv will be implemented between years 2011 and 2014 and are based on stricter EU particulate emission standards. C-scenarios refer to the introduction of selective catalytic converters on working machinery to reduce NO_x emissions, and consequently, PM emissions. In theory, the B and C scenarios could be combined, and it is possible that a combined scenario could be cost-effective if the reduction of NO_x emissions is also considered. Further analyses are required to estimate PM and NO_x synergies.

Table 6-7. Scenario Analysis Regarding Abatement Measures for Off-Road Mobile Machinery and Tractors in Sweden (IVL, 2009)

Scenario	Reduction of PM_{25} in 2020 (tonnes)	Total costs		Abatement costs	
		Million SEK/year	Million Euros/year	SEK/kg, year	Euros/kg, year
1Bi	20	4.6	0.52	229	25.9
1Bii	60	22.9	2.6	381	43.1
1Biii	80	32	3.6	400	45.3
1Biv	130	54.8	6.2	422	47.8
1Bv	260	799.8	90.5	3,076	348.2
1Ci	20	242.2	27.4	12,111	1,371.0
1Cii	40	585	66.2	14,624	1,655.4
1Ciii	90	808.9	91.6	8,988	1,017.4

6.3.2 International Marine Shipping

Marine shipping in the Arctic region is a relatively small source of BC emissions, yet potentially high in its impact due to its proximity to Arctic snow and sea ice. Emissions from this sector may increase significantly due to increases in global marine shipping traffic, as well as a lower prevalence in summer sea ice cover. Marine shipping is also a significant source of the precursors that lead to higher levels of local ozone, which impacts public health as well as the climate.

The Arctic Council nations comprise 90% of current shipping activities in the Arctic region (Arctic Council, 2009); therefore, they have a unique ability to influence the development of future BC emissions by enacting early voluntary technical and non-technical measures and by engaging in international regulatory regimes such as the IMO. Other measures to reduce BC from marine shipping in and near the Arctic region could include:

- Adopting voluntary measures both by Arctic Council and non-Arctic Council countries to decrease BC emissions (specifically cruise ships);
- Encouraging cruise ships and large fishing vessels in harbour to use land-based energy solutions, such as renewable energy;
- Supporting the IMO submission on BC by Norway, Sweden, and the United States, which raised the importance of BC emissions impacts from marine shipping on the Arctic climate and identified a range of technical and operational measures (e.g., speed reduction, improved engine turning, energy efficiency enhancements, better fuel injection, use of diesel particulate filters);
- Fuel switching to less-polluting fuels (i.e., low sulphur diesel);
- Supporting adoption of the proposed amendment of MARPOL Annex VI to establish an Energy Efficiency Design Index for new ships;
- Conducting ongoing provision of new scientific and technical developments to the IMO by AMAP and other Arctic Council working groups and vice versa.

There are few studies that have investigated the costs associated with these measures. One example is from Sweden (IVL, 2009), which analysed the reduction potential of fuel switching in the national shipping industry by replacing heavy fuel oils with marine diesel (**Table 6-8**). Results show that a significant PM$_{2.5}$ reduction occurs from the lower sulphur fuel content at a relatively low cost. It is not clear how this might affect BC emissions (IVL, 2009).

Table 6-8. Analysis of Two Scenarios for Reducing PM Emissions from Shipping (2020)

Scenario	Reduction of PM$_{2.5}$ in Tonnes (2020)	Total Cost (Million SEK or Euros/year)	Abatement Cost (SEK or Euros/kg-year)
Replace on-board electricity generation with national electrical grid supply in harbours	10	12.8 SEK	1,280 SEK
		1.5 Euros	144.9 Euros
Replace heavy fuel oils with marine diesel or gas oil	150	58.5 SEK	390 SEK
		6.62 Euros	44.5 Euros
Total	160	71.3 SEK	Not applicable
		8.07 Euros	

Source: IVL, 2009.

6.3.3 Fishing Vessels

Fishing is a major industry in Arctic Council nations, and government programs to reduce small-scale fishing operations and/or replace the existing small fishery fleet are likely to decrease emissions by 2030. No comprehensive studies of the consequences on BC and OC emissions have been conducted to date in Arctic Council nations. Denmark is developing a program focused on energy efficiency in the fishery source category that will introduce energy inspections of vessels and a subsidy scheme for investments in energy-efficiency improvements for the existing fleet. Currently, 30 vessels have been tested by the Danish Technological Institute.[38] Results from this study may be beneficial to other countries and cities.

6.4 Energy and Industrial Production and Waste

6.4.1 Energy Production

The majority of PM emissions from the Energy and Industrial Production, Waste sector stem from district heating plants. There is potential to reduce PM emissions in this sector from retrofitting, retiring, or replacing old combustion boilers, engines, and other equipment, but more research and analysis needs to occur.

According to the Swedish District Heating Association's database for district heating plants, there are about 1,000 total district heating plants in Sweden. Of those, 64% (637)

---

[38] Fiskeri Tidende, 20. August 2009: 30 energisyn er gennemført – energisyn forud for investeringer i brændstofeffektivitet er kommet godt fra start. Available at: http://danmarksfiskeriforening.dk/default.asp?id=34308&visnyhed=9508&newscode=20098

are smaller than 10 MW and 23% (231) are between 10 and 30 MW. A third of the plants smaller than 10 MW and 9% of the plants between 10 and 30 MW are lacking total solid particulates (TSP) separation, indicating that there is a potential to reduce $PM_{2.5}$ emissions. A cost-efficient analysis for several plants indicated a relatively high cost of implementation at 2,000–3,150 SEK (226–357 Euros) per kg reduced particulate emissions. However, the data are poor, and more knowledge about the emission status and abatement potential and costs need to be gathered for small district heating plants. If a more thorough analysis indicates that cost-efficient measures are at hand, general rules under the environmental code can be the most efficient road to get particle reduction measures implemented.

