Improved emission inventories of SLCP

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Authors preface

This project, Improved Nordic emission inventories of Short-Lived Climate Pollutants – SLCP, was proposed by the Swedish presidency of the Nordic Council of Ministers (NMR) in 2013 and was approved in June 2013. It is planned for a three year period and all five Nordic countries participate and contribute actively in the work.

The overall objective of the project is to improve the Nordic emission inventories of Short Lived Climate Pollutants (SLCP), with a focus on Black Carbon (BC). This report presents the results from the first phase of the project, an analysis of the present status of knowledge. The next phase will draw on the results from this background analysis in designing and implementing an emission measurement program, where the objective is to expand the knowledge and develop well documented and reliable emission factors, primarily for BC, for use in future national emission inventories.

The work has been excellently guided by a project steering group with participants from the Nordic countries as well as from NMR.

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Summary

Emission inventories of Short Lived Climate Pollutants (SLCP), and especially of Black Carbon (BC), are uncertain and not always comparable. Comparable and reliable emission inventories are essential when aiming for efficient strategies and policies for reduced emissions. This report presents the Nordic emissions and emission inventories of SLCP, the important emission sources and their development over time. It also discusses knowledge gaps, factors contributing to the uncertainties, and possibilities for improved emission estimates. The report focuses on BC and particulate matter (PM_{2.5}) emissions from residential biomass combustion, on-road and non-road diesel vehicles, and shipping.

SLCP is a group of substances comprising BC, tropospheric ozone (O₃), methane (CH₄), and hydro fluorocarbons. O₃ is formed in atmospheric chemical reactions involving CH₄, nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compound (NMVOC) and sunlight. The SLCPs have, in comparison to the long lived greenhouse gases e.g. carbon dioxide (CO₂) and nitrous oxide (N₂O), a short residence time in the atmosphere.

There is an increasing attention and interest especially in the role of BC in climate change and the possibilities to slow down the on-going global temperature increase by reducing emissions of BC and other SLCPs. Emission reductions of SLCP can also have a regional effect on climate change. Furthermore, the adverse effects on human health from exposure to particulate matter have long been recognized. Recent assessments of the health effects of BC as a component of PM_{2.5} have indicated that there is sufficient evidence of an association with health effects from both short-term (daily) variations in BC concentrations, as well as long term average BC exposure (WHO, 2012). Reduced emissions of BC would thus benefit both climate change and human health.

In May 2012 a revised Gothenburg Protocol under the UNECE CLRTAP (United Nations Economic Commission for Europe, Convention on Long-Range Transboundary Air Pollution) was adopted. The revised protocol includes a ceiling for national emissions of PM_{2.5} and for SO₂, NO_x, NH₃ and NMVOC. In the amended protocol text, a general recommendation is given that sources of PM_{2.5} with the largest emitted fractions of BC should be prioritised when implementing emission reduction

actions. In order to be able to assess and report anticipated emission reductions in a consistent and accurate manner, improved knowledge, and an improved methodology for emission inventories, are needed.

The overall objective of the current project is to improve the Nordic emission inventories of SLCP, with focus on BC (and $PM_{2.5}$). As a first step this Background analysis has been performed, in order to assess and summarise current Nordic emissions and knowledge, and lay the basis for an emission measurement program to be performed in the second phase of the project. As BC is a component of emitted $PM_{2.5}$, accurate emission inventories of $PM_{2.5}$ are an important basis for estimating emissions of BC, why also $PM_{2.5}$ is included in the analyses in this project.

National official emission inventories for air pollutants and greenhouse gases, including $PM_{2.5}$ and CH_4 , as well as CO and NMVOC (precursors for ozone) are annually reported from all Nordic countries to international conventions. BC is not yet part of the reporting program, but it will be included as voluntary reporting to CLRTAP in the near future as a consequence of BC being highlighted in the revised Gothenburg protocol. All Nordic countries, except Iceland, have however already developed preliminary emission inventories of BC. The time series of estimated Nordic aggregated emissions of BC is presented in the figure below.

Estimated Nordic emissions of BC (Gg), 2000–2011

The Nordic emission inventories show that the largest contributing source to emissions of BC and $PM_{2.5}$ is residential combustion, contributing more than 40% of the Nordic BC and $PM_{2.5}$ emissions. In 2011 the emissions of $PM_{2.5}$ from residential combustion in the Nordic countries

was about 64 Gg or 50% of the total Nordic PM_{2.5} emissions. For BC the estimated emissions was 10 Gg, 45% of Nordic total emissions. For BC there are also significant contributions from road traffic (~20% in later years) and non-road mobile machinery (~15%). The Nordic national shipping contributed ca. 1.3 Gg BC in 2011, or 6% of the aggregated Nordic emissions. There are however large differences between the Nordic countries, where national shipping in Norway contributes ~17% of national Norwegian BC emissions, ~6% in Sweden, and ~1% in Denmark and Finland. There is less data reported on BC from international shipping in the inventories; Denmark and Sweden report 0.58 and 0.86 Gg BC respectively.

The aggregated Nordic emission of CH₄ is dominated by the agriculture and waste sectors. These sectors together contribute with more than 85% of the total CH₄ emissions. The aggregated Nordic emissions of NMVOC show a declining trend with 45% reduction from 2000–2011. While fuel combustion sources show decreases in the order of 65–70%, especially the source category “solvent and product use” remains high and stable over time. Residential combustion of biomass contributes approximately 15% to Nordic NMVOC emissions. The largest contributing sources to emissions of CO in later years have been residential combustion and road traffic.

The background analysis has focused on emissions of BC and PM_{2.5} and has identified three Nordic main emission sources; residential biomass combustion, mobile diesel vehicles and machinery, and shipping.

Residential biomass combustion

All Nordic countries, except Iceland, have developed emission inventories for PM_{2.5} and BC from residential biomass combustion. Conditions regarding residential biomass combustion are more differentiated than might be expected between the Nordic countries. The types and uses of combustion appliances are quite different; in Norway stoves are primarily used, a combination of stoves and boilers are used in Denmark, Sweden has the highest share of boilers and Finland is the only country with significant use of masonry heaters and sauna stoves, in addition to boilers and other stoves. These differences are also reflected in the inventory methodologies in the countries, where different structuring and different level of detail are applied for technologies and emission factors in the emission calculations.

A further differentiation is in the measurement methodologies underlying the national emission factors for PM_{2.5} (and BC) where Denmark,

Norway and Finland have used dilution tunnel measurements while the Swedish emission factors are based on hot flue gas measurements. These two principally different measurement methods do not, especially in case of incomplete combustion conditions, give the same results, as PM from the dilution tunnel measurement also include particles formed as semi-volatile gases are condensed, adding to the PM mass. Differences of in the order of 2–4 times, as reported in the literature, and a factor of up to 10 in worst cases, obviously makes it difficult to compare the results.

The assessment and comparison of the nationally used emission factors for PM_{2.5} show that emission factors vary widely, both between technologies but also between countries for supposedly similar technologies. These differences can be attributed partly to the non-comparable measurement methods underlying the emission factors, but also to assumptions made regarding firing habits, fuel quality etc., which influences the calculated emissions. It is also not unlikely that conditions influencing emissions, like for example firing habits, in reality are different in the Nordic countries.

Given the variations in combustion technology stock, emission measurement methodology and other important influencing factors (as assumptions or in reality), a straightforward comparison between the countries is not easily accomplished.

For residential wood combustion in general information on emission factors for BC is scarce, with some exceptions (e.g. recent results from measurements on Norwegian stoves, under Norwegian conditions, and some measurements in Finland). In the Finnish and Norwegian emission inventories national emission factors for BC are used where available, while the Danish and Swedish BC emission inventories, at present, rely on information on BC as a fraction of emitted PM_{2.5} from the EMEP/EEA Air Pollutant Emission Inventory Guidebook, which represents the currently best available collected knowledge. Using emission factors from the Guidebook will give results that are acceptable, but as conditions differ between the Nordic countries it is unclear how well country specific conditions and circumstances are reflected in the factors presented in the Guidebook.

Summary and main conclusions, BC and PM_{2.5} from residential biomass combustion

Emissions

- Residential biomass combustion is a significant source for BC and PM_{2.5} emissions in the Nordic countries, contributing more than 40% of the total Nordic emissions.
- Emission reporting of PM_{2.5} (and BC) from residential biomass combustion is not comparable between the Nordic countries, partly due to different measurement methodologies underlying the national emission factors (hot flue gas, dilution tunnel).

Measurements

- Nordic national information on BC is scarce and there is a general lack of BC emission measurements, except from recent measurements on old and new stoves in Norway, and some measurements in Finland.
- Presently there is no defined measurement standard prescribed as a basis for PM_{2.5} emission factor development within the CLRTAP convention (or EU). It is stated in the EMEP/EEA Guidebook (EMEP/EEA, 2013) that recent studies based on diluted flue gas sampling were prioritised when updating the Guidebook. In addition, emission data that includes the whole combustion cycle were prioritised as the emission during ignition, part load and burnout are much higher than at full load conditions.
- The fact that emission factors for PM are based on different, but official, emission measurement standards (hot flue gases or diluted) that may give significantly different results raises the question on what is needed and wanted from the point of view of the potential use of data from national emission inventories. Reported emission data may be used for modelling purposes, in assessments of compliance, comparability and health impact etc. Depending on the purpose the requirements may differ. For comparability and compliance purposes, the important issue is to base the estimates on comparable measurement standards, irrespective of standard. For modelling purposes and in assessment of health effects, it seems that results from diluted sampling would be favored, since those data are considered to better reflect real conditions in the atmosphere after an emission has occurred.

Emission factors

- At present, both results on EC (Elemental Carbon) and BC are used interchangeably for emission factor development, even though they strictly do not represent identical particle fractions. The possible errors introduced by these assumptions are, however, probably minor compared to other uncertainties in national emission inventories.
- There are uncertainties when using emission factors for BC expressed as a fraction of PM_{2.5}. The problem arises when emission factors for PM_{2.5} are not well defined as with or without condensable organic matter included in the mass. The fraction of BC will be different depending on if condensable organic matter is included in the PM_{2.5} mass or not. BC is theoretically already present in hot flue gases, even though some addition of mass could occur at dilution and condensation. For specific emission factors for BC (e.g. in the unit g/GJ) this problem does not exist. Care should however be taken not to report inconsistent data for PM_{2.5} and BC if specific emission factors from different measurements or literature sources are used.
- Many national specific emission factors exist in the Nordic countries, but it is not always that national activity data (e.g. stock of combustion technologies in use), or knowledge on for example combustion practices are available to make full use of existing information. There is work to be done in the countries to adapt national information to already available emission factors. A more comparable disaggregation of emission sources would also facilitate the use of harmonised emission factors.

As residential biomass combustion is such a dominating source of PM_{2.5} and BC emissions in the Nordic countries, the present uncertainties and knowledge gaps need to be reduced in order for the inventory results to serve as a sufficiently reliable basis for policy development and actions. As conditions are different in different countries, we would not necessarily expect possible future results from investigations in non-Nordic countries to be representative and readily usable for Nordic conditions. The measurement program in this project should therefore prioritise residential wood combustion under Nordic conditions.

Mobile diesel vehicles and machinery

For on-road mobile sources, reductions in PM and BC emissions by the implementation of EURO-standards are expected, and the BC emissions are comparatively well characterized. The same EURO standards also exist in other countries, why future increased knowledge from other non-Nordic investigations can be used in the Nordic countries. No measurements on road diesel vehicles are therefore foreseen in the proposed measurement program in this project.

For the non-road mobile machineries there are very few measurements and the emission inventories normally rely on BC fractions of PM from similar road diesel engines. However, also the PM emission factors must be considered as uncertain for non-road mobile machinery. In inventories the emission factors are normally related to the legal limits for PM emissions which are measured in engine bench tests with test cycles comprising of a number of stationary points. Thus, these emission factors will not account for cold starts or transient operation. Field measurements to capture real time conditions would be desirable, but there are substantial discussions needed regarding how to perform such measurements in order to achieve enough representative results for use in national inventories. This would be too large an undertaking for the measurement program in this project.

Shipping

Shipping must be considered as a significant source of PM_{2.5} and BC emissions, even though complete data is not reported from all the Nordic countries. For shipping the measured emissions of PM_{2.5} will depend on a number of factors such as fuel quality, engine type, operational mode, engine maintenance and engine load. There are also different measurement methods where there will be a large difference between in stack sampling and diluted sampling. Furthermore, for BC there are a number of different BC instruments that may give somewhat different results. When expressing BC as a fraction of PM one must use different values for diluted and in-stack measurements since the BC should be relatively insensitive to if dilution is made, while other types of particles (sulphates, organic compounds etc) will be significantly influenced.

Work is going on internationally regarding shipping emissions, for example discussions on the definitions of BC. Until the shipping community has decided on measurement standards and the definition of BC it may not be very useful to devote resources to shipping emissions within

this project, as our overall objective is to improve the national Nordic BC inventories.

Strategy for BC emission measurements from residential wood burning in the second phase of the project

The objective of the measurement program in the second phase of the project is to improve the Nordic emission factors for BC (and PM_{2.5}) for residential wood burning.

The current understanding of the commonly used appliances and other factors impacting the actual emission levels in the Nordic countries does not allow selecting clear and representative example cases of the most polluting appliances common for all Nordic countries. In preparation of the measurement program, combustion technologies/appliances where knowledge is scarce and which have a significant contribution to emissions have to be defined in the Nordic (and country specific) context. Measurement results are at the moment not available for several appliance types and different operational procedures, and there are also different sampling and analysis methods for PM and BC. It will not be possible to solve all problems, but rather to increase the knowledge for some of the more important variables, such as the impact of the measurement standard on the measurement results, and the contributions of different use practices to the emission levels.

Field measurements of course better reflect real world conditions, but to achieve a large enough basis to be able to generalise to the national (or Nordic) level, a vast measurement program would need to be designed. We propose to focus on a well-designed measurement program with lab measurements as a basis to answer some of the questions, and to verify those measurements by a suitable number of field measurements, or simulated field measurements, to capture some of the variations introduced by field conditions.

Reading instructions

The background, project objectives as well as other relevant projects and processes are presented in Chapter 1. The status of national emissions and emissions inventory methodologies in the Nordic countries are presented in Chapter 2, and the aggregated Nordic emissions in Chapter 3. Chapter 4 goes into detail regarding residential biomass combustion in the countries, while Chapter 5 covers non-road and on road diesel vehicles, and Chapter 6 shipping. For shipping there are further

details presented in Annex A. In Chapter 7 the measurement strategy for the next phase of the project is discussed in relation to knowledge gaps identified in the previous chapters and conclusions regarding BC and PM_{2.5}. Chapter 8 contains a discussion on the design of a measurement program for BC from residential wood burning

1. SLCP – Short Lived Climate Pollutants – definitions and glossary

1.1 Definitions

Substances considered as SLCPs include Black Carbon (BC), methane (CH₄) and tropospheric ozone (O₃). Also hydro fluorocarbons (HFCs) are included as SLCPs even though the HFCs have a longer residence time in the atmosphere than the other SLCPs.