Sweden also estimated potential abatement reductions and costs related to $PM_{2.5}$ for 20–80 MW plants (ÅF, 2010). Estimated emissions from individual plants varied significantly, and measurements are mainly performed on TSP and not $PM_{2.5}$. The abatement analysis showed a possible reduction of approximately 80%, with installation of particulate filters related to an estimated cost of 2000 to 3150 SEK (226 to 357 Euros) per kg for the studied plants. It is estimated that 25 to 30% of existing district heating plants had this potential to reduce their PM-emissions, and the total reduction potential in Sweden from these plants might amount to 0.5 Gg/year, which, according to the fraction analysis in **Table 3-7** in ***Section* 3** and **Table E-4** in ***Appendix E***, could be around 0.1 Gg of BC and 0.25 Gg of OC. The rest of the existing plants have already implemented state-of the art filter technology.

Switching to more renewable energy sources is another means to avoid BC and OC emissions generated during traditional electricity production. A fifth hydropower plant is currently under construction in Ilulissat, Greenland, and a feasibility study for a sixth plant is being conducted. When the Ilulissat hydropower plant is operational in 2013, energy production from renewable energy sources will rise to 60% country-wide. Small-scale sustainable energy sources are being developed and tested in the Arctic with government funding, but potentials in BC and OC mitigation from current operations are yet to be assessed.

6.4.2 Industrial Production

Emissions from industrial production are not considered a key sector in many Arctic Council nations with respect to BC and OC emissions, but a large majority of industrial activities do take place relatively close to residential areas where emissions may be impacting public health. One direct and effective way to reduce BC and OC emissions is to require the use of low sulphur fuels (i.e., fuels containing a maximum of 0.2% sulphur), which will also reduce sulphate emissions. More research needs to be done to determine the effectiveness of retrofitting, retiring, or replacing combustion boilers and equipment and the associated net Arctic climate effects.

6.5 Agricultural and Open Biomass Burning

Agricultural burning and open biomass burning (prescribed forest burning and wildfires) appear to be a very significant source of BC in the Arctic region, but there are significant uncertainties about the applicability and effectiveness of emissions-reduction techniques targeting BC and OC emissions from these diverse, site-specific sources.

This section discusses different emissions-reduction techniques for open biomass burning that are expected to reduce the amount of $PM_{2.5}$ emissions. It is unclear to what extent BC and OC emissions will be reduced through implementation of these techniques. All forms of agricultural and open biomass burning release much larger amounts of OC compared to BC. Therefore, the contribution of these carbonaceous emissions to global warming may be unclear. However, due to the reflective Arctic surface, emission reductions of BC and OC from biomass burning in the Arctic region are likely to help slow Arctic warming. Depending on local conditions, alternatives to agricultural burning or prescribed forest burning may raise other environmental issues.

The available cost data associated with reducing BC emissions from open biomass burning are extremely limited. Many of the emission-reduction techniques described in this section require infrastructure, substantial resource investments, or the existence of a market for biomass utilization products (e.g., wood pellets or biochar). Due to this, the costs will vary regionally and will be dependent on site-specific environmental conditions within which the techniques are applied.

Sarofim and colleagues (2010) conducted a survey of the available literature to develop cost estimates for the major emission-reduction techniques described in this section (i.e., increase combustion efficiency, reduce fuel consumed, reduce fuel loadings, and reduce the area burned) and found that these techniques are on the whole likely to be quite expensive for the amount of BC reduced. There may be a potential for lower cost mitigation approaches in locations where markets for biomass utilization exist. The United States recently initiated research efforts to evaluate and reduce BC emissions from open biomass burning in and around the Arctic, as described below. The U.S. Department of Agriculture's (USDA's) multi-agency program contains the following components (USDA, 2010):

- **Research Activities.** USDA scientists (led by the U.S. Forest Service and Agricultural Research Service) will seek to improve estimation of emission and transport of BC from agricultural burning and forest fires by quantifying spatial and temporal patterns of these emissions in Eurasia and conducting an assessment of long-range transport of BC from fires in Russia and adjoining regions to the Arctic. The research will identify meteorological conditions and potential source locations for Arctic transport of smoke and analyze agronomic practices in Eurasia to identify opportunities for reduced use of agricultural burning.
- **Technical Exchange and Other Cooperative Activities.** The U.S. Forest Service and Foreign Agricultural Service will implement technical exchanges and cooperation between U.S. and Russian experts on BC, agricultural burning, and fire management. These efforts will support training activities and the development and implementation of innovative, local-level "pilot" programs designed to illustrate strategies and practices that could be more broadly applied to reduce any negative environmental impacts of agricultural and forest fires. Key issues include interagency cooperation on fire management, fire budgets, and geographic information systems (GIS) and remote sensing. USDA will also facilitate public–private partnerships to develop local-level fire wardens and fire brigades in Russia and outreach to farmers in the Russian Federation to increase awareness of approaches to reduce BC emissions from agricultural burning.

6.5.1 Agricultural Burning

Emission-reduction techniques to reduce PM emissions, and consequently, BC and OC emissions, during intentional agricultural burning are briefly described in this section (U.S. EPA, 2011).

- Reduce the number of acres burned
    - Reduce burning through conservation tillage, soil incorporation, or collecting and hauling crop residues to central processing sites (WRAP, 2002).
    - Apply alternate-year burning, which involves alternating open-field burning with various methods of mechanical removal techniques. The period may involve burning every other year or every third year (U.S. EPA, 1992).
- Increase combustion efficiency
    - Stacking and/or baling the agricultural residue prior to burning will increase fire efficiency and lead to a more complete combustion, thereby reducing PM emissions. Emissions may be decreased by more efficient and controlled burning techniques (e.g., central or consolidated locations, use of biochar) or through measures to control the timing of burns, moisture enhancement, or by removing fuel material before the burn. These techniques may not reduce BC specifically, but may change the timing of the emissions and activity.
    - Propane flamers are an alternative to open-field burning.
    - Use of backing fires (“backburning”), which refers to burning against the wind direction, increases the combustion efficiency by promoting a more efficient flaming phase as opposed to smouldering (Ottmar et al., 2001). Flaming combustion is cleaner than smouldering combustion.
- Reduce fuel loadings by removing straw/stubble before the burn
- Convert land use to a crop that does not require burning or to non-agricultural use
- Educate farmers on proper burning techniques that reduce emissions.

6.5.2 Prescribed Forest Burning

Prescribed forest burning can prevent wildfires and result in increased biomass activity, thereby reducing PM and GHG emissions over the long term. Narayan and colleagues (2007) estimate that CO_2 emissions from wildfires could be reduced by up to 50% with prescribed burning techniques. Fernandes (2005) concluded that, in the long term, emissions from prescribed burning would be less than emissions from wildfires. There are several emission-reduction techniques associated with prescribed burning, as described below (U.S. EPA BC RTC, 2011).

- Use mosaic burning
    - Landscapes often contain a variety of fuel types that are non-continuous and vary in fuel moisture content. Prescribed fire prescriptions and patterns can be assigned to use this fuel and fuel moisture non-homogeneity to mimic a natural wildfire and create patches of unburned areas or burn only selected fuels (Ottmar et al., 2001).

- Reduce the amount of fuel consumed by
    - Providing dry, fine fuels that have a rapid ignition point, which can increase combustion efficiency by reducing the amount of time that the fire smoulders.
    - Burning fuel when moisture content is high. Fuel consumption and smoldering can be minimized by burning under conditions of high fuel moisture of duff, litter, and large woody fuels.
    - Conducting burns before precipitation. Scheduling a prescribed burn before a precipitation event may limit the consumption of large woody material, snags, stumps, and/or organic ground matter.
- Reduce fuel loadings by
    - Burning outside the growing season, burning after timber harvest, and burning frequently. Prescribed burning at appropriate times can help reduce the size and magnitude of wildfires.
    - Promoting the use of biomass in other markets. Woody biomass can be used in various industries, such as pulp and paper, methanol production, and garden bedding. This alternative is most applicable in areas that have large-diameter woody biomass and biomass that is plentiful and accessible so as to make biomass utilization economically viable. Biomass can also be pyrolyzed to produce biochar, a fine-grained charcoal, for use as a soil amendment.
    - Mechanically removing biomass to reduce a wildfire hazard, or to remove logging waste materials to prepare a site for replanting or natural regeneration. On-site chipping or crushing of woody material, removal of slash for off-site burning or biomass utilization, whole tree harvesting, and yarding (pulling out) of unmerchantable material may accomplish these goals. Mechanical treatments are normally limited to accessible areas (i.e., terrain that is not excessively rough, slopes of 40% or less, sites that are not wet, areas not designated as national parks or wilderness, areas not protected for threatened and endangered species, and areas without cultural or paleological resources).
    - Chemically treating areas to prevent, reduce, or remove certain plant species from an area. The environmental hazards must be assessed prior to incorporating this technique.
    - Increasing grazing by sheep, cattle, or goats before burning on rangelands and other lands to reduce grassy or brushy fuels prior to burning and reduce burn frequency.
- Increase combustion efficiency
    - Mass ignition of the fuel rapidly consumes dry, surface fuels and creates a strong convection column that draws heat away from the fuel bed and prevents drying and preheating of larger, moister fuels. The fire should die out shortly after the dry, fine fuels are consumed and smouldering and/or consumption of larger fuels should not occur (Ottmar et al., 2001).
    - Properly managing the fire to increase combustion efficiency and promote flaming rather than smouldering.
    - Changing the timing of burns to alter the extent or direction that smoke is transported.

  - Placing fuels in clean, dry piles or windrows will provide a concentrated source, allowing the fire to burn hotter and more efficiently. Greater consumption occurs and emissions are lower (Ottmar et al., 2001).
  - Use backing fires (explained above).
  - Use air curtain incinerators, which are large metal containers or pits with a powerful fan device to force additional oxygen into the fire, to produce a very hot and efficient fire with very little smoke. Air curtain incinerators offer a useful alternative to current fuel reduction and disposal methods, providing the benefits of producing lower smoke emissions compared to pile or broadcast burning; burning a greater variety, amount, and size of materials from dead to green vegetation; reducing fire risk; operating with fewer restrictions in weather and burn conditions; and containing burn area to a specific site.
- Train resource managers on proper burning techniques to reduce emissions.