Black Carbon (BC) is emitted from incomplete combustion of fuels, along with other types of particulate matter of various compositions, as well as carbon monoxide (CO) and volatile organic compounds (VOC). The emitted particles include BC but also organic matter (OM) as well as inorganic aerosols such as sulphates and nitrates. BC and OC, carbonaceous aerosols, are always emitted together, but in different proportions depending on source. Organic carbon, in contrary to BC, has a cooling effect on the climate.

Methane (CH₄) is formed in anaerobic decomposition of organic material e.g in waste landfills and in wetlands and peat lands. Methane is also emitted to the atmosphere from cattle as well as from exploration and transport of fossil fuel. Methane is also emitted from combustion of fuels.

Tropospheric ozone (O₃) is formed in atmospheric chemical reactions involving methane (CH₄), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compound (VOC) and sunlight. Reductions of particularly CH₄ and CO have the potential to reduce the O₃-concentration in the troposphere. A reduction of VOC would also contribute to decreased levels of tropospheric ozone, while NO_x has more complex effects where the net climate effect of reduced NO_x emissions is considered to be small.

Hydro fluorocarbons (HFC) are industrially produced chemical substances which are used extensively as substitutes for ozone depleting freon (CFCs) in technical applications such as refrigeration and cooling.

Sources: Integrated Assessment of Black Carbon and Tropospheric Ozone, Summary for Decision Makers, UNEP, and Information webpage on SLCP, <http://www.smhi.se/slcp/Om-SLCP>

1.2 Glossary

- *Elemental Carbon, EC*
Refers to all carbon in elemental form. The term EC is often used with thermal analysis to indicate the carbon that does not oxidise below a certain temperature (usually 550–650 °C).
- *Black Carbon, BC*
Commonly known as soot, is the dark, light absorbing part of the particles. BC is measured by optical methods. BC mainly consist of EC, but may also include some light absorbing organic compounds. BC refers to the whole light absorbing fraction of carbonaceous aerosols. In the literature EC and BC are usually treated as equal, even though this is not completely true.
- *Organic Matter/Organic Mass (OM)*
Refers to the non-carbonate (non-CO₃) carbonaceous particles other than BC (or EC) and it includes numerous organic compounds. OM is estimated by multiplying OC by a factor to account for other elements than carbon in the organic molecules. The factor may vary depending on the origin and age of the OM, but usually 1.2–1.4 is used.
- *Organic Carbon, OC*
Refers to the carbon content in OM. It is the carbon that is not classified in the analysis as BC/EC or carbonate carbon (CO₃ carbon)
- *PM_{2.5}*
Particulate matter including all particles with an aerodynamic diameter less 2.5 µm (defined as particles passing an inlet with 50% efficiency at 2.5 µm). Emitted PM_{2.5} consists of BC/EC, OM and inorganic compounds.

Sources: Aasestad, K. (2013), Hansson *et al.* (2011).

2. Background

Short Lived Climate Pollutants, SLCP, is a group of substances comprising aerosol particles, tropospheric ozone, methane, and hydro fluorocarbons. These substances have, in comparison to the long lived greenhouse gases e.g. carbon dioxide (CO₂) and nitrous oxide (N₂O), a short residence time in the atmosphere.

At the Nordic Environmental Ministers meeting in March 2012 the Ministers decided to enhance actions to reduce the emissions of SLCP. Emissions of SLCP have a negative impact on climate, air quality and human health. By reducing the levels of soot and tropospheric ozone in the atmosphere positive effects on both climate and air quality can be achieved.

There is an increasing attention and interest especially in the role of Black Carbon (BC) (e.g. Arctic Council Task Force on Short-Lived Climate Forcers, 2011, AMAP, 2011) in climate change and the possibilities to slow down the on-going temperature increase by reducing emissions of BC and other SLCPs. Reduced emissions of SLCP, and in particular BC, will give a more rapid response in climate change in comparison to reducing CO₂ emissions due to the shorter life time of these species in the atmosphere. For the same reason, emission reductions of SLCP can also have a regional effect on climate change. For sensitive regions such as the Arctic, reducing BC emissions is thus an attractive policy option. Emission reductions of SLCP can also have a regional effect on climate change. Furthermore, the adverse effects on human health from exposure to particulate matter have long been recognized. Recent assessments of the health effects of BC as a component of PM_{2.5} have indicated that there is sufficient evidence of an association with health effects from both short-term (daily) variations in BC concentrations, as well as long term average BC exposure (WHO, 2012). Reduced emissions of BC would thus benefit both climate change and human health.

In order to assess and understand the contribution from BC to a changing climate in the Arctic, and the contribution to health effects, a sound basis of knowledge regarding emissions of BC in Northern countries is essential. It is important to understand the magnitude and sources of origin of emissions of BC when priorities regarding measures to abate climate change and health effects need to be weighed against each other.

The three primary BC emitting sectors in the eight Arctic Council countries (Denmark, Finland, Iceland, Norway, Sweden, Canada, USA and Russia) are, according to the Arctic Council Task Force on Short-Lived Climate Forcers (2011), the transport sector, primarily due to emissions from on-road transportation, but including both on-road and off-road diesel vehicles; the domestic sector due to emissions from domestic heating, primarily wood but also coal combustion; and open biomass burning, 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.

In May 2012 a revised Gothenburg Protocol under the UNECE CLRTAP was adopted. The revised protocol includes a ceiling for national emissions of particulate matter (PM_{2.5} i.e. particles with an aerodynamic diameter <2.5 µm) and for SO₂, NO_x, NH₃ and NMVOC. Black Carbon (or soot) is a component of emitted PM_{2.5}. In the amended protocol text, a general recommendation is given that sources with the largest emitted fractions of BC should be prioritised when implementing emission reduction actions for PM_{2.5}. The revised Gothenburg protocol implies that Norway and Finland are to reduce their national emissions of PM_{2.5} by 30%, Denmark by 33% and Sweden 19% between 2005 and 2020. In order to be able to assess and report these anticipated emission reductions in a consistent and accurate manner, improved knowledge and an improved methodology for emission inventories is needed.

As Black Carbon is a component of emitted PM_{2.5}, accurate emission inventories of PM_{2.5} are an important basis for estimating emissions of BC and other components of PM. A better understanding of PM composition is also essential for the assessment of climate benefits of emission reduction actions since PM also can have a cooling effect on the climate.

More knowledge regarding the sources and the magnitude of emissions of PM_{2.5} and BC is a prerequisite to be able to take effective action and to be able to evaluate if the actions have had desired effect.

Currently PM (as PM_{2.5}), and from 2015 also BC as voluntary reporting, is included in the emission reporting program under the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP). Generally there are substantial uncertainties associated with reported emission inventories of PM_{2.5}.

2.1 Project objectives

This project was proposed by the Swedish presidency of the Nordic Council of Ministers in 2013 and was approved in June 2013. It is planned for a three year period and all five Nordic countries participate and contribute actively in project work.

The primary priority in the project is to improve the knowledge regarding Black Carbon, BC. Since BC in emission inventories is usually derived as a fraction of estimated and reported emissions of PM_{2.5}, the project also deals with PM_{2.5}.

The overall project objectives are to:

- Increase the knowledge on emissions of SLCP (primarily BC/PM_{2.5}, but also CH₄, CO and NMVOC) from Nordic sources.
- Identify mitigation actions to reduce emissions of BC in the Nordic countries.
- Coordinate/cooperate with other relevant international activities, e.g. emission inventory work within TFEIP (Task Force on Emission Inventories and Projections) under CLRTAP as well as groups within the Arctic Council.
- Provide support to the Nordic negotiators in the “Task Force for action on Black Carbon and Methane (TFBCM)” which was established at the Arctic Council meeting of foreign ministers in Kiruna, May 2013.

The project is planned for a 3 year period, 2013–2016, and includes the following main steps:

- Background analysis.
- Design of measurement program.
- Emission measurements.
- Development of emission factors and emission inventories.
- Suggestions for abatement measures for reduced emissions of SLCP in the Nordic countries.

Four reports will be produced:

- Report 1, Background analysis, autumn 2014. Screening of earlier work, identification of knowledge gaps, recommendations for prioritising measurements.
- Report 2, Measurements, July 2015. Measurement results, recommended emission factors and inventory methodology for the Nordic countries.
- Report 3, Abatement measures, December 2015. Suggested abatement measures for the Nordic countries.
- Final report, April 2016. Final summary report for the project, including recommendations for further work in the Nordic countries.

This current report is the first in the series and presents the result of the background analysis performed as a literature review and includes a compilation of results from previous emission inventories and emission measurements. It includes a survey of sources of SLCP in the Nordic countries and identifies knowledge gaps where measurements may improve future emission inventories. The report discusses methods for estimation of emission of PM_{2.5} and BC, as well as the measurement methods underlying the emission factors for PM_{2.5} and BC. It also includes a discussion on the contribution from international shipping to emissions of SLCP in the Nordic area. Finally, the report discusses strategies for the measurement program for PM_{2.5} and BC in the next step of the project.

2.2 Other relevant projects and processes

CLRTAP TFEIP – Convention on Long-Range Transboundary Air Pollution, Task Force on Emission Inventories and Projections. Provides methodological guidance for emission inventories and supports Parties in reporting of air emissions and projections to the Convention by providing a technical forum and expert network.

Arctic Council TFBCM – Task Force for action on Black Carbon and Methane. Was established at the Arctic Council meeting of foreign ministers in May 2013. The mandate of the TFBCM is to develop arrangements on actions to achieve enhanced black carbon and methane emission reductions in the Arctic. The Task Force had its first meeting in September 2013 and will report to the Ministerial Meeting in 2015.

EU – Eco design directive. The Ecodesign Directive provides with consistent EU-wide rules for improving the environmental performance of energy related products (ERPs) through ecodesign. It prevents disparate national legislations on the environmental performance of these products from becoming obstacles to the intra-EU trade. Currently negotiations are ongoing regarding for example Energy-using products (EUPs) such as solid fuel boilers and local space heaters. The results of these negotiations will have an impact on the future required performance of residential combustion appliances.

The Commission for Environmental Cooperation (CEC) (includes USA, Canada, Mexico) – *North American Black Carbon Emissions Estimation Guidelines.* To be developed in a two-year project starting spring 2014. The project involves three main tasks:

- A review of black carbon emissions estimation methodologies available or in use in North America and around the world.
- A series of consultations with emission estimation experts to identify and develop consensus recommendations, including consultations with experts participating in the LRTAP Convention (EMEP/TFEIP) and the Climate and Clean Air Coalition (CCAC).
- The development of a document that will provide guidance on estimating black carbon emissions from individual source types that can be applied by the three North American countries.

A project under *ACAP* (Arctic Contaminants Action Program) – “Reduction of Black Carbon emissions from residential wood combustion in the Arctic”. The project covers Black Carbon inventory, abatement instruments and measures.

During the course of the project contacts have been maintained with all of the above ongoing projects and processes. For example, project progress and interim results were presented and discussed at the TFEIP meeting in May 2014 in Ghent. Regarding TFBCM, a presentation of the CLRTAP reporting and review process was given at one of the TFBCM meetings, and comments have been submitted on the proposed reporting and review cycle in the TFBCM negotiations. We have kept ourselves updated regarding the measurement methods proposed in the Eco-design negotiations for solid fuel boilers and local space heaters, and for the North American Black Carbon Emission Estimation Guidelines we have participated in the expert group created to review and comment the proposals developed in the North American project.

3. Current emission inventories of SLCP in the Nordic Countries

National official emission inventories for air pollutants, including PM_{2.5}, CO and NMVOC, are annually reported from all Nordic countries to the Convention on Long-Range Transboundary Air Pollution, CLRTAP,¹ under the EU National Emission Ceilings Directive NECD, and national emissions of greenhouse gases, including CH₄, to the United Nations Framework Convention on Climate Change, UNFCCC.² Black carbon, BC, is not yet part of the reporting program, but from submission 2015 it will be included as voluntary reporting to CLRTAP as a consequence of BC being highlighted in the revised Gothenburg protocol from May 2012. Revised Reporting Guidelines, including BC, were adopted in December 2013 by the Executive Body of CLRTAP.

For reporting of emission inventories of air pollutants to LRTAP, methodological guidance is provided by TFEIP (Task Force on Emission Inventories and Projections), which supports Parties in reporting of air emissions and projections to the Convention by providing a technical forum and expert network to identify problems and establish methodologies for the emission estimation. The EMEP/EEA Air Pollutant Emission Inventory Guidebook provides methodological and technical guidance for emission inventory compilation,³ and has recently been revised to include guidance also on black carbon.

For reporting of greenhouse gas emissions to the UNFCCC, methodological and technical guidance is provided in the 1996 and 2006 IPCC Guidelines for National Greenhouse Gas Inventories, and in the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.⁴

¹ <http://www.ceip.at/ceip/>

² www.unfccc.int

³ <http://www.eea.europa.eu/publications/emep-eea-guidebook-2013>

⁴ <http://www.ipcc-nggip.iges.or.jp/public/index.html>

Generally in an inventory emissions are calculated by the equation: $E = AD \times EF$, where E = emissions, AD = activity data and EF = emission factor for the specific substance. BC can be calculated with specific emission factors for BC or, which is more common, as a fraction of estimated emissions of $PM_{2.5}$. The revised EMEP/EEA Air Pollutant Emission Inventory Guidebook provides information on the fractions of BC in $PM_{2.5}$ for most of the relevant emission sources.

Emission inventories can be performed based on different levels of disaggregation regarding e.g. technologies, fuel type etc. The level of disaggregation of sources applied in an inventory depends on the availability of activity data and emission factors for the specific sources.

3.1 Denmark

Denmark annually produces inventories of CH_4 , NMVOC, CO and $PM_{2.5}$ that are reported to the UNFCCC and the UNECE. For BC, Danish Inventories and projections have been made for the years 1990–2030. This work, however, is now some years old (Winther & Nielsen, 2011).

3.1.1 Methodology

Denmark's air emission inventories are based on the EMEP/EEA Guidebook and is prepared at the more detailed SNAP level rather than at the NFR level that is only suitable for reporting.⁵ The background data (activity data and emission factors) for estimation of the Danish emission inventories is collected and stored in central databases located at the Danish Centre for Environment and Energy (DCE) at Aarhus University. The databases are in Access format and handled with software developed by the European Environmental Agency (EEA) and DCE. As input to the databases, various sub-models are used to estimate and aggregate the background data in order to fit the format and level in the central databases.

The activity data used in the Danish inventories come from a number of institutions and organisations, e.g. the Danish Energy Agency, Statistics Denmark, DTU (Technical University of Denmark) Transport and the Danish Centre for Food and Agriculture. The emission factors are in most cases

⁵ Source Nomenclature for Air Pollutants (SNAP) is a technology based source classification for air pollutant emission inventories.

either country specific or refer to the EMEP/EEA Guidebook. The largest sources of NMVOC, CO, PM and BC emissions in Denmark are residential wood combustion and road transport. For residential wood combustion the emission factors refer to the EMEP/EEA Guidebook as well as Danish and Swedish studies. For road transport, Denmark uses the emission factors from the COPERT model. More information is available in the Danish documentation reports to the UNECE (Informative Inventory Report) and the UNFCCC (National Inventory Report).

3.1.2 Particulate matter and Black Carbon, $PM_{2.5}$ and BC

Estimated national emissions

For $PM_{2.5}$ the Danish inventory is not complete. Several sources of fugitive PM have not been estimated, e.g. emissions from mining/quarrying, construction/demolition, agricultural field work and landfills. In the current inventory the emissions are dominated by residential combustion (67%).

Figure 1. $PM_{2.5}$ emissions in Denmark 2000–2011 (Gg)

The trend in $PM_{2.5}$ emission is dominated by the trend in emissions from residential plants. Emissions from residential plants increased from 2000 to 2007 due to an increase in wood consumption that was so high that even though older technologies were being replaced with newer technologies with lower emission levels, the total emission level increased. From

2007 onwards the wood consumption stagnated and only showed a small increase in some years. Due to the replacement of old stoves and boilers this meant a reduction in the total emissions. The emissions from the transport sector have decreased due to the renewal of the vehicle fleet with legislation regulating the PM emissions from vehicles.

Inventories and projections of BC have been made for Denmark for the years 1990–2030. This work, however, is now some years old (Winther & Nielsen, 2011). The dominant sources are residential wood combustion (63%), road transport (20%) and other mobile combustion (14%). The emission is projected to decrease as a result of the implementation of newer technologies in the residential sector and stricter legislative requirements for PM for mobile sources which will have an emission effect on BC. In 2014, BC will be included as part of the regular emission inventory work. Hence, the inventory for BC will be updated taking into account new knowledge both from the updated EMEP/EEA Guidebook and from this project.

Uncertainties

The uncertainties regarding the emission inventory for residential wood combustion are substantial. The uncertainties are both related to the activity level and the emission factors. Regarding the activity data, a large part of the wood consumption is untraded. In Denmark the uncertainty has been reduced in later years since the Danish Energy Agency in cooperation with the Danish Environmental Protection Agency has initiated and expanded a biennial survey to investigate the wood consumption in residential plants. However, there is still considerable uncertainty regarding the wood consumption in residential plants. The emission factors are also uncertain. For PM_{2.5} there is a substantial number of measurements available, however, the variability in the reported measured data is significant. For BC there are fewer measurements available and therefore the uncertainty will be even higher.

For road transport, the uncertainties are lower than for the residential wood combustion sector. The Danish calculations use the European COPERT IV model methodology (EMEP/EEA, 2013). Emission factors for PM and BC fractions of PM are quite well described by this latter reference, and Danish fleet and mileage numbers (activity data) are accurate and detailed according to the vehicle layers defined in COPERT IV model.

For non-road mobile machinery, due to lack of detailed statistical data the machinery stock composition is less certain compared to the fleet description available for road transport. The emission factors from EMEP/EEA (2013) are less certain as well. PM emission factors for non-road machinery are represented by a relatively small number

of measurements and in some cases emission factors are assumed based on assessment of emission limit values from the EU directives. Due to very scarce emission data, and due to road-non road engine similarities, the source for non-road BC emission information is in many cases road transport.

For navigation, the Danish national estimates are based on fuel sold, and hence the shipping activity data have a good precision which appears from the Danish energy statistics. The PM emission factors rely on fuel sulphur content, and this PM-sulphur relation is regarded as relatively certain. For BC, the emission data are less certain; currently there is a large variation in the BC fraction of PM reported by different measurement studies, c.f. EMEP/EEA (2013), and more measurements are needed in order to obtain a more consolidated picture of BC emissions from ship engines.

3.1.3 Methane, CH₄

The inventory of CH₄ is considered relatively certain being dominated by agriculture and waste emissions. Emissions from combustion cover a small part of the total emissions (< 7%) and are mainly related to combustion of natural gas in gas engines and from residential wood combustion.

Figure 2. Methane emissions in Denmark 2000–2011 (Gg)

The trend in CH₄ emissions shows a very stable total emission. The emissions from enteric fermentation have decreased due to a decrease in the number of cattle while emissions from manure management have increased due to a shift towards slurry based animal waste management systems. CH₄ emissions from solid waste disposal on land decreases, this is a result of more waste being incinerated rather than landfilled.

3.1.4 Non-methane volatile organic compounds, NMVOC

Regarding NMVOC the challenge is the many sources contributing to this category, e.g. solvent use (33%), residential combustion (18%), transport (16%), and emissions from oil/gas (11%). Several of these sources are associated with significant uncertainties. In addition the Danish inventory at the moment does not consider NMVOC emissions from animal husbandry and manure management. The data available in the EMEP/EEA Guidebook suggest that this will be a very important source.

The trend of NMVOC emissions shows significant reductions in the emissions from transport and solvent use. These reductions are a result of legislative regulation to limit the emissions from these sources. The emission from residential plants has increased due to an increase in the wood consumption, see the discussion in Chapter 2.1.2.

Figure 3. NMVOC emissions in Denmark 2000–2011 (Gg)

3.1.5 Carbon monoxide, CO

The CO emission inventory has not been given a lot of attention since it is not covered by any reduction commitments. Mobile combustion and residential combustion dominates the emissions. The emission estimate for residential combustion is very uncertain.

Figure 4. Carbon monoxide emissions in Denmark 2000–2011 (Gg)

The trend of CO emissions shows a large decrease in emission from transport due to legislative demands and an increase in emissions from residential plants due to the aforementioned increase in wood consumption in residential stoves and boilers. The emission from commercial and institutional plants has increased due to an increase in the biomass consumption in this sector.

3.2 Finland

3.2.1 Methodology

The Finnish air pollutant emission inventories are prepared in accordance with the EMEP/EEA Emission Inventory Guidebook and the inventory for greenhouse gases in accordance with IPCC methodologies. National methods and emission factors, as well as emission data reported by the plants according to their environmental permits are used in the

inventory when available. The inventories and projections are reported annually under the UNFCCC, the UNECE and the EU.

Detailed documentation of the inventories can be found through the EIONET CDR website in the relevant NIR and IIR reports. The inventories are largely bottom up and include data reported by the plants, where available, or emissions calculated at SNAP level using sector specific calculation models,⁶ which are located at research institutes (VTT, Metla, MTT)⁷ or at inventory agencies (SYKE for air pollutants and Statistics Finland for greenhouse gases).

Residential wood combustion

A national methodology is used to estimate emissions from residential combustion. The method takes into account:

- Activity sector where wood is combusted.
- Shares of wood (firewood, wood chips and pellets) combusted in different equipment.
- Shares of normal and bad combustion conditions.
- User influence through the shares of normal and bad combustion conditions (the share of fuel as well as the impact on emission factors), which are estimated separately for each pollutant for 13 technologies.
- The development of technology over time.

3.2.2 Particulate matter: $PM_{2.5}$ and BC

Estimated national emissions

The main sources for $PM_{2.5}$ emissions in Finland are the energy sector (approximately 60%), road transport (25%) and industrial processes (10%). Almost half of the energy sector emissions originate in residential combustion of wood.

⁶ Source Nomenclature for Air Pollutants (SNAP) is a technology based source classification for air pollutant emission inventories.

⁷ VTT State Technical Research Centre, MTT Agrifood Research Finland, Metla Finnish Forest Research Institute.

Particulate matter emissions fluctuate from year to year due to variations in energy consumption, which is affected by the level of imported electricity and fossil fuel based condensing power in annual energy production. Energy consumption reflects the energy intensity of the Finnish industry (forest industry, chemical industry and manufacture of basic metals), extensive consumption during the long heating period, as well as energy consumption in the transport sector due to long distances in the sparsely inhabited country. During the last decades large decreases in specific emissions have been achieved through implementation of abatement techniques especially in peat and oil combustion.

Finland carried out the first black carbon inventory for 2000–2012 in autumn 2013 and the preliminary results voluntarily reported under the CLRTAP may change to the first official reporting under the CLRTAP in February 2015. In the preliminary inventory, the key sources for black carbon were transport (60%), where road transport contributed to 54% and off-road machinery to 44%, and the energy sector (40%), where 96% of the emissions originated in residential combustion.

PM_{2.5} and BC emission time series for 2000–2011 are presented in Figure 5 and 6, respectively. Note that the sources of PM_{2.5} are not equal to sources of BC. Peat production, for instance, which dominates the fugitive emissions of PM_{2.5}, is not a source for BC.

Figure 5. PM_{2.5} emissions in Finland 2000–2011

Figure 6. Black carbon emissions in Finland 2000–2011

Emissions from the energy and industrial processes sectors are for the large plants based on TSP emissions reported by the operators. PM₁₀ and PM_{2.5} emissions are calculated as fractions of TSP while BC emissions are calculated as fractions from PM_{2.5} emissions. For the smaller plants country-specific emission factors or Guidebook methods are used together with statistical data or data collected from industry associations or through surveys.

BC emissions for mobile combustion are calculated using emission factors from EMEP/EEA Emission Inventory Guidebook (2013) and for tyre wear, brake wear and road abrasion using methods from the Norwegian inventory (Aasestad, 2013).

For product use particle emissions are calculated using statistical data and country-specific emission factors or Guidebook methods. The only source for BC emissions in the agricultural sector is on-field burning of stubble and straw and these emissions are calculated using the method from the Norwegian inventory (Aasestad, 2013). Detailed information on the methods used to estimate PM_{2.5} and BC emissions is provided in the Finnish IIR.

In the waste sector TSP emissions reported by the plants are used for calculation of PM_{2.5} emissions, BC emissions are calculated from PM_{2.5} emissions.

No legislation in Finland specifically target BC and OC emissions, although these emissions are considered by a number of policy initiatives (e.g., Arctic Council, UNECE). Because BC is co-emitted with pollutants that are controlled by current legislation (e.g. PM_{2.5}), reductions are expected in several sectors. Air pollution control legislation in Finland is largely 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. 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. For factory-made stoves the CE-labelling since 1st January 2012 requires that the appliances need to meet the requirements in the EN test standards, which are currently available for kitchen ranges (EN 12815), hand fed solid fuel fired inset appliances (EN 13229), roomheaters fired by solid fuel (EN 13240), slow heat release appliances fired by solid fuel (EN 15250) and for sauna stoves.

Uncertainties

The uncertainty for the PM_{2.5} emission inventory for the year 2011 was estimated at -41.50%. The highest uncertainties were estimated to be in the industrial processes and in the agriculture sectors. Detailed information of the uncertainty assessment is provided in the Finnish IIR. The first uncertainty analysis for BC will be carried out later in 2014.

3.2.3 Methane, CH₄

Waste sector and agriculture are the most important sources of methane emissions (both about 45% in 2011). Emissions are calculated from statistical data and country-specific or IPCC default emission factors.

Methane emissions have been decreased by 33% from the 1990 level. This is mainly due to improvements in waste treatment and a contraction in animal husbandry in the agriculture sector.

Figure 7. Finnish methane emissions 2000–2011 (Statistics Finland, official submission under the UNFCCC)

3.2.4 Non-methane volatile organic compounds, NMVOC

NMVOC emissions are generated mainly in the energy sector (~50%), while transport and solvent and other product use sector both contribute to 20%, and industrial processes to less than 10% of emissions (Figure 8). Small scale combustion covers 60% of emissions from the energy sector. Emissions have been decreased especially in the transport sector due to catalyst techniques in new cars since 1990 and in the product use sector impacted mainly by the introduction of water-based paints.

The uncertainty of emissions has been estimated at -26.27%, and is the highest in the transport sectors.

National or Guidebook methods have been used in the inventory, as well as questionnaires to plant operators or annual emission reports by the plants, when available. Detailed information on the methods used to estimate emissions as well as on the uncertainty assessment is provided in the Finnish IIR.

Figure 8. NMVOC emissions in Finland 2000–2011

3.2.5 Carbon monoxide, CO

The main contributors to carbon monoxide emissions are the energy and transport sectors (58% and 40% in 2011, respectively). Small combustion contributes to approximately 40% of the energy sector emissions. Emissions have been decreased especially in the transport sector resulting from the increased amount of cars with catalytic converters.

The uncertainty emissions has been estimated at -31.37%. The highest uncertainties were estimated in the transport, industrial processes and waste sectors.

For the energy and industrial processes sectors carbon monoxide emissions are often reported by the plants, and while not reported, calculated using EMEP/EEA Guidebook methods. Detailed information on the methods used to estimate emissions as well as on the uncertainty assessment is provided in the Finnish IIR.

Figure 9. CO emissions in Finland 2000–2011

3.3 Iceland

Iceland annually produces inventories of CH₄, NMVOC and CO that are reported to the UNFCCC and CLRTAP. No inventories for PM_{2.5} or BC are available.

3.3.1 Methodology

The Icelandic inventories are prepared in accordance with IPCC methodologies and guidelines and are in accordance with IPCC's Good Practice Guidance. National methods and emission factors are used in the inventory when they are available. The activity data in Icelandic inventories come from many sources, both from individual plants and operators and governmental agencies such as Statistics Iceland and the Icelandic Energy Authority. The inventories are compiled and calculated at the Environmental Agency of Iceland.

3.3.2 Particulate matter and Black Carbon, PM_{2.5} and BC

There are no official inventories for PM_{2.5}. The estimated main sources are road transport, construction/demolition, agricultural fieldwork and the fishing industry. Natural sources for PM_{2.5} are severe erosion in many parts of the country and wildfires. 96% of all houses in Iceland are heated with geothermal energy and the majority of the remaining 4% are heated by electricity and an ever decreasing number by oil, so residential combustion is a limited source.

There are no official inventories for BC in Iceland. The estimated main sources are road transport and the fishing industry which collectively may account for more than 80% of all BC emissions (expert judgement). Other possible emission sources are agricultural fieldwork and other off road activities. A national inventory for both BC and PM_{2.5} are on the long term plan of the inventory team at the Environmental Agency of Iceland.