6.5.3 Wildfires

Wildfires are a natural part of many ecosystems, but also are a large source of often uncontrollable emissions. Many wildfires result from lightning strikes and intentionally set fires (i.e., prescribed burns) that subsequently burn out of control. Inappropriately managing forested areas may lead to catastrophic or frequent wildfires, but preventive measures can be adopted to reduce the occurrence of events. These measures involve a combination of education, engineering, and enforcement techniques.

Education strategies are low-cost approaches for preventing unwanted fires in fire-prone areas. Raising public awareness through educational campaigns and outreach through media such as newspapers, radio, and television also can be effective in preventing unwanted fires (e.g., the U.S. Forest Service's "Smokey Bear" campaign is among the most successful fire prevention awareness and education campaigns ever conducted [National Wildfire Coordinating Group, 2007]).

Other preventive measures include removing fuel (dead trees, branches, forest floor litter) build-up on the forest floor, using prescribed burning techniques discussed in ***Section 6.5.2***, and harvesting fuel for a biomass-based energy source.

Developing fire management programs and strategies aimed at preventing accidental wildfires and avoiding unnecessary application of fire in land management will increase fire responsiveness, and hopefully, the duration and extent of the burn. In addition, expanding resources for fire monitoring, fire management decision support, and fire response will increase the response rate and time.

6.6 Gas Flaring

The significance of BC emissions from gas flaring remains highly uncertain, but is a source of potential concern in the High Arctic, especially as oil and gas activities expand. Reporting of PM emissions from gas flaring to international bodies, such as the CLRTAP, is scarce, but estimates of BC emissions, from the GAINS model in particular, shown throughout this report, are a key reason why this source is being highlighted. Examples of more effective methods to quantify BC emissions from flaring currently being developed include a Canadian research effort involving Carleton University and Natural Resources Canada, and efforts by Norway to engage the oil and gas private sector. Some countries, such as Norway, have developed technologies and practices to reduce emissions from flaring petroleum products, including

- Extinguished flaring systems with pilot flames that are ignited automatically when the speed of the gas exceeds a defined limit rather than pilot flames that burn continuously;
- Flare gas recovery systems which reduce the emissions associated with flaring;
- Using natural gas as a flush gas instead of using natural gas in the depressurization system;
- High Integrity Pressure Protection System (HIPPS), an instrumentation system with a quick valve solution for overpressure protection.

The applicability and implementation of such technologies will vary depending on site-specific conditions.

Oil and gas activities also constitute a very large Arctic source of methane emissions, and studies could determine methane emissions and leakage in parallel to work on BC, including

- Funding for immediate work on in-field measurements and scientific and technical analysis, in concert with the private sector, aimed at filling current information gaps;
- Obtaining better BC emissions data, as well as location and other basic information on flaring practices;
- Providing information on best practices and regulatory options from the energy industry where there has been progress on reducing flaring (e.g., Canadian provinces such as Alberta);
- Ensuring coordination with other international efforts to address venting and flaring, such as the Global Gas Flaring Reduction Partnership and Global Methane Initiative.

References

[This page intentionally left blank.]

ACIA (Arctic Climate Impact Assessment). 2004. *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. New York: Cambridge University Press.

ÅF (Ångpanneföreningen). 2010. *Consultant Report, Commission no C32069*5. (In Swedish)

Amann M., I. Bertok I., J. Borken-Kleefeld, J. Cofala, Ch. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj, R. Sandler, W. Schöpp, F. Wagner, W. Winiwarter. 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. *Environmental Modelling & Software* (currently under review).

AMAP (Arctic Monitoring and Assessment Programme). 2011. *The Impact of Black Carbon on Arctic Climates.* AMAP Expert Group on Short-Lived Climate Forcers. By: P.K. Quinn, A. Stohl, A. Arneth, J.F. Burkhart, J. Christensen, M. Flanner, K. Kupianien, H. Lihavainen, M. Shepherd, V. Shevchenko, H. Skov, and V. Vestreng. Arctic Monitoring and Assessment Programme (AMAP). Oslo, Norway. Available at: http://www.amap.no/.

Andreae, M.O., and P. Merlet. 2001. Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles 15*(4):955–966.

Anenberg S.C., K. Talgo, S. Arunachalam, P. Dolwick, C. Jang, and J.J. West. 2011. *Impacts of Global, Regional, and Sectoral Black Carbon Emission Reductions on Surface Air Quality and Human Mortality*. Atmos. Chem. Phys. Discuss., 11, 10653-10691.

Arctic Council. 2009. *The Arctic Marine Shipping Assessment*. Available at: http://www.pame.is/amsa/amsa-2009-report.

Baron, R.E., W.D. Montgomery, and S.D. Tuladhar. 2009. *An Analysis of Black Carbon Mitigation as a Solution to Climate Change*. Copenhagen Consensus on Climate, Copenhagen Business School, Frederiksberg, Denmark.

Bond, T.C. 2007. Can warming particles enter global climate discussions? *Environmental Research Letters 2*(4); doi: 10.1088/1748-9326/2/4/045030.

Bond, T.C. 2009. Personal communication of year 2000 emissions data for the eight Arctic Council nations, based on methodology in Bond (2007).

Bond, T.C. and H.L. Sun. 2005. Can reducing BC emissions counteract global warming? *Environmental Science & Technology 39*(16).

Bond, T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J. Woo, and Z. Klimont, 2004. A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research 109*(D14203):43; doi: 10.1029/2003JD003697.