3.3.3 Methane, CH₄

The inventory for methane is considered to be complete with agriculture and waste treatment the main sources of methane emissions since 2000 (Figure 10). The main methane source in the agricultural sector is enteric fermentation, in the waste sector solid waste disposal on land. Together they account for around 90% of sector methane emissions. Emissions from agriculture has decreased by 7% since 1990 due to an gradual decrease in livestock populations, but increased by 32% from the waste sector in the same period, mainly due to changes in waste management with an ever larger share of waste going into well managed solid waste disposal sites.

Figure 10. Emissions of methane (Gg) in Iceland 2000–2011

3.3.4 Non-methane volatile organic compounds, NMVOC

The main sources of non-methane volatile organic compounds are transport and solvent use. Emissions from transport are dominated by road transport. These emissions decreased rapidly after the use of catalytic converters in all new vehicles became obligatory in 1995. Emissions from solvent use have been mostly stable for the same period. Other emission sources include food processing and drink production.

3.3.5 Carbon monoxide, CO

Transport is the most prominent contributor to CO emissions in Iceland with road transport the main source. These emissions have decreased rapidly since 1995 when catalytic converters became obligatory in all new vehicles. Since residential combustion is on a small scale in Iceland it is not a significant emission source.

3.4 Norway

Norway annually produces inventories of CH₄, NMVOC, CO and PM_{2.5} that are reported to the UNFCCC and the UNECE. In 2013 the first inventory of BC was made for the years 1990–2011 (Aasestad, 2013).

3.4.1 Methodology

Emission estimates are mainly based on data from Statistics Norway. The general emission model is based on equation (2.1).

(2.1) Emissions (E) = Activity level (A) – Emission Factor (EF)

For emissions from *combustion*, the activity data concern energy use. In the Norwegian energy accounts, the use of different energy products is allocated to industries (economic sectors). In order to calculate emissions to air, energy use must also be allocated to technical sources (e.g. equipment). The energy use data are combined with a corresponding matrix of emission factors. In principle, there should be one emission factor for each combination of fuel, industry, source, and pollutant.

Emissions of some pollutants from major manufacturing plants (point sources) are available from measurements or other plant-specific calculations. When such measured data are available it is possible to replace the estimated values by the measured ones.

(2.2) Emissions (E) = [(A - A_{PS}) · EF] + E_{PS}

Where A_{PS} and E_{PS} are the activity and the measured emissions at the point sources, respectively.

Emissions from activity for which no point source estimate is available, are estimated based on activity data and emission factor, using equation 2.1.

Non-combustion emissions are generally calculated by combining appropriate activity data with emission factors according to equation 2.1. Some non-combustion emissions are available from measurements or other plant-specific calculations (equation 2.2).

The main source for calculation of emissions from energy combustion is the energy balance, which annually is prepared by Statistics Norway. Many different sources are utilised in the preparation of the energy balance. E.g., energy use in extraction of oil and gas, which constitutes an important part of Norwegian energy use, is reported from the Norwegian Petroleum Directorate. Other energy producers, such as oil refineries and district heating plants, also report their own energy use to Statistics Norway. However, for some major manufacturing plants, emissions of one or more compounds, reported to the Norwegian Environment Agency from the plants, are used instead of calculated figures. Other important sources are the European Union Emission Trading Scheme (EU ETS), the operators annual legal environmental reports, agricultural and forestry statistics, as well as data on production (e.g. cement) and consumption (e.g. fluorinated gases: F-gases) obtained directly from the major producers and consumers, respectively.

Emission factors used are either developed nationally or are internationally recommended default factors. The calculation methods used are, as far as possible, in accordance with the strict demands formulated in the international emission conventions.

Uncertainties

The uncertainty in the Norwegian greenhouse gas emission inventory has been investigated by a tier 2 analysis in 2011 (Flugsrud and Hoem, 2011). The uncertainty in the Norwegian emission estimates of long-range air pollutants was investigated in 2001 (Rypdal and Zhang 2001).

Uncertainty in activity data

The uncertainty in the national emission inventory depends on the uncertainty in activity data and in emission factors. The activity data in the Norwegian national inventory are collected and compiled by Statistics Norway, using surveys and statistical methods to produce figures of national fuel consumption of different fuels in different sectors. Generally, the uncertainty in activity data is assumed to be low for fuels traded on the market and the fuelwood used in households. The heat and power industry as well as the manufacturing industries have good records of their fuel use, and report this annually. Activity data under those conditions can be assumed to have a low uncertainty level, in the order of 2–5%. The uncertainty in the activity data is $\pm 3\%$ of the mean for oil, $\pm 4\%$ for gas and $\pm 5\%$ of the mean for coal/coke and waste. An uncertainty analysis was conducted in 2011 for wood consumption in households. The coefficient of variation of the estimated total consumption in Norway is a little less than 3%. For fuel use in the mobile sectors the national overall fuel consumption can be assumed to have a quite low uncertainty, while the uncertainty in activity data increases when this total amount is disaggregated and allocated to different end uses.

Uncertainties in emission factors, completeness etc. are described under each component.

3.4.2 Particulate matter and Black Carbon, $PM_{2.5}$ and BC

Estimated national emissions $PM_{2.5}$

Emissions of fine particles ($PM_{2.5}$) was 36,700 tonnes in the year 2011 (see Figure 11). There is a reduction of 12% since 1990. 58%, or about 21,400 tonnes, of the emissions of particulate matter ($PM_{2.5}$) in 2011 came from residential wood-burning. The wood consumption decreased by 12% from 2010 to 2011. At the same time, the calculated emissions of particulate matter from this source decreased by 13%. This is due to a higher share of wood stoves with new technology. Process emissions from manufacturing and mining amounted to 4,400 tonnes, or 12% of the emissions of fine particles ($PM_{2.5}$) in 2011. Motorized equipment and coastal navigation were responsible for 8 and 6% of the emissions of $PM_{2.5}$ respectively.

Figure 11. Trends in PM_{2.5} emissions in Norway, 2000–2011 (Gg)

Estimated national emissions of BC

The Norwegian estimates of the BC (and OC) emissions are mainly based on estimated fractions of officially reported national emissions of particulate matter, PM_{2.5}, to the Convention on Long-Range Transboundary Air Pollution (LRTAP) and work done by the International Institute for Applied Systems Analysis (IIASA). Everywhere where the Norwegian inventory estimates emissions of PM_{2.5} (Finstad, Haakonsen *et al.* 2003), it has been considered whether there also are emissions of BC and OC. Emissions of BC are estimated on source and fuel basis. Source specific emission factors have been used for wood combustion in residential sector and for flaring, in order to estimate other emissions on a source and fuel basis, fractions of BC of emitted PM from IIASA have been used in combination with Norwegian PM_{2.5} emission factors.

The most important sources for BC, according to the estimates are presented in Figure 12. Estimated total emissions in Norway of BC were 5,100 tonnes in 2011. This is the same level as in 1990. The percentages of BC emissions from different sectors for 2011 are presented in Figure 13. Heating in households is the main source and contributed to 1,205 tonnes or 23% of total BC emissions in 2011, and 20% in 1990. Between 1990 and 2009 the BC emissions from the domestic sector has increased by 18%. In the same period consumption of wood has increased by 26%. Stoves with new technology (stoves manufactured after 1998) produce fewer airborne particles and are more energy-efficient than stoves with the old technology. The BC emissions from heating in

households rose by 12% from 2009 to 2010. The wood consumption rose by 11%.

Road traffic was responsible for 780 tonnes, or 15%, of the BC emissions in 2011, compared to 17% in 1990. The actual emissions decreased by 8%. Emissions from diesel passenger cars were 3.8 times higher than in 1990. Emissions from heavy duty diesel vehicles have decreased by 47% during the same time period. Since 1990, traffic has grown by more than 50%. Domestic sea transport and fishing were responsible for 910 tonnes or 18% of the BC emissions in 2011. The emissions were 11% higher in 2011 than in 1990. Oil and gas activities were responsible for 12% of the BC emissions in 2011, approximately the same percentage as in 1990 (13%). Emissions from manufacturing industries and mining were 60% lower in 2011 than in 1990, and while these emissions constituted 8% of the total in 1990, the share was reduced to 3% in 2011. Emissions from motorized equipment contributed 1,220 tonnes or 24% of the emissions of black carbon in 2011. The calculations show that the emissions have increased by more than 50% from 1990 to 2011. The uncertainty is particularly high for emissions from motorized equipment.

Figure 12. Emissions of Black Carbon (BC) to air by source in Norway, 2000–2011 (1,000 tonnes)

Figure 13. Distribution of BC emissions between sources, 2011 (per cent)

Uncertainty due to lack of completeness, PM_{2.5}

With regard to sectoral coverage, the following sources with relevant emission amounts are not covered in the inventory even if emissions can be expected:

- Energy sector:
 - Emissions of particulate matters from clutch wear (1A3b).
 - Emissions of particulate matters from use of unpaved roads (1A3b).
 - Emissions of particulate matters from sand strewing (1A3b).
- Waste sector:
 - Emissions of particulate from burning of bonfire and emissions of particulate matters from burning of animal carcasses and burning of waste in household stoves (6C).

The reasons for not including these emission sources are mainly lack of activity data, emission factors or known calculation methodology.

Uncertainty in emission factors BC /EC (elemental carbon)

For residential small scale combustion, closed stoves, the uncertainty for the emission factors for EC and OC are estimated to 5–7% (Seljeskog, Goile *et al.* 2013). Actual emissions depend on several factors such as heating habits, wood consumption and types of appliances. Emission factors for PM can vary by several orders of magnitude.

For the other sectors, there are no estimated uncertainties for the emission factors for BC. For mobile sources we assume that the lowest emission factor uncertainty is found in road transport emissions, while the emission factors for off-road machinery and navigation/shipping are as-

sumed to be higher. Emissions from motorized equipment are considered to have the largest uncertainty, due to uncertain usage of taxfree diesel.

The uncertainties in the BC emission factors given by IIASA, and used in the calculations of Norwegian BC emissions are not known. According to Kupiainen & Klimont, 2004 there are significant uncertainties in BC emission estimates. For future work they recommend that one of the main tasks in the future will be to reduce these uncertainties.

Uncertainty due to lack of completeness BC

As the estimated emissions of PM is the basis for calculation of BC emissions, an uncertainty and possible underestimation of PM emissions also influences the estimated emissions of BC.

These sources are included in the Norwegian emission inventory for at least one pollutant, but are not included in the PM emission inventory, and hence not in the BC inventory:

- Asphalt production plants.
- Road traffic: Motor cycles and mopeds.
- Off-road machinery: Snow scooter.
- Railway contact wire abrasion.
- Oil and gas extraction:
 - Cold flaring and leakage, offshore (process emissions).
 - Oil loading, offshore (process emissions).
 - Oil loading, onshore (process emissions).
 - Gas terminals, onshore (process emissions).

Process emissions from these sources are included in the Norwegian PM_{2.5} emission inventory, but are not included in the BC inventory:

- Petrochemistry.
- Fertilizer.
- Carbides.
- Chemical industry, other.
- Other metals.
- Other mining.
- Agriculture, other.
- Oil refining.

It is assumed that carbonaceous particulate emissions from most of the processes in petrochemistry, production of fertilizers, production of non-ferrous metal probably are small and therefore zero emissions are assumed for the time being (Kupiainen and Klimont 2004).

According to the updated EMAP/EEA Guidebook 2013, no emissions of BC are assumed to occur for production of carbides.

“Agriculture other” includes various types of non-combustion emissions of particles. This is for example dust from crops that are harvested, soil dust from work with agricultural machines, wood particles from felling of trees etc. It is assumed that BC does not occur in these processes.

Uncertainty in method BC

To ensure that the emissions of BC in the Norwegian inventory do not exceed the PM_{2.5} emissions, the emission factors for BC are estimated as shares of the PM_{2.5} emission factors based on information from IIASA. This may lead to underestimation for some sources if the Norwegian emission factor for PM is too low.

If the emission factors used by IIASA do not fully reflect the Norwegian conditions, using the share of BC to PM_{2.5} may in some situations be better than using the emission factor used by IIASA. If the emission factor used by IIASA reflects Norwegian conditions better than the share used in the inventory, this will make the emissions estimated more uncertain.

For sources where emission factors for BC were not available, the following equation has been used if emissions of BC are expected to occur:

$$PM_{2.5} = BC + OM + Z$$

Where Z = inorganic compounds, and where it is assumed that OM = F*OC, where F =1.4 (Factor for OC to organic mass). F is not 1.4 for all sources (although it is assumed for several). The factor may vary depending on the origin and age of the OM. The factor is usually between 1.2 and 1.8. In the GAINS-model F is assumed to be 1.8 for burning of fuelwood, and 1.2 or 1.3 for diesel combustion (pers. comm. IIASA 2012).⁸

⁸ E-mail from Zigniew Klimont IIASA 12th June 2012.

3.4.3 Methane, CH₄

Emissions of CH₄ were 204,000 tonnes in 2011. More than fifty per cent, or about 106,000 tonnes, of the emissions of methane in 2011 came from agriculture. Landfill gas was the second most important source and contributed to 51,000 tonnes or 25% of the emissions in 2011. Emissions from oil and gas extraction amounted to 29,000 tonnes, or 14% of the emissions of methane in 2011. Heating in household and costal navigation were responsible for 3 and 2% of the emissions respectively. Methane emissions have decreased by 14% between the years 1990 and 2011. This is mainly due to reduced amounts of waste deposited at municipal solid waste disposal sites and due to lower emissions from agriculture.

Figure 14. Trends in CH₄ emissions in Norway, 2000–2011 (Gg)

Uncertainty in emission levels

The national emissions of CH₄ (LULUCF sector excluded) in 1990 are estimated with an uncertainty of 17% of the mean. The uncertainty level was 14% of the mean in 2009.

Uncertainty in emission trends

The decrease in the total CH₄ emissions from 1990 to 2009 is 9%, with an uncertainty in the trend on ±10 percentage points.

3.4.4 Non-methane volatile organic compounds, NMVOC

Emissions of non-methane volatile organic compounds (NMVOC) were 136,000 tonnes in 2011. The NMVOC emissions are distributed between most source categories, and in 2011 the source which include solvent use, was the largest one comprising 31%. Emissions from oil and gas extraction, loading of crude oil offshore, was the second most important source and contributed to 35,000 tonnes or 26% of the emissions in 2011. Emissions from motorized equipment and manufacturing industries and mining were responsible for 11 and 10% of the emissions respectively.

NMVOC emissions have declined by 54% between the years 1990 and 2011. This is mainly due to reduced emissions within crude oil loading and due to lower emissions from passenger cars. Stricter emission standard for petrol passenger cars have led to reduced emissions. In addition, the increased share of diesel cars within the vehicle fleet has strengthened the downwards trend.

Figure 15. Trends in NMVOC-emissions, Norway, 1990–2011 (1,000 tonnes)

Uncertainty NMVOC

The uncertainty in estimated emission level of NMVOC in 2010 was 15% of the mean, while the uncertainty in emission trend 1990–2010 was estimated to be 13%.

For stationary combustion and activities connected to oil and gas production, the uncertainty has been assessed to ± 40 –50%. Point sources do not report NMVOC from stationary combustion and the emissions are estimated using emission factors.

Emissions from loading of oil offshore are considered more uncertain than loading on shore (Rypdal 1999). The uncertainties are 30 and 40%, respectively, due to high variability and difficulties in performing measurements. Emissions from on shore activities are considered to be less variable.

Emissions from gasoline distribution are difficult to estimate. The uncertainty is assessed to be $\pm 50\%$ based on EEA (2000). Uncertainties in emissions from solvent use were in Rypdal (1995) assessed to be $\pm 30\%$.

Emission factors for road traffic have been determined from national and international literature (Bang *et al.* 1999) and take into account actual technology in use as well as changes in this technology. Uncertainties are reflected by the spread in available data as well as uncertainty in the effect of ageing in engines and the relationship between standardised emission cycles and vehicles in use. Uncertainties have been assessed in cooperation with national experts.⁹ More emission data are available for vehicles meeting modern emission standards and this is reflected in a lower uncertainty ($\pm 25\%$) compared to older technologies ($\pm 30\%$). The uncertainty for passenger cars and heavy duty vehicles is assessed to be about the same, while emissions from light duty vehicles have been assigned an uncertainty of ($\pm 30\%$) for all technologies. Motorcycles have been assessed to have somewhat higher uncertainty ($\pm 40\%$) due to more limited measurement data. For other mobile vehicles there are less measurement data.

Source for the uncertainty estimates for long-range transboundary air pollutants is Rypdal and Zhang (2001).

Uncertainty due to lack of completeness NMVOC

With regard to sectoral coverage, the following sources with relevant emission amounts are not covered in the inventory even if emissions can be expected:

- Industry sector:
 - Emissions of NMVOC from asphalt roofing (2A5) and NMVOC and PAH from road paving with asphalt (2A6).
 - Emissions of NMVOC from ammonia production (2B1).
 - Emissions of NMVOC from Nitric acid production (2B2).

⁹ Arild Skedsmo, Institute of Technology, pers. comm.

- Emissions of NMVOC from the pulp and paper industry (2D1).
- Agricultural sector:
 - Emissions of NMVOC from manure management (4B).
 - Emissions of NMVOC from agricultural soils (4D).
 - Emissions of NMVOC from field burning of agricultural wastes (4F).
- Waste sector:
 - Emissions of NMVOC from solid waste disposal on land (6A).
 - Emissions of NMVOC from waste-water handling (6B).

The reasons for not including these emission sources are mainly lack of activity data, emission factors or known calculation methodology.

3.4.5 Carbon monoxide, CO

Emissions of Carbon monoxide, CO were 309,000 tonnes in 2011. Road traffic used to be the main source of carbon monoxide emissions in Norway, but today wood-firing is contributing the most, 42%. Emissions from road transport and motorized equipment were responsible for 21 and 17% respectively. Norway has no international commitments regarding this pollutant.

There has been a decline almost every year since 1990, CO emissions have declined by 59% between the years 1990 and 2011. Emissions have decreased especially in the transport sector resulting from increased amount of cars with catalytic converters.

The uncertainty of 2011 emissions was estimated at -31.37%. The highest uncertainties were estimated in the transport, industrial processes and waste sectors.

Figure 16. Trends in CO emissions in Norway, 2000–2011 (1,000 tonnes)

Uncertainty due to lack of completeness, CO

With regard to sectoral coverage, the following sources with relevant emission amounts are not covered in the inventory even if emissions can be expected.

- Waste sector:
 - Emissions of CO from solid waste disposal on land (6A).

3.5 Sweden

Sweden has inventories of CH₄, NMVOC, CO and PM_{2.5} and the inventories are reported to UNFCCC and CLRTAP. During 2014 a national emission inventory of BC has been developed for the time series from 2000–2012 and it will be reported to CLRTAP in 2015.

3.5.1 Methodology

Emission estimates are mainly based on data from national or official Swedish statistics, e.g. energy statistics, European Union Emission Trading Scheme (EU ETS), the operators annual legal environmental reports, agricultural and forestry statistics, as well as data on production (e.g. cement) and consumption (e.g. fluorinated gases: F-gases) obtained directly from the major producers and consumers, respectively.

Emission factors and thermal values used are either developed nationally or are internationally recommended default factors.

The methodologies used for Sweden's greenhouse gas and air emissions inventory are in accordance with the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)¹⁰ and, in general, in line with IPCC's Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (Good Practice Guidance).¹¹ Some parts of the methodologies are taken directly from the IPCC Guidelines, the Good Practice Guidance and the EMEP/EEA Air Pollutant Emission Inventory Guidebook,¹² Information from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)¹³ is used in some parts of the inventory.

3.5.2 Particulate matter and Black Carbon, PM_{2.5} and BC

Estimated national emissions

Emissions of fine particles (PM_{2.5}) was nearly 28 ktonnes in the year 2011 (Figure 17). The total emissions of PM_{2.5} is approximately on the same level for the whole time series 2000–2011. The largest source of emissions of PM_{2.5} is the energy sector (including transport). It contributed with approximately 76% of the emissions in 2011, followed by industrial processes with about 20%. The most dominating sources of PM_{2.5} in the energy sector are residential combustion in households (approximately 33% of the emissions within the energy sector) – and road traffic, including road abrasion and tyre and brake wear (approximately 29% of the emissions within the energy sector).

¹⁰ The IPCC Guidelines can be found at: <http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm>

¹¹ The Good Practice Guidance can be found at: <http://www.ipcc-nggip.iges.or.jp/public/gp/english/>

¹² The EMEP/EEA Guidebook can be found at: <http://tfeip-secretariat.org/unece.htm>

¹³ The 2006 IPCC Guidelines can be found at: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>

Figure 17. Emissions of PM_{2.5} in Sweden 2000–2011 (Gg)

The Swedish BC inventory (Skårman *et al.*, 2014) is based on the submission 2014 PM_{2.5} inventory together with BC emission factors expressed as percentages of the PM_{2.5} emissions, as available in the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EEA, 2013). The inventory includes emissions from year 2000 and onward.

The total emissions of BC were nearly 4.4 ktonnes in year 2011 (Figure 18), which corresponds to a reduction by about 10% since 2000. The largest source of emissions of BC is the energy sector (including transport). It contributed with approximately 95% of the emissions in 2011, followed by industrial processes which contributed with nearly 5%. The predominant sources of BC within the energy sector in 2011 were residential wood combustion (approximately 27%) and road traffic (approximately 25%, where heavy duty diesel vehicles dominates).

The most significant changes in emission levels between 2000 and 2011 can be found from residential wood combustion and road traffic. The BC emissions from residential combustion have increased by about 52% since 2000, mainly due to colder winters during later years compared to in the beginning of the period. BC emissions from road traffic were reduced by about 30% since 2000, due to the introduction of more stringent emission standards.

Figure 18. Emissions of BC in Sweden 2000–2011 (Gg)

Uncertainties

The combined uncertainty of PM_{2.5} for all sectors in submission 2013 was estimated to be 15%. The uncertainties are mainly related to the emission factors. The highest uncertainties can be found for the emission factors in the following subcategories: residential wood combustion (62%), asphalt roofing (100%), other mineral use (67%), other product use (75%), manure management (90%), pasture range and paddock manure (200%) and waste incineration (200%). Uncertainties for BC have not been evaluated.

3.5.3 Methane, CH₄

Estimated national emissions

The total emissions of methane, including emissions from LULUCF, totaled 237 ktonnes in 2011 (Figure 19), which is equivalent to 5.0 million tonnes calculated as carbon dioxide equivalents or 8% of total greenhouse gas emissions. Emissions have decreased by 20% since 2000, largely due to measures taken in the waste sector. Almost 60% of the emissions of methane (CH₄) originate from the agricultural sector. Around 30% is emitted in the waste sector and 12% is emitted in the energy sector.

Figure 19. Emissions of CH₄ in Sweden 2000–2011 (Gg)

Uncertainties

The uncertainties for CH₄ are mainly related to the uncertainties of the emission factors. The highest combined uncertainties can be found for the following subcategories: civil aviation (197%), railways (118%), military use (107%), navigation (196%), residential wood combustion (100%) and oil and natural gas (583%).

3.5.4 Non-methane volatile organic compounds, NMVOC

Estimated national emissions

In 2011, the emissions of non-methane volatile organic compounds (NMVOCs) totaled around 177 ktonnes, which corresponds to a reduction by about 20% since 2000. The energy sector (mainly road traffic, wood combustion in the residential sector) and the solvent and other product use sector are the dominant sources of emissions contributing with 48% and 44%, respectively (Figure 20). The most significant changes in emission levels between 2000 and 2011 can be found in road traffic and residential wood combustion. Emission from road traffic was reduced by about 66% since 2000 due to the introduction of new exhaust emission requirements. The emissions from residential combustion have increased by about 35% since 2000, mainly due to colder winters during the end compared to the beginning of the period 2000–2011.

Figure 20. Emissions of NMVOC in Sweden 2000–2011 (Gg)

Uncertainties

The combined uncertainty of NMVOC for all sectors in submission 2013 was 16%. The uncertainties are mainly related to the emission factors. The highest uncertainties can be found for the emission factors in the following sectors or subcategories: industrial processes (40–400%) and civil aviation and aviation (98–100%).

3.5.5 Carbon monoxide, CO

Estimated national emissions

Emissions of CO have decreased by almost one-half, from 825 ktonnes in 2000 to 570 ktonnes in 2011 (Figure 21). Carbon monoxide emissions from the energy sector decreased from around 800 ktonnes in 2000 to around 546 ktonnes in 2011, which corresponds to a reduction by about 20%. Around 96% of emissions come from the energy sector in which transport and residential wood combustion are the largest sources. They contribute about 30%, respectively.

Figure 21. Emissions of CO in Sweden 2000–2011 (Gg)

Uncertainties

The combined uncertainty of CO for all sectors in submission 2013 was estimated to be 15%. The uncertainties are mainly related to the emission factors. The highest uncertainties can be found for the emission factors in the following sectors: energy (19–100%), industrial processes (50–100%) and solvent and product use (101%).

3.6 International shipping emissions in Nordic inventories

According to the definitions of the UNECE and UNFCCC conventions, international shipping emissions include the emissions from fuels used by vessels of all flags that are engaged in international water-borne navigation. The navigation activities include journeys that depart in one country and arrive in a different country, and may take place at sea, on inland lakes and waterways and in coastal waters. International shipping emissions are estimated by using fuel activity data per fuel type from fuel statistics, and technology specific emission factors. The fuel activity data represents the fuel sales in a country for vessels (regardless of flag) with a foreign destination, as prescribed by the UNECE and UNFCCC conventions.

Emissions from international shipping are formally not included in the national total emissions reported from countries to LRTAP. International shipping emissions are however reported as memo items, separately from the national emissions. The relative importance of the SLCPs emitted from international shipping, as defined by the convention reporting, is presented in Table 1. The reported Nordic emissions from international shipping are comparable to 1% of Nordic reported land-based NMVOC emissions, 1% of CO emissions, less than 0.05% of aggregated Nordic CH₄ emissions and in the order of 10% or more of the PM_{2.5} emissions from the Nordic countries. Aggregated PM_{2.5} emissions for international shipping are underestimated as these emissions have not been estimated by all countries. BC emissions from international shipping, estimated by Denmark and Sweden, amount to 6–7% of land based Nordic emissions in later years. This implies that international shipping is not an insignificant source of PM and BC emissions in the Nordic area.

Table 1. Contribution from international shipping to the Nordic emissions of SLCPs (% of land based emissions)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
PM _{2.5} *	12	11	8	9	10	12	14	10	9	9	8	7
BC**	16	13	11	11	11	13	16	8	8	8	7	6
NMVOC	0.8	0.8	0.7	0.8	0.8	1.0	1.2	1.2	1.2	1.0	1.0	1.0
CO	0.8	0.7	0.7	0.7	0.8	0.8	1.0	1.0	1.0	0.8	0.8	0.8
CH ₄	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.03	0.03	0.04

* Includes estimates from Denmark, Norway and Sweden only.

** Includes estimates from Denmark and Sweden only.

The reported aggregated emissions of CO, PM_{2.5}, NMVOC, BC and CH₄ from international shipping from the Nordic countries are presented in Figure 22.

Figure 22. Nordic aggregated emissions of CO, PM_{2.5}, NMVOC, BC and CH₄ from international shipping, 2000–2011 (Gg). Data for PM_{2.5} from Denmark, Norway and Sweden; data for BC from Denmark and Sweden

4. Aggregated emissions of SLCP from the Nordic countries

The total aggregated emissions of SLCPs from the Nordic countries are presented for the time period 2000–2011 in the figures below. The figures include emissions from international shipping, which normally are not included in the estimated national total emissions.

The estimated total emissions of PM_{2.5} from the Nordic countries have been quite stable since 2000 (Figure 23 and Table 2). The largest contributing source is residential combustion (including all fuels) contributing more than 40% of the Nordic PM_{2.5} emissions.

Figure 23. Aggregated emissions of PM_{2.5} from the Nordic countries 2000–2011 (Gg)

Table 2. Aggregated emissions of PM_{2.5} from the Nordic countries 2000–2011 (Gg)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Energy prouction +combustion in industry	21	21	20	21	20	20	22	21	23	21	22	20
Road traffic, incl road abrasion	21	20	20	20	20	19	19	19	19	18	17	17
Off road mobile	10	10	10	10	9	9	8	8	8	7	8	8
National Shipping	4	4	4	4	4	4	4	4	3	4	4	4
Residential combustion	58	60	63	64	61	61	61	65	66	67	72	64
Industrial processes	17	16	16	14	17	17	15	15	14	10	11	12
Agriculture, waste, prod. use	6	6	6	6	6	6	6	5	5	5	5	4
International shipping*	17	15	12	13	14	16	19	14	13	12	11	10
<i>Total</i>	<i>154</i>	<i>153</i>	<i>150</i>	<i>151</i>	<i>151</i>	<i>152</i>	<i>154</i>	<i>150</i>	<i>149</i>	<i>143</i>	<i>149</i>	<i>147</i>

* Emissions from international shipping from Denmark, Norway and Sweden only.