Boverkets (Swedish National Board of Housing, Building and Planning). 1994. *BBR (Boverkets Byggregler) [Building and Design Regulations]*. Swedish National Board of Housing, Building and Planning, Karlskrona, Sweden. (In Swedish)

Chung, S.H., and J.H. Seinfeld. 2005. Climate response of direct radiative forcing of anthropogenic black carbon. *Journal Geophysical Research – Atmospheres 110*(D11102); doi: 10.1029/2004JD005441.

Cofala, J., M. Amann, Z. Klimont, K. Kupianen, and L. Hoglund-Isaksson. 2007. Scenarios of global anthropogenic emissions of air pollutants and methane until 2030. *Atmospheric Environment 41*(38):8486–8499.

Corbett, J.J., D.A. Lack, J.J. Winebrake, S. Harder, J.A. Silberman, and M. Gold. 2010. Arctic shipping emissions inventories and future scenarios. *Atmospheric Chemistry and Physics Discussions 10*: 10271–10311.

Eionet (European Environment Information and Observation Network). 2010. *_CRF_GRL: Greenhouse Gas Inventories (UN), Denmark*. Resubmission of Denmark's Greenhouse Gas reporting, 2010 (including Greenland emission inventory). Eionet Central Data Repository. Available at: http://cdr.eionet.europa.eu/dk/Air_Emission_Inventories/Submission_UNFCCC/coltmeqza/envtmeroq.

Fernandes, P. 2005. *Emissions from Controlled Fire Versus Fire*. Technical Report for Proposed Plan of National Defence Against Forest Fires [*Emissoes provenientes de fogo controlado versus incendio*. Relatorio para a Proposta Tecnica do Plano Nacional de Defesa da Floresta Contra Incendios. UTAD, Vila Real.] University of Tras-os-Montes and Alto Douro, Vila Real, Portugal. (In Portuguese)

Flanner, M.G., C.S. Zender, J.T. Randerson, and P.J. Rasch. 2007. Present-day climate forcing and response from BC in snow. *Journal of Geophysical Research*-*Atmospheres 112*(D11); doi: 10.1029/2006JD008003.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schultz, R. Van Dorland, G. Bodeker, O. Boucher, W.D. Collins, T.J. Conway, E. Dlugokencky, J.W. Elkins, D. Etheridge, P. Foukal, P. Fraser, M. Geller, F. Joos, C.D. Keeling, S. Kinne, K. Lassey, U. Lohmann, A.C. Manning, S. Montzka, D. Oram, K. O'Shaughnessy, S. Piper, G.-K. Plattner, M. Ponater, N. Ramankutty, G. Reid, D. Rind, K. Rosenlof, R. Sausen, D. Schwarzkopf, S.K. Solanki, G. Stenchikov, N. Stuber, T. Takemura, C. Textor, R. Wang, R. Weiss, and T. Whorf. 2007. Changes in atmospheric constituents and in radiative forcing. In: *Climate Change 2007: The Physical Science Basis*. Edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Frey A.K., J. Tissari, K.M. Saarnio, H.J. Timonen, O. Tolonen-Kivimäki, M.A. Aurela, S.K. Saarikoski, U. Makkonen, K. Hytönen, J. Jokiniem, R.O. Salonen, and R.E.J. Hillamo. 2009. Chemical composition and mass size distribution of fine particulate matter emitted by a small masonry heater. *Boreal Environmental Research 14*:255–271.

Garrett, T.J., and C. Zhao. 2006. Increased Arctic cloud longwave emissivity associated with pollution from mid-latitudes. *Nature 440*(7085):787–789.

Garrett, T.J., C. Zhao, X. Dong, G.G. Mace and P.V. Hobbs. 2004. Effects of varying aerosol regimes on low-level Arctic stratus. *Geophysical Research Letters 31*(L17105). Available at: http://dx.doi.org/10.1029/2004GL019928.

Greenland (Government of Greenland). 2009. Assessment: potential instruments in GHG mitigation 2008 – 2012. *Annex 3: Cost-Assessment for Selected Instruments within the Heating Sector, INUPLAN*. August.

Greenland (Government of Greenland). 2009. *Greenland Parliament Act of 7 December 2009 on Mineral Resources and Mineral Resource Activities (the Mineral Resources Act)*. Unofficial translation. Bureau of Minerals and Petroleum, Nuuk, Greenland. Available at: http://www.bmp.gl/images/stories/faelles/mineral_resources_act_unofficial_translation.pdf.

Greenland (Government of Greenland). 2010. *Greenland Act No. 21 of 18th November 2010 on Environmental Taxes on Products Used for Energy Production [Inatsisartut lov nr. 21 af 18. november 2010 om miljøafgift på produkter til energifremstilling*]. Available at: http://www.lovgivning.gl/gh.gl-love/dk/2010/ltl/L_21-2010_energiafgift/L_nr_21-2010_dk.htm. (In Greenlandic and Danish)

Greenland (Government of Greenland). 2011. *BMP Guidelines for Preparing an Environmental Impact Assessment (EIA)*. Report for Mineral Exploitation in Greenland. Bureau of Minerals and Petroleum, Nuuk, Greenland. Available at: http://www.bmp.gl/images/stories/minerals/EIA_guidelines_mining.pdf.

Greenland (Government of Greenland). 2011. *Environmental Regulation*. Bureau of Minerals and Petroleum, Nuuk, Greenland. Available at: http://www.bmp.gl/petroleum/environment/environmental-regulation.