The Nordic countries (except Iceland) have developed annual emission inventories of Black carbon from 2000. The aggregated data are presented in Figure 24 and in Table 3. Residential combustion is the major single source, contributing > 40% in later years. There are also significant contributions from road traffic (~20% in later years) and from off-road mobile machinery (~15%). Only Denmark and Sweden has estimated BC emissions from international shipping.

Figure 24. Aggregated emissions of BC from the Nordic countries 2000–2011 (Gg). International shipping includes data from Denmark and Sweden

Table 3. Aggregated emissions of BC from the Nordic countries 2000–2011 (Gg). International shipping includes data from Denmark and Sweden

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Energy industries	0.13	0.15	0.15	0.18	0.18	0.21	0.24	0.22	0.24	0.25	0.30	0.26
Energy other	1.33	1.45	1.32	1.26	1.26	1.34	1.41	1.41	1.34	1.30	1.37	1.36
Fugitive	0.58	0.64	0.42	0.36	0.35	0.36	0.38	0.77	0.71	0.41	0.54	0.40
Road traffic	6.50	6.28	6.04	5.98	5.85	5.69	5.64	5.64	5.32	4.88	4.71	4.46
Off-road mobile	4.98	4.93	4.65	4.51	4.39	3.97	3.85	3.80	3.64	3.36	3.50	3.44
National Shipping	1.45	1.34	1.35	1.44	1.40	1.41	1.35	1.36	1.27	1.38	1.38	1.32
Residential combustion	7.47	8.03	8.25	8.78	8.70	9.14	9.40	10.3	10.2	10.5	10.7	9.50
Industrial processes	0.36	0.36	0.37	0.33	0.39	0.36	0.35	0.31	0.27	0.17	0.22	0.25
Agriculture	0.13	0.10	0.08	0.07	0.07	0.06	0.05	0.05	0.05	0.03	0.04	0.03
Waste	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.01	0.02	0.01
Internat. shipping*	4.2	3.6	2.7	2.7	2.7	3.4	4.3	2.1	1.9	1.9	1.6	1.5
Total	27.2	26.9	25.3	25.6	25.3	26.0	27.0	26.0	25.0	24.2	24.4	22.5

* Includes estimates from Denmark and Sweden only.

The aggregated Nordic emissions of methane (Figure 25 and Table 4) show a declining trend and that the dominating sources are the agriculture and waste sectors. These sectors together contribute to more than 85% of the total CH₄ emissions. Residential combustion contributes in the order of 5% while the contribution from mobile sources (road traffic, off road mobile and national shipping) is minor.

Figure 25. Aggregated Nordic emissions of CH₄ 2000–2011 (Gg)

Table 4. Aggregated Nordic emissions of CH₄ 2000–2011 (Gg)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Energy industries	18	19	19	19	19	17	16	15	15	15	18	15
Energy other	9	9	9	9	10	9	9	9	9	9	9	9
Fugitive	46	52	48	50	53	47	45	50	46	44	44	41
Road traffic	12	11	10	10	9	8	8	7	7	6	6	5
Off-road mobile	1	1	1	1	1	1	1	1	1	1	1	1
National Shipping	1	0	0	1	1	1	1	2	2	3	3	3
Residential combustion	34	34	36	37	37	38	37	38	38	40	41	39
Industrial processess	2	2	2	2	2	2	2	1	1	1	1	1
Agriculture	550	503	501	500	493	492	490	487	486	483	486	482
Waste	399	388	364	350	336	315	317	302	284	275	266	258
Internat. shipping	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.2
<i>Total</i>	<i>1,071</i>	<i>1,020</i>	<i>991</i>	<i>979</i>	<i>960</i>	<i>931</i>	<i>927</i>	<i>913</i>	<i>891</i>	<i>876</i>	<i>876</i>	<i>856</i>

The aggregated Nordic emissions of NMVOC show a declining trend of 45% from 2000–2011 (Figure 26 and Table 5). While combustion sources, such as energy production and combustion in industry, as well as road traffic show decreases in the order of 65–70%, especially the source category “solvent and product use” remains high and stable over time. NMVOC emissions from residential combustion show a slight increase from 2000–2011.

Figure 26. Aggregated Nordic emissions of NMVOC, 2000–2011 (Gg)

Table 5. Aggregated Nordic emissions of NMVOC, 2000–2011 (Gg)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Energy prod. +comb. in industry	363	369	322	279	245	196	172	167	135	124	118	108
Road traffic	218	200	183	169	152	140	126	115	104	95	87	77
Off road mobile	66	67	68	68	69	66	64	62	58	53	53	52
National shipping	24	23	23	22	21	21	21	21	16	16	17	15
Residential combustion	56	58	59	62	60	60	58	62	66	69	74	68
Industrial processes	39	38	37	36	37	35	34	35	33	30	32	30
Solvent and product use	188	181	183	181	186	180	179	176	172	161	169	172
Agriculture, waste	5	4	5	5	3	3	3	3	4	3	3	3
International shipping	8	7	6	7	7	7	8	8	7	6	6	5
<i>Total</i>	<i>967</i>	<i>947</i>	<i>886</i>	<i>827</i>	<i>780</i>	<i>708</i>	<i>665</i>	<i>650</i>	<i>595</i>	<i>558</i>	<i>558</i>	<i>538</i>

Emissions of CO have decreased in the Nordic countries since 2000 (Figure 27 and Table 6), especially from road traffic (60%). From off road mobile sources and from residential combustion emissions are estimated to have increased by 18 and 15% respectively. The largest contributing sources in later years have been residential combustion and road traffic.

Figure 27. Aggregated Nordic emissions of CO, 2000–2011 (Gg)

Table 6. Aggregated Nordic emissions of CO, 2000–2011 (Gg)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Energy prod. +comb. in industry	426	419	402	381	379	353	351	330	313	295	309	294
Road traffic	1,359	1,266	1,166	1,081	979	910	823	763	701	645	599	531
Off road mobile	292	297	304	308	324	327	339	349	348	336	339	344
National shipping	67	67	68	67	67	68	68	68	63	63	65	59
Residential combustion	479	487	501	525	486	514	489	527	539	558	586	550
Industrial processes	70	69	65	57	52	53	49	51	52	40	41	43
Agriculture, waste, product use	23	18	18	18	15	13	14	17	15	15	10	9
Internat. shipping	21	19	16	18	18	18	21	21	19	15	16	15
<i>Total</i>	<i>2,738</i>	<i>2,642</i>	<i>2,540</i>	<i>2,455</i>	<i>2,319</i>	<i>2,255</i>	<i>2,154</i>	<i>2,128</i>	<i>2,050</i>	<i>1,967</i>	<i>1,964</i>	<i>1,853</i>

4.1 Important sources of SLCPs in the Nordic countries

As can be concluded from the presentation of the aggregated Nordic emissions of the individual SLCPs above, residential combustion, road traffic and off road mobile sources are large contributing emission sources to PM_{2.5}, BC and CO in the Nordic countries. For NMVOC, the contributions from these sources are also significant, while the agriculture and waste sectors are the important sources for CH₄ emissions.

Residential combustion and mobile sources are thus identified as being the most important SLCP-sources, particularly for PM_{2.5} and BC. The remainder of this report therefore concentrates the further analysis on these sources.

The importance of the residential combustion as a significant source for BC also in the future is further highlighted by the analysis made in the EU Clean Air Policy Package,¹⁴ which was adopted 18/12 2013. Background information for the package was developed as a “baseline” scenario, or option 1, in the Impact Assessment (European Commission, SWD(2013)531). Option 1 is defined as “No additional EU action”, which means that no new EU policies are envisaged. For the Impact assessment, calculations of emissions were made with the GAINS model (Scenario PRIMES_2013_REF_CLE) for all European and Nordic countries for the years 2000–2030 in 5 year intervals. Aggregated emissions of BC in the Nordic countries 2000–2030, derived from the baseline scenario in the background material for the EU Clean Air Policy Package are presented in Figure 28. Future reduction in emissions of BC from road transport and non-road mobile sources is expected due to implementation of Euro standards. According to the baseline scenario residential and commercial combustion will increase in relative importance and dominate Nordic BC emissions in the future. The expected absolute emission reductions from residential/commercial combustion are due to assumed increased fuel efficiency and improved combustion technologies.

¹⁴ http://ec.europa.eu/environment/air/clean_air_policy.htm

Figure 28. Aggregated emissions of BC (Gg) in the Nordic countries according to the baseline scenario, adapted from the EU Clean Air Policy Package, adopted 18 December 2013

In the baseline scenario the total estimated emissions of BC from the Nordic countries in 2000, 2005 and 2010 are 24.7, 22.9 and 21.1 Gg respectively. In the aggregated Nordic inventories, as presented in Table 3, the corresponding total emissions of BC (excl. international shipping) are well comparable and amount to 23.0, 22.6 and 22.8 Gg.

5. Residential biomass combustion

5.1 Combustion appliances used in the Nordic countries and disaggregation in national inventories

Even though Denmark, Finland, Iceland, Norway and Sweden are all Nordic countries, the conditions regarding the extent of biomass use in different types of technical combustion appliances differ. Table 7 presents the disaggregation on combustion technologies that are applied in the national Nordic emission inventories, as well as the amount of biomass fuel combusted in each, and the resulting nationally estimated emissions of $PM_{2.5}$. Denmark differentiates in its inventory on 10 technologies, Finland on 13, Norway on 3 technologies and Sweden on 6. To some extent this represents the differentiated use of residential combustion appliances in the Nordic countries, but not entirely. Denmark, Finland and Norway for example differentiate between old and new equipment while Sweden only differentiates between three main technology types, boilers, stoves and open fireplaces. Finland is the only country which includes specific data for masonry heaters and sauna stoves, which is relevant since these are more common in Finland than in the other countries. In all countries, where relevant, differentiation is made between the types of fuel; wood logs, wood chips or pellets.

Table 7. National disaggregation of combustion technologies for residential biomass combustion in national inventories, use of biomass fuel (TJ and %) and estimated emissions of PM_{2.5} (Gg and %) per Nordic country (2011 or 2012). (Acc= accumulator tank, # in-built heat storage)

	Category	Technology	Acc.	Activity (TJ)	Share of activity	Emissions PM _{2.5} (Gg)	Share of PM _{2.5} emission
DK	Stove	Old stove, pre-1990		3,479	11%	2.6	18%
DK	Stove	New stove, with DS mark 1990–2005		7,739	24%	5.7	41%
DK	Stove	Modern stove, conforming with Danish legislation (2008)		2,817	9%	1.7	12%
DK	Stove	Eco labelled stove		3,169	10%	0.8	5%
DK		Other stove, incl open fireplaces		271	1%	0.2	1%
DK	Boiler	Old boiler, pre-1980	Yes	941	3%	0.8	6%
DK	Boiler	Old boiler, pre-1980	No	622	2%	1.1	8%
DK	Boiler	New boiler, post-1980	Yes	3,229	10%	0.4	3%
DK	Boiler	New boiler, post-1980	No	1,615	5%	0.4	3%
DK		Pellet boilers/stoves		9,095	28%	0.3	2%
DK	All			32,976	100%	14.1	100%
FI*	Stove	Iron stoves conventional (firewood)		1,579	2%	0.16	11%
FI	Stove	Iron stoves modern (firewood)		0	0%	0	0%
FI	Boiler	Automatic Fed Wood Chips		11,816	17%	0.16	5%
FI	Boiler	Automatic Fed Pellets		1,314	2%	0.02	0.3%
FI	Boiler	Manually Fed (firewood)	Yes	10,327	15%	1.25	7%
FI	Boiler	Manually Fed (firewood)	No	2,778	4%	1.74	16%
FI	Boiler	Manually Fed Modern (firewood)		0	0%	0	0%
FI		Open fire place and other stove (firewood)		2,239	3%	1.24	15%
FI	Stove	Kitchen range (firewood)		5,928	9%	0.28	7%
FI	Stove	Masonry Heaters Conventional (firewood)	#	11,607	17%	1.43	16%
FI	Stove	Masonry Heaters Modern (firewood)	#	2,087	3%	0.09	2%
FI	Stove	Masonry Ovens (firewood)	#	10,199	15%	0.44	12%
FI	Stove	Sauna stoves (firewood)		8,863	13%	3.70	10%
FI	All			68,737	100%	10.5	100%
NO	Open fireplace			1,297	5%	1.0	5%
NO	Stove	Stove old technology (before 1998)		12,265	47%	12.6	59%
NO	Stove	Stove new technology (after 1998)		12,434	48%	7.6	36%
NO	All			25,997	100%	21.3	100%
SE	Boiler	wood logs		26,208	57%	3.9	74%
SE	Boiler	wood chips		2,803	6%	0.3	5%
SE	Boiler	pellets		7,742	17%	0.2	4%
SE	Stove	wood logs		7,387	16%	0.7	14%
SE	Stove	pellets		1,109	2%	0.0	1%
SE	Open fireplace	wood logs		646	1%	0.1	2%
SE	All			45,895	100%	5.3	100%

*For Finland: division in three periods; before 2000/2000–2010/after 2010. The shares of different technologies are further divided between sectors: agriculture, commercial/industrial, recreational and residential (which is further divided into block houses, row houses, one-family houses), between which the AD is divided – in this table the sums are presented.

In Figure 29 the data from Table 7 on biomass fuel consumption and estimated emissions of PM_{2.5} for each technology type is presented per country (blue=activity (TJ) and red=emissions of PM_{2.5} (Gg)). The main combustion technologies and use patterns differ between the Nordic countries.

In Denmark, the categories “new stoves” and “pellet boilers/stoves” use the largest quantities of biomass fuel (24 and 28% respectively), while

the new stoves emit 41% the pellet boilers/stoves emit only 2% of the PM_{2.5} from biomass combustion in residential combustion technologies.

In Finland, the biomass fuel use is more evenly distributed on some technologies, where about 15–17% each is used in automatic fed wood chips boilers, manually fed boilers, conventional masonry heaters, and masonry ovens, and 13% in sauna stoves. This results in PM_{2.5} emissions amounting to 5, 15, 16, 12 and 10% of the total from residential biomass combustion in Finland.

In Norway, approximately equal amounts of biomass are used in old and new technology stoves (47 and 48% respectively). The emissions of PM_{2.5} however, amount to 59% from the old technology stoves and 36% from new technology stoves.

In Sweden the dominating technology is wood boilers, where 57% of the biomass is used. Wood boilers contribute to 74% of the PM_{2.5} emissions.

Figure 29. Technology types, fuel use and emissions of PM_{2.5} in the Nordic national inventories in 2011. (Blue= Activity (TJ), Red= Emissions of PM_{2.5} (Gg))

5.1.1 Main combustion appliances and emission sources in Nordic countries

In order to try to clarify which technologies are the most commonly used in the Nordic countries as a whole, and which are those contributing most to PM-emissions, an effort to group the differentiated technologies (from Table 7) on the Nordic level is presented in Table 8 and Figure 30.

Table 8. Technology types, activities and emissions in the Nordic countries (2011 or 2012)

Technology	Activity (TJ)	Share of activity	Emissions of PM _{2.5} (Gg)	Share of emissions	IEF* (g/GJ)
Boilers, wood logs (all types)	45,720	26%	9.43	18%	206
Boilers+stoves, pellets+wood chips	33,879	20%	1.4	3%	43
Old stoves	17,323	10%	16.5	31%	953
New/modern/ecolabelled stoves	33,546	19%	16.6	31%	494
Masonry heaters, sauna stoves, kitchen range (only FI)	38,684	22%	5.7	11%	147
Open fireplaces	4,453	3%	3.14	6%	705
<i>Total</i>	<i>173,605</i>		<i>52.8</i>		

*IEF=Implied Emission Factor.

Figure 30. Technology types, activities and emissions in the Nordic countries

Most biomass is combusted in wood log boilers, but this includes all types of wood logs boilers, both new and old as well as those with and without accumulator tank, since finer disaggregation was impossible to assess from the individual country information. Pellet boilers and stoves are also used extensively and approximately as much as the group of new/modern/ecolabelled stoves. Another group where a large share of the biomass is used is typically Finnish and contains masonry heaters, sauna stoves and kitchen range stoves.

Most emissions of PM_{2.5} are estimated to be emitted from old stoves and the group of new/modern/ecolabelled stoves, followed by wood log boilers. Emissions of PM from pellet fuelled boiler and stoves are very low.

One or several technologies dominate emissions in each country but a specific appliance type common for all countries cannot be pointed out. The contribution of certain technologies to emissions from residential biomass combustion in the national inventories is affected by the share of wood nationally combusted in certain appliances and the nationally used emission factors. However, as the use pattern of the appliances differ between countries it is challenging to compare the actual emission levels between the countries even for appliances that are the most alike.

5.2 Factors influencing uncertainties for residential wood combustion

Emission inventories of PM from residential biomass combustion are generally regarded as rather uncertain. This is partly due to difficulties in correctly estimating the activity data but mostly due to a high variability in reported emission factors. The emission factors are a result of e.g. technical characteristics in the source and fuel quality, but are also strongly dependent on combustions practices, as inefficient and incomplete combustion gives higher emissions of PM than under efficient combustion conditions (e.g. Todorovic *et al.*, 2007).

Several studies have shown great variations in emission factors depending on variables such as wood species, water content of the wood, log size, batch size and the general operating conditions such as the air flow etc. (Nielsen *et al.*, 2010). It is also clear that the emissions vary between different types of appliances. Stoves and boilers have different emission characteristics depending on for example age and maintenance condition.

In Table 9 factors influencing the estimated emissions and the uncertainties of emission inventories are presented. In the sections below the factors from the table are further elaborated.

Table 9. Factors influencing emission estimation and uncertainties in emission inventories for residential wood combustion (not in order of importance)

Factor	Why/how?	Judged importance	Possible/feasible to improve?
Emission measurement method for deriving emission factors (chapter 4.2.1)	Sampling methods, sample treatment and analysis differ in different measurement standards. For instance, hot flue gas/diluted flue gas measurements give different results.	Critical	Harmonise measurement methods and data processing used for deriving emission factors and document factors influencing measurement results
Operation and handling Chapter 4.2.2	Firing habits, e.g. firing with restricted air supply results in incomplete combustion and higher emissions.	Critical, especially for manually fed devices. Should be taken into account in the EF based on information from measurements and knowledge of national practices	Education/information. Estimated impact of judged current practices can be included in the EFs (included e.g. in the Finnish inventory).
Activity data (fuel consumption) Chapter 4.2.3	There is an inherent uncertainty in the activity data for residential wood combustion. Solid data requires surveys potentially coupled with energy demand modelling.	Important	Not feasible to improve within this project. New ways to collect detailed enough data
Activity data (combustion technology) Chapter 4.2.4	The split of the overall wood consumption into technologies is very important. This can only be achieved by detailed surveys within each country.	Very important. Emission factors can vary significantly between technologies	Not feasible to improve within this project. Surveys by chimney sweepers, sales statistics, expert estimates
Activity data (fuel quality) Chapter 4.2.2	A few studies have investigated the importance of e.g. wood type, moisture content, etc. however, many of these aspects are still poorly understood	Less important. If possible, should be taken into account in the EF, by expert assumptions	Difficult to improve, expert assumptions

5.2.1 Emission measurement methods for residential biomass combustion

General emission factors, valid on the national scale, should be derived based on representative emission measurements for the national conditions. The different standards for sampling emissions of particles may however heavily affect the measured particle concentration and hence the calculation of emission factors (Nielsen *et al.*, 2010, Kindbom and Munthe, 2013).

There are several different methods available for measuring PM emissions. They can roughly be divided into the following categories (Winther, 2008):

- In-stack gravimetric methods (e.g. VDI2066 bl.2).
- Out-stack gravimetric methods without dilution tunnel (e.g. SS028426).
- Gravimetric methods with dilution tunnel (e.g. Force Technology/NERI, NS3058).
- Electrostatic methods (e.g. BS3841).
- Cascade impactors (e.g. VDI2066 bl. 5).
- Low pressure impactors (e.g. ELPI, DLPI).
- Optical scanners (e.g. LASX, SMPS).

The main difference is whether the emission measurement is carried out in the hot flue gas or if the measurements are carried out after the semi-volatile compounds have condensed. There are advantages and disadvantages with both sampling methods. Measurements in the chimney require less instrumentation since no dilution is needed. The purpose of a dilution is to simulate what happens to the flue gas when it reaches the ambient air, and the flue gas is diluted and cooled with large amounts of ambient-tempered air prior to sampling. Measurements by sampling using dilution generally gives higher results than those from sampling in the flue gas channel, due to additional condensation of organic compounds on particles in the lowered temperature in the dilution tunnel (e.g. Gaegauf *et al.*, 2011, Jokiniemi *et al.*, 2008, Ryde and Johansson, 2007). The difference between the two sampling methods is not constant, and the differences increase with increasingly poor and inefficient combustion conditions (Ryde and Johansson, 2007). Nussbaumer *et al.*, (2008) notes that particles from well designed and well operated automatic wood combustion consist mainly of inorganic matter such as salts, while particles from wood stoves operated under poor conditions consist mainly of soot and organic substances. Båfver *et al.*, (2011) showed that measurements of PM_{2.5} in hot flue gases in modern wood stoves and pellet stoves were rather similar. However, a considerably higher (typically more than 30 times) emission of organic gaseous carbon from combustion of wood logs (in comparison to pellets) indicated a potential additional contribution to the emissions from condensable organic particles formed as the flue gas cools down.

The choice of sampling methodology may also give rise to different results regarding the BC content of the measured particles. Jokiniemi *et al.* (2008) found that the fraction of BC in sampled PM is higher if measurements are performed in hot flue gases. After dilution and condensation of gaseous substances, the BC fraction will be lower due to condensation of other gaseous organic substances, yielding a higher total mass of PM, while the mass of BC does not increase.

A comparative study of the sampling methods showed that the emission factors for PM found when using a dilution tunnel are between 2.5 and 10 times higher than when only taking into account the solid particles measured directly in the chimney (Nussbaumer *et al.*, 2008). This range is also reported by Båfver (2008).

A test on a wood stove carried out by the Danish Technological Institute showed a ratio of approximately 4.8 between an in-stack measurement and a measurement in a dilution tunnel (Winther, 2008). A similar Swedish test on two wood stoves (Ryde and Johansson (2007) showed ratios of 4.3 and 4.1 as an average of four tests on each stove. Ryde and Johansson also made a comparison for a wood boiler at nominal effect, where the measurements in the dilution tunnel were 2.2 times higher than the hot flue gas measurements, as an average of four tests. The measurement standards used in the Swedish study were Swedish standard SS028426 (hot flue gas measurement) and Norwegian standard NS 3058-2 (dilution tunnel).

Typically, Swedish laboratory measurements (e.g. Johansson *et al.*, 2004) are based on Swedish Standard (SS028426), which is an out-stack heated filter – meaning that the semi-volatile compounds will not have condensed. In the field measurements by Johansson *et al.* (2006) an in-stack filter was used to measure PM. The Swedish emission factors for residential combustion of biomass (Paulrud *et al.*, 2006) are based on these types of measurements, which thus is expected to give lower results for PM than if sampling in a dilution tunnel would have been used.

The measurements carried out in Denmark all use out-stack methods with dilution tunnel comparable to Norwegian Standard (Glasius *et al.*, 2005; Glasius *et al.*, 2007; Winther, 2008). Therefore, the measurement method can be the reason why the Swedish measurements show a significantly lower level compared to the Danish measurements.

The proposal for a European standard for measuring PM from residential solid fuel burning appliances propose to measure the particles in a dilution tunnel (Gaegauf & Griffin, 2007). However, in the published standard (CEN/TS 15883:2009) three different methods are presented in its annex A. These include both measurements in dilution tunnels

(Norwegian standard) and in the stack (German/Austrian standard). In the present CEN draft, there are two methods: dilution tunnel and hot filter. They are the present Norwegian method and a revised version of the German method.

In order to ensure comparability between PM (and BC) emission inventories in the future there is a need to establish a common emission measurement method for deriving emission factors, since differences of a factor of up to 10, in worst cases, obviously makes it impossible to compare results.

An important factor influencing the emission factors chosen to be used in the national inventories is the processing of data from measurement results to develop emission factors. Data processing and reporting of measurement results differ and are not possible to compare without proper documentation. If documentation of wood combustion conditions (combustion technology, fuel quantity/quality, use pattern, etc.) and measurement conditions (sampling, sample treatment, analysis etc) are poorly documented, it may not be possible to judge the representativeness of the results for national conditions.

The measurements carried out in a dilution tunnel best represent the actual emission of PM when the flue gas is emitted from the chimney, whereas measurements done in the hot flue gas will neglect the contribution to the PM emission from semi volatile compounds that forms PM when the temperature decreases.

5.2.2 Operation and handling, and fuel quality

In manually fed combustion appliances the user has significant impact on the combustion process and emissions in fuel selection and by ensuring good equipment maintenance and combustion conditions. Independent of whether the appliance is old or new, it can be used skilfully by correct operation and maintenance such as ensuring sufficient air supply, by correct ignition of the wood and by correctly maintaining the combustion cycle.

Equipment: The equipment should be located according to the specifications of the manufacturer and be connected to the flue duct-chimney construction designed for it. The draught conditions should be optimized taking into account replacement air/forced ventilation requirements. The appliance should be regularly sooted to remove soot in the smoke ducts and combustion chamber. The combustion chamber should be kept ash-free by the user.

Selection and storage of wood: Only clean wood, pellets or bricks should be burned, no waste. The different wood fuels have different heat contents. The user can influence the quality of the wood by keeping it in under dry well-ventilated conditions, and moving it to a warm environment in advance of use (1–2 days) to allow the wood warm up before use. The first batch during the combustion cycle should be of smaller sized wood logs than the following phases (phase “Moisture evaporizes”, Figure 31).

Figure 31. The process of burning, Alakangas et al. (2008)

Start up: Sufficient draught through the chimney should be ensured throughout the combustion by regulating the air intake and outlet and by ensuring sufficient replacement air in the room. The ignition of the wood should be carried out according to the user manual of the appliance, (phase “Ignition”, Figure 31).

Combustion: Both good and bad combustion conditions generate emissions. Most of the particle mass from wood combustion is generated during incomplete burning conditions. Good combustion requires at the minimum 3.7 m³ air per kilogramme of wood, in practice the air factor is 2–2.5 (i.e. 7.5–10 m³/kg of wood) in closed stoves and 10–30 in open fireplaces. It should be ensured that air mixes with gases released from the wood.¹⁵

¹⁵ Air factor = The ratio of additional air needed for complete combustion to theoretically calculated volume of air (usually 1.2–1.3) A large air factor reduces formation of soot but lowers the coefficient of efficiency.

Most of the emissions are generated during the pyrolysis. Kalium, sodium and chlorine in the wood are easily evaporated and form inorganic particulate substances of less than 1µm in diameter, part of which are carried with the flue gas. In addition to particle emissions also hydrocarbon and carbon monoxide emissions are generated. A too vigorous burning can be managed by regulating the air intake, the size of wood logs and the size of the batch (wood should not to be added in large batches). Emissions are highest when the combustion chamber is full of dry, small sized loosely piled wood. Both restricted air intake and too much intake of air increases emissions. However, if the air intake is not sufficient, soot and tar will be attached to the combustion chamber and flue ducts and harmful emissions will be generated. This condition can be identified from the dark colour of the flue gas. In good combustion conditions the flue gas is light coloured. During ignition and each time a batch is added, the colour will be momentarily darkened (phase “Pyrolysis”, Figure 31).

Shut down: The ember phase is slow because gaseous substances have been combusted and only coal remains to be combusted. The red ember releases heat, about 25–50% of the energy content of the wood. Air inlets can be shut and outlet reduced when the flames have died (phase “Carbonized residue”, Figure 31) (Alakangas *et al.* 2000, 2007, 2008, HSY 2008a and b).

Fuel wood quality

Moisture: Dry wood burns clean and hot. The moisture in the wood lowers the temperature of the flame and increases emissions. Combustion is low-emitting at >850 °C. The burning temperature of dry wood is higher than for moist wood and thus produces more heat than moist wood. The moisture content in recently cut wood is approximately 50%. In excellent conditions wood can be dried outdoors to 25% moisture content during the period of one spring and summer. Often, however, drying outdoors for 2 summers is needed to get the moisture content below 20%. The ideal moisture content is 15–20%.

Contamination: Waste, contaminated, painted or treated wood should not be burned, neither chipboard nor plywood as these create harmful emissions and can damage the equipment.

Studies on operating conditions

Many studies show the importance of the operating conditions on the resulting emissions. Klippel & Nussbaumer (2007) has made several measurements under different operating conditions. Measurements have been made with wood with varying water content, of different

loads and for different stages of the combustion process. As expected this causes the emission factors to fluctuate significantly.

Tissari *et al.* (2008) investigated the impact on PM emissions of appliance type, batch size and log size during the three main stages of combustion (firing, combustion and burn-out). The study showed that the PM emission was highest in a sauna stove, while the conventional and modern masonry heaters were lower. The conventional masonry heater was only significantly higher in emissions than the modern masonry heater during the firing phase. As expected the firing phase produced the highest emissions of PM for all three appliance types. Regarding log size the study found that small logs resulted in higher emissions of PM₁ than big logs. The average emission factor for small logs was almost five times higher than the emission factor for big logs.