Hall, A., and X. Qu. 2006. Using the current seasonal cycle to constrain snow albedo feedback in future climate change. *Geophysical Research Letters 33*(L03502); doi: 10.1029/2005GL025127. Available at: http://www.atmos.ucla.edu/csrl/publications/Hall/Hall_Qu_2006.pdf.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis*. Edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IVL (IVL Swedish Environmental Research Institute). 2009. *Analysis of Measures to Reduce Swedish Emissions by 2020 for* NO_x, $PM_{2.5}$ *and NMVOC – Non-road Machinery and Shipping*. IVL archive no. U2617. Stockholm, Sweden.

Johnson, M.R., R.W. Devillers, and K.A. Thompson. 2011. Quantitative field measurement of soot emission from large gas flare using Sky-LOSA. *Environmental Science and Technology 45*:345–350.

Kandlikar, M., C.C.O. Reynolds, and A.P. Grieshop. 2009. *A Perspective Paper on Black Carbon Mitigation as a Response to Climate Change*. Copenhagen Consensus on Climate, Copenhagen Business School, Frederiksberg, Denmark.

Karlsvik, E. 2004. Antydning av utslippsnivå for partikler fra tradisjonelle ovner i Oslo. SINTEF project 17X001.98. (In Norwegian)

Karlsvik, E., J.E. Hustad, and O.K. Sønju. 1993. Emissions from wood stoves and fireplaces. In *Advances in Thermochemical Biomass Conversion, Volume 1*. Edited by A.V. Bridgewater. London: Blackie Academic & Professional.

Karvosenoja, N. 2008. *Emission scenario model for regional air pollution*. Monographs of the Boreal Environment Research No. 32. Finnish Environmental Institute, Helsinki.

Klif (Klima- og forurensningsdirektoratet). 2009. *Pollution Regulations: Chapter 27. Pollution from combustion plants fired with clean fuels*. Norwegian Climate and Pollution Agency, Oslo, Norway. Available at: http://www.klif.no/english/english/Legislation/Pollution-Regulations/Chapter-27-Pollution-from-combustion-plants-fired-with-clean-fuels-/.

Kupiainen, K., and Z. Klimont. 2007. Primary emissions of fine carbonaceous particles in Europe, Atmospheric environment. *Atmospheric Environment 41*(10):2156-2170.

Kupiainen, K.J., N. Karvosenoja, P. Porvari, M. Johansson, M. Tainio, and J.T. Tuomisto. 2006. *Emissions of Primary Carbonaceous Particles, their Uncertainties and Spatial Allocation in Finland.* Proceedings of the 15th IUAPPA Regional Conference / 17th EFCA Speciality Conference, Lille, France, September 6–8.

Lamarque, J.F., T.C. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D. Lee, C. Liousse, A. Mieville, B. Owen, M.G. Schultz, D. Shindell, S.J. Smith, E. Stehfest, J. Van Aardenne, O.R. Cooper, M. Kainuma, N. Mahowald, J.R. McConnell, V. Naik, K. Riahi, and D.P. van Vuuren. 2010. Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmospheric Chemistry and Physics Discussions 10*:4963–5019.

Lesins, G., P. Chylek, and U. Lohmann. 2002. A study of internal and external mixing scenarios and its effect on aerosol optical properties and direct radiative forcing. *Journal of Geophysical Research D: Atmospheres 107*(9–10):5–1

Levin, I., R. Graul, and N.B.A. Trivett. 1995. Long term observations of atmospheric CO_2 and carbon isotopes at continental sites in Germany. *Tellus 47B*:23–34.

McDaniel, M. 1983. *Flare Efficiency Study*. EPA-600/2-83-052. Prepared for U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. Available at: http://www.epa.gov/ttn/chief/ap42/ch13/related/ref_01c13s05_jan1995.pdf.

MD (Miljøverndepartementet [Norwegian Ministry of the Environment]). 2009. *Norway's Fifth National Communication under the Framework Convention on Climate Change*. Status report, December 2009. Publication number T-1482 E. Oslo, Norway.

Meteorologisk institutt. 2011. *Temperature and Snow Cover in Oslo, Norway, in Autumn 2002*. Meteorological Institute, Oslo, Norway. Available at http://met.no/.

Narayan, A., P. Sachdeva, K. Sharma, A.K. Saini, and Y. Singh. 2007. Serine threonine protein kinases of mycobacterial genus: phylogeny to function. *Physiological Genomics 29*:66–75.

National Snow and Ice Data Center (NSIDC). 2008. Press Release: Arctic sea ice down to second-lowest extent; likely record-low volume. Figure 3. Available at: http://nsidc.org/news/press/20081002_seaice_pressrelease.html.

National Wildfire Coordinating Group. 2007. Chapter 8: Fire prevention. In *Communicator's Guide for Wildland Fire Management: Fire Education, Prevention, and Mitigation Practices*. Available at: http://www.nifc.gov/preved/comm_guide/wildfire/files/pdf%20%20files/linked%20pdfs/8%20fire%20prevention.pdf.

OLF (Oljeindustriens Landsforening). 1993. *Miljøprogram Fase II. Sammendragsrapport [Environmental Programme Phase II. Summary Report*]. Norwegian Oil Industry Association, Forus, Norway. (In Norwegian)

Ottmar, R.D., J.L. Peterson, B. Leenhouts, and J.E. Core. 2001. Smoke management: techniques to reduce or redistribute emissions. In *Smoke Management Guide For Prescribed and Wildland Fire: 2001 Edition*. Edited by C.C. Hardy, R.D. Ottmar, J.L. Peterson, J.E. Core, and P. Seamon. National Wildfire Coordination Group.

Perovich, D.K. and J.A. Richter-Menge. 2009. Loss of sea ice in the Arctic. *Annual Review of Marine Science 1*:417–441.