Paulrud *et al.* (2006) reports emission measurements from 20 different tests carried out for different species of wood, different water content, different batch sizes and different ignition conditions. The emissions of PM varied from 20–180 mg pr MJ.

Other studies have focused on the influence on the wood species in connection with emissions. Schauer *et al.* (2001) measured emissions from a fireplace combusting pine, oak and eucalyptus. The lowest PM emission was measured from oak (5.1 g pr kg) while eucalyptus and pine had considerably higher emission rates at 8.5 and 9.5 g pr kg, respectively.

Another important factor sometimes overlooked is the age of the combustion appliance. Due to the increased attention to the air pollution originating from wood stoves and boilers, modern appliances have significantly lower emissions compared to older appliances. Glasius *et al.* (2007) found that wood stoves over three years old had an emission factor that was 40% higher compared to wood stoves that was three years old or less. Johansson *et al.* (2004) reported measurements carried out on both old boilers and modern boilers. For the old boilers the resulting emission factors were between 87 and 2,200 mg pr MJ and the modern boilers showed emission rates between 18 and 89 mg pr MJ. So it is clear that in order to have a reliable emission inventory it is necessary to have solid information regarding the technology distribution of wood combustion appliances, e.g. number of old boilers vs. new boilers.

5.2.3 Activity data (fuel consumption)

There are uncertainties regarding the activity level for residential biomass consumption. For example, the self-supply and direct purchase of the wood might not be taken into account when energy statistics are

based mainly on data obtained from the fuel suppliers. This could lead to a significant underestimation of the wood consumption, especially in countries with abundant wood supplies and greater share of heating with stoves and small boilers. In that case, the data on wood consumption should be adjusted.

Particularly in the case of the residential sector the surveys should be based on a representative sample survey. In some countries the means of heating of the households are regionally very inhomogeneous with a significantly greater share of individual stoves and boilers in rural areas without connection to a public supply of district heating. Additional data could be obtained from the chimney-sweeper organisations.

As described in Broderick & Houck (2003) a number of circumstances should be considered when preparing and conducting a survey of residential wood consumption. More technical issues related to surveys are provided in Eastern Research Group (2000), that provides a detailed description on issues to be considered, when conducting a survey, e.g. survey techniques, sample size, elaboration of questions and handling of answers. In relation to residential wood consumption, it is important to include a clear definition of volume of wood, as a number of measures are used, e.g. loose volume of logs (logs thrown into e.g. a box), stacked volume of logs (around 70% of loose volume) and stacked volume before cutting into logs. Furthermore, it is important to include questions on the type and technology of combustion appliances. Age and certifications according to emission limits could be helpful information, as determination of appliance types is not simple, and homeowners might not be able to differentiate the types or have knowledge of the technology of their appliances.

While good data on wood consumption are very important, the improvements will have to come from the authorities responsible for the energy statistics in the individual countries.

5.2.4 Activity data (combustion technologies)

In order to estimate emissions from residential wood combustion it is necessary to include appliance population per installation type, to ensure use of appropriate emission factors. Sales statistics are valuable data sources for this purpose. Sales statistics from the past can be used to estimate the population of old appliances and statistics for more recent years can be used to incorporate substitution rates to newer appliances.

Denmark

Wood combustion is an important source of heat in households in Denmark. It is estimated that there is about 750,000 wood stoves in Denmark, while there is about 16,000 fireplaces and about 47,000 wood boilers. In addition to this comes installations that are burning wood pellets.

The consumption of wood in residential plants in 2012 was 23.9 PJ an significant increase compared to the wood consumption in residential plants in 1990 and 2000 of 9.6 PJ and 12.5 PJ respectively. The consumption of wood pellets increased from no consumption in 1990 to 2.1 PJ in 2000 and 8.7 PJ in 2012. The statistics for wood consumption in residential plants used in the national emission inventory is based on the official Danish energy statistics. The Danish Energy Agency is basing the statistics on a biennial survey, where telephone interviews are conducted to assess the wood consumption. This survey also provides some information on the distribution of the wood consumption between different technologies.

The information on how the wood consumption is distributed to different technologies is included in Table 7.

Finland

Wood combustion is the primary heating source in approximately a quarter of residential detached and most recreational buildings in Finland, and the secondary source in almost all residential and recreational buildings. There are approximately 2.2 million residential wood burning devices and, in addition, 1.5 million sauna stoves (Tissari *et al.*, 2008). Residential combustion of wood has increased in the last decades to almost 60 PJ per year, and comprises about 35% of total primary heating energy in detached housing.

Residential wood combustion appliances and burning habits in Finland differ from those in other Nordic countries, in the way that the goal is to achieve a high combustion rate with short operating time (Tissari *et al.*, 2008).

The largest share of wood is combusted in masonry ovens, log boilers and sauna stoves. Masonry heaters are energy efficient with high combustion rate, high heat storing capacity and low emissions, and are typically located centrally in the building to maximize the heat radiation. Log boilers and sauna stoves have lower energy efficiency and higher emissions.

Figure 32. Residential wood use by combustion appliance type in Finland 2012 (Finnish IIR 2015, manuscript)

Masonry heaters are typically massive (500–6,000 kg) with an upright firebox. The exhaust gas flows to an upper combustion chamber, then down through the ducts and then to the chimney (Figure 33). The large mass efficiently stores heat and releases it slowly (average rate of 1–3 kW) in a period ranging from 10 hours to two days. Most new detached houses in Finland are equipped with a masonry heater. The low emission rate is based on hot and closed surfaces of the firebox that support the completeness of combustion. The modern models are equipped with a secondary combustion chamber and secondary air input (Tissari 2008, Paunu 2012).

Figure 333. Air flow in a masonry oven (Alakangas et al., 2008)

The firebox in a *sauna stove* is small and there is no secondary combustion as the use purpose is different from appliances that are designed to heat residential spaces: the heating need in a sauna room is temporarily high and therefore the combustion rate is high. *Water boilers*, common in sauna buildings, have similar construction and are used to heat water to be used directly from the boiler (Tissari, 2008).

Wood log boilers in Finland are typically updraught boilers and do not always have a heat storage tank. These boilers often have low thermal output and high emissions and are mainly used as the main heating device in rural areas.

Other typical heating appliances include *wood chip boilers*, with a capacity of 100–200 kW, used to heat large agricultural buildings and school spaces, and *multifuel boilers*, where oil, wood and pellets can be combusted. *Masonry cooking stoves* are built to include both a wood burning oven and a masonry heater in the same structure.

The use of pellet burners or iron stoves is not common in Finland. (Tissari, 2005).

The national emission inventory is based on the use of 13 different wood combustion techniques in residential, recreational, agricultural and commercial/industrial buildings.

Norway

Electricity is the most important energy product in Norwegian households and accounted for almost 80% of the energy consumption in 2012. Residential combustion of wood was the second most important energy product, which comprised about 16%. There are approximately 2.1 million residential wood burning devices in Norway, in addition, 0.4 million wood burning devices in recreational buildings (Aasestad, 2014).

Figure 34. Number of wood burning devices in Norway by technology, 2012.
Source: Statistics Norway's survey on consumer expenditure 2012

The estimated use of *wood* in households is based on figures on the amount of wood burned from the annual survey on consumer expenditure for the years before 2005 and for 2012. The statistics cover purchase in physical units and estimates for self-harvest. The survey figures refer to quantities *acquired*, which not necessarily correspond to *use*. The survey gathers monthly data that cover the preceding twelve months; the figure used in the emission calculations (taken from the energy balance), is the average of the survey figures from the year in question and the following year. For the years 2005–2011 the figures are based on responses to questions relating to wood-burning in Statistics Norway's Travel and Holiday Survey. The figures in this survey refer to quantities of wood *used*. The survey quarterly gathers data that cover the preceding twelve months. The figure used in the emission calculations is the average of 5 quarterly surveys. Combustion takes place in open fire places and in small ovens/stoves in private households.

Emission factors for fuelwood are based on data for different oven technologies. Ovens made in 1998 and later have significantly improved combustion and reduced emissions. The factors are weighted based on information from the surveys of the amount of wood burned in ovens with the different technologies.

Figure 35. Residential wood use by combustion appliance type in Norway 2012.
Source: Statistics Norway's Travel and Holiday Survey 2012

Sweden

In Sweden there is no regular and systematic collection of information regarding residential biomass combustion technologies or their age. The disaggregation level in the national emission inventory is thus not particularly detailed and only contains boilers, stoves and open fireplaces. In 2005 (Paulrud *et al.*, 2006a) a more detailed survey was conducted covering local space heaters, divided in stoves, heat accumulating ovens, open fireplaces, open fire places with insert, and kitchen stoves. In 2005, 37% of the local space heaters were stoves (257,000), 19% (134,000) open fireplaces, 20% (136,000) open fireplaces with inserts and 12% (84,000) respectively were kitchen stoves and heat accumulating ovens.

The year of installation was also investigated (pre-1991, 1991–1999 and 2000–2005). The results showed that in 2005 more than half (51%) of the local space heaters were installed prior to 1991. For stoves and open fireplaces with inserts 44% were older than 1991, 35% were installed between 1991–1999 and 21% were installed between 2000 and 2005.

In Todorovic *et al.* (2007) an assessment of the total number of biomass combustion appliances of different types was made. The number of local space heaters was taken from Paulrud *et al.* (2006a) above, amounting to 695,000 units in 585,000 households. From chimney sweeper statistics, a number of 230,000 boilers and 67,000 pellets boilers were derived. According to the chimney sweepers statistics, the number of local space heaters was larger than 695,000 (1,200,000 in 2005), but since there was no information on wood consumption from those, they were assumed not

to use wood extensively, and were regarded a less important in the assessment made by Todorovic *et al.* (2007).

Recent chimney sweeper statistic for 2012 (MSB, 2013) show the number of combustion appliances (Table 10) to be 209,900 solid fuel boilers, 87,000 pellets boilers and 1,726,000 local space heaters, of which 15,000 were for pellets. Compared to the information for 2005, used in Todorovic *et al.* (2007), the number of solid fuel (biomass) boilers have decreased by about 20,000 units (9%) while the number of pellets boilers instead have increased by about 20,000 units (30%). In Todorovic *et al.* (2007) there is no mentioning of local space heaters using pellets, why these can be assumed to have increased substantially in number in since 2005.

Table 10. Swedish chimney sweeper statistics for 2012 on existing number of appliances. Solid fuel is assumed to be biomass

Conventional solid fuel boilers	Solid fuel boilers (ceramic)	Pellets boilers (pellets or similar)	Local space heaters	Local space heaters, pellets
117,553	9,351	86,757	1,711,073	15,112

From the chimney sweeper statistics it is not possible to derive the age, detailed technologies, or the share of “bad firing habits”. In Todorovic *et al.* (2007), based on field studies (Johansson *et al.* 2006, Paulrud *et al.*, 2006) and further assumptions, it was estimated that in the order of 5% of the wood boilers were fired with restricted air supply resulting in considerably higher emissions.

In conclusion, for Sweden there is some detailed information available about the stock of biomass combustion appliances from about 10 years ago. In order to improve the emission inventory for residential biomass combustion and make full use of technology specific emission factors from the other Nordic countries and/or the EMEP/EEA Air Emission Inventory Guidebook it is necessary to improve the collection of activity data, specifically, the age and stock of biomass combustion technologies, as well as their respective use of fuel in Sweden.

5.3 Residential biomass combustion emission factors for PM_{2.5} and BC in the Nordic inventories

The emission factors used in estimating emissions from residential biomass burning in the Nordic countries has been compiled, and the emission factors for PM_{2.5} and BC are presented in Table 11, Table 12, Table 13 and Table 14 below. Efforts have been made to group similar technologies, where performances would be expected to also be reasonably similar. National circumstances may however contribute to the different levels of emission factors, as discussed above.

The emission factors for PM_{2.5} in Denmark, Finland and Norway are generally developed based on emission measurements using dilution while the Swedish emission factors for PM_{2.5} are derived from hot flue gas measurements. The BC emission factors, as shares of PM emission, are mostly those available in the EMEP/EEA Guidebook, representing dilution tunnel measurements. For Norway emission factors for EC (Elemental carbon) for wood stoves are based on measurements performed in 2012/2013 (Seljeskog, Goile *et al.*, 2013), see chapter 4.5.2.

Table 11. Emission factors for PM_{2.5} and BC for open fireplaces in the Nordic countries

	Category	Technology	EF PM _{2.5} (g/GJ)	EF BC
FI	Open fireplace	Open fire place and other stove	638	35 g/GJ (5% of PM _{2.5})
DK	Open fireplace	Other stove, incl open fireplaces	740	10% of TSP
NO	Open fireplace	Open fireplace	802 (16.435 g/kg)	1.414 g/kg (9% of PM _{2.5})
SE	Open fireplace	Wood logs	150	7% of PM _{2.5}

*FI emission factors are calculated Implied emission factors.

** NO emissionsfactors for PM_{2.5} recalculated for comparison from g/kg to g/GJ using heating value of 16.8 GJ/ton.

Table 12. Emission factors for PM_{2.5} and BC for boilers using biomass in the Nordic countries

	Category	Technology	EF PM _{2.5} (g/GJ)	EF BC
DK	Boiler	Old boiler, pre-1980, no acc	1,800	30% of TSP
DK	Boiler	Old boiler, pre-1980, acc	900	35% of TSP
FI*	Boiler	Manually Fed without accumulator	700	210 g/GJ (30% of PM _{2.5})
DK	Boiler	New boiler, post-1980, no acc	413	30% of TSP
DK	Boiler	New boiler, post-1980, acc	206	35% of TSP
FI	Boiler	Manually Fed with accumulator	135	24 g/GJ (18% of PM _{2.5})
FI	Boiler	Manually Fed Modern	17	0.5 g/GJ (3% of PM _{2.5})
SE	Boiler	Boiler wood logs	150	16% of PM _{2.5}
FI	Boiler	Automatic Fed Wood Chips	16	0.5 g/GJ (3% of PM _{2.5})
SE	Boiler	Boiler wood chips	100	15% of PM _{2.5}
DK	Boiler	Pellet boilers/stoves	32	35% of TSP
FI	Boiler	Automatic Fed Pellets	20	0.6 g/GJ (3% of PM _{2.5})
SE	Boiler	Boiler pellets	30	15% of PM _{2.5}

*FI emission factors are calculated implied emission factors.

Table 13. Emission factors for PM_{2.5} and BC for open fireplaces in the Nordic countries

	Category	Technology	EF PM _{2.5} (g/GJ)	EF BC
FI	Open