Perovich, D.K., J.A. Richter-Menge, K.F. Jones, and B. Light. 2008. Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007. *Geophysical Research Letters 35*(L11501); doi: 10.1029/2008GL034007.

Polyak, L., J.T. Andrews, J. Brigham-Grette, D. Darby, A. Dyke, S. Funder, M. Holland, A. Jennings, J. Savelle, M. Serreze, and E. Wolff. 2009. History of sea ice in the Arctic. Pp. 358–420 in *Past Climate Variability and Change in the Arctic and at High Latitudes*. A report by the U.S. Climate Change Program and Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA.

Quinn, P., G. Shaw, E. Andrews, E. Dutton, T. Ruoho-Airola, and S. Gong. 2007. Arctic haze: Current trends and knowledge gaps. *Tellus B 59*:99–114.

Quinn, P.K., T.S. Bates, E. Baum, T. Bond, J.F. Burkhart, A.M. Fiore, M. Flanner, T.J. Garrett, D. Koch, J. McConnell, D. Shindell, and A. Stohl. 2008. *The Impact of Short-Lived Pollutants on Arctic Climate*. AMAP Technical Report No. 1. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Ramanathan, V. 2010. Interactive comment on “Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse” by T.C. Bond, et al. *Atmospheric Chemistry and Physics Discussions 10*:C6227-C6241. Available at http://www.atmos-chem-phys-discuss.net/10/C6227/2010/acpd-10-C6227-2010.pdf.

Rypdal, K., N. Rive, T. Berntsen, Z. Klimont, K. Mideksa, G. Myhre, and R.B. Skeie. 2009. Costs and global impacts of BC abatement strategies. *Tellus B 61*(4):625–641.

Saathoff, H., K.-H Naumann, M. Schnaiter, W. Schöck, O. Möhler, U. Schurath, E. Weingartner, M. Gysel, and U. Baltensperger. 2003. Coating of soot and $(NH_4)_2SO_4$ particles by ozonolysis products of α-pinene. *Journal of Aerosol Science 34*(10):1297–1321.

Saikawa, E., V. Naik, L.W. Horowitz, J. Liu, and D.L. Mauzerall. 2009. Present and potential future contributions of sulfate, black and organic carbon aerosols from China to global air quality premature mortality and radiative forcing. *Atmospheric Environment 43*(17): 2814–2822.

Schultz, M.G., A. Heil, J.J. Hoelzemann, A. Spessa, K. Thonicke, J. Goldammer, A.C. Held, J.M. Pereira, M. van het Bolscher. 2008. Global wildland fire emissions from 1960 to 2000. *Global Biogeochemical Cycles 22*(GB2002):17; doi: 10.1029/2007GB003031.

SFT (Norwegian Pollution Control Authority). 2006. *Assessments of Measures to Reduce Particulate Emissions [Tiltaksanalyse for partikkelutslipp]*. Norwegian Ministry of the Environment, Oslo, Norway. (In Norwegian)

Shindell, D.T., M. Chin, F. Dentener, R.M. Doherty, G. Faluvegi, A.M. Fiore, P. Hess, D.M. Koch, I.A. MacKenzie, M.G. Sanderson, M.G. Schultz, M. Schulz, D.S. Stevenson, H. Teich, C. Textor, O. Wild, D.J. Bergmann, I. Bey, H. Bian, C. Cuvelier, B.N. Duncan, G. Folberth, L.W. Horowitz, J. Jonson, J.W. Kaminski, E. Marmer, R. Park, K.J. Pringle, S. Schroeder, S. Szopa, T. Takemura, G. Zeng, T.J. Keating, and A. Zuber. 2008. A multi-model assessment of pollution transport to the Arctic. *Atmospheric Chemistry and Physics 8*, 5353–5372.

Sippula, O., J. Hokkinen, H. Puustinen, P. Yli-Pirilä, and J. Jokiniemi. 2009. Particle emissions from small wood-fired district heating units. *Energy & Fuels 23*:2974–2982.

Sippula, O., K. Hytönen, J. Tissari, T. Raunemaa, and J. Jokiniemi. 2007. Effect of wood fuel on the emissions from a top-feed pellet stove. *Energy & Fuels 21*:1151–1160.

Smith K.R., and E. Haigler. 2008. Co-benefits of climate mitigation and health protection in energy systems: scoping methods. *Annual Review Public Health 29*:11–25.

SSB (Statistics Norway). 2001. *Emissions to Air from Wood Combustion in Norway [Utslipp til luft fra vedfyring i Norge]*. SSB-rapport 2001/36. Oslo–Kongsvinger, Norway. Available at http://www.ssb.no/emner/01/04/10/rapp_200136/rapp_200136.pdf. (In Norwegian)

SSB (Statistics Norway). 2010. *The Norwegian Emission Inventory 2010, Documentation of Methodologies for Estimating Emissions Of Greenhouse Gases and Long-range Transboundary Air Pollutants*. Edited by Trond Sandmo. Oslo–Kongsvinger, Norway. Available at http://www.ssb.no/english/subjects/01/90/doc_201021_en/doc_201021_en.pdf.

Statistics Greenland. 2009. *Greenland's Import and Export [Grønlands Udenrigshandel]*. Table 3: Total export in 2008 and 2009, by products. Available at: http://www.stat.gl/LinkClick.aspx?link=Udenrigshandel+%26+Eksport%2fGr%c3%b8nlands+udenrigshandel+2009+_forel%c3%b8bige+tal_.pdf&tabid=101&mid=524&language=da-DK. (In Danish)

Streets, D.G. 2007. Dissecting future aerosol emissions: warming tendencies and mitigation opportunities. *Climatic Change 81*:313–330; doi 10.1007/s10584-006-9112-8.

Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze. 2007. Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters 34*(L09501); doi: 10.1029/2007/GL029703. Available at: http://www.ualberta.ca/~eec/Stroeve2007.pdf.

Swedish EPA (Environmental Protection Agency). 2007. Annex 3. Pp. 67–100 in *Report 5781*. Stockholm, Sweden. (In Swedish)

Tissari, J., J. Lyyränen, K. Hytönen, O. Sippula, U. Tapper, A. Frey, K. Saarnio, A.S. Pennanen, R. Hillamo, R.O. Salonen, M. Hirvonen, and J. Jokiniemi. 2008. Fine particle and gaseous emissions from normal and smouldering wood combustion in a conventional masonry heater. *Atmospheric Environment 42*:7862–7873.

Tissari, J., K. Hytönen, J. Lyyränen, and J. Jokiniemi. 2007. A novel field measurement method for determining fine particle and gas emissions from residential wood combustion. *Atmospheric Environment 41*:8330–8344.

Tissari, J., K. Hytönen, O. Sippula, and J. Jokiniemi. 2009. The effects of operating conditions on emissions from masonry heaters and sauna stoves. *Biomass and Bioenergy 33*:513–520.

U.S. EPA (Environmental Protection Agency). 1992. Prescribed burning background document and technical information document for best available control measures. EPA-450/2-92-003. U.E. EPA, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

U.S. EPA (Environmental Protection Agency). 1995. *Compilation of Air Pollutant Emission Factors*. AP-42, Fifth Edition. U.S. EPA, Office of Air Quality Planning and Standards, Technology Transfer Network, Clearinghouse for Inventories & Emissions Factors, Washington, DC.

U.S. EPA (Environmental Protection Agency). 1998. *Interim Air Quality Policy on Wildland and Prescribed Fires*. White paper. U.S. EPA, Washington, DC.

U.S. EPA (Environmental Protection Agency). 2002. *Compilation of Air Pollutant Emission Factors*. AP-42, Fifth Edition. Volume 1, Stationary Point & Area Sources, Update 2001 & Update 2002. U.S. EPA, Office of Air Quality Planning and Standards, Technology Transfer Network, Clearinghouse for Inventories & Emissions Factors, Washington, DC.

U.S. EPA (Environmental Protection Agency). 2005. *National Emissions Inventory (NEI)*. U.S. EPA, Office of Air Quality Planning and Standards, Technology Transfer Network, Clearinghouse for Inventories & Emissions Factors, Washington, DC. Available at: http://www.epa.gov/ttn/chief/eiinformation.html.

U.S. EPA (Environmental Protection Agency). 2008. *SPECIATE Version 4.2*. U.S. EPA, Office of Air Quality Planning and Standards, Technology Transfer Network, Clearinghouse for Inventories & Emissions Factors, Washington, DC. Available at: http://www.epa.gov/ttn/chief/software/speciate/index.html.

U.S. EPA (Environmental Protection Agency). 2009. *Integrated Science Assessment for Particulate Matter (Final Report)*. EPA/600/R-08/139F. U.S. EPA, Washington, DC.

U.S. EPA (Environmental Protection Agency). 2011. *Report to Congress on Black Carbon: External Peer Review Draft*. EPA-450/D-11-001. Department of the Interior, Environment, and Related Agencies Appropriations Act, 2010. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/fedrgstr_activites/BC%20Report%20to%20Congress?OpenDocument.

UNEP (United Nations Environmental Programme). 2011. *Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers*. UNEP/GC/26/INF/20. UNEP, Kenya.

USDA (United States Department of Agriculture), 2010. *USDA Arctic Black Carbon Initiative*. Fact sheet by the USDA, Washington, DC. September.

Van der Werf, G., J.T. Randerson, L. Giglio, G.J. Collatz, P.S. Kasibhatla, and A.F. Arellano, Jr. 2006. Interannual variability in global biomass burning emissions from 1997 to 2004. *Atmospheric Chemistry and Physics 6*:3423–3441.

Wang, M., and J.E. Overland. 2009. A sea ice free summer Arctic within 30 years? *Geophysical Research Letters 36*(L07502); doi: 10.1029/2009/GL037820. Available at: http://mrc.org/pdf/WANG-OVERLAND-ARCTIC%20SEA%20ICE%20ESTIMATE.pdf.

Warren, S.G., and W.J. Wiscombe. 1980. A model for the spectral albedo of snow, II: Snow containing atmospheric aerosols. *Journal of Atmospheric Science 37*:2734–2745.

West, J.J., A.M. Fiore, L.W. Horowitz, and D.L. Mauzerall. 2006. Global health benefits of mitigating ozone pollution with methane emission controls. *Proceedings of the National Academy of Sciences USA 103*(11):3988–93.

Western Air Regional Partnership (WRAP). 2002. *Non-burning Management Alternatives on Agricultural Lands in the Western United States, Volume II: Non-Burning Management Alternatives and Implementation Plan Strategies*. Prepared by Eastern Research Group, Inc. Available at: http://www.wrapair.org/forums/fejf/tasks/FEJFtask4.html.

Wilkinson, P., K.R. Smith, M. Davies, H. Adair, B.G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne, and Z. Chalabi. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet 374*(9705):1917–29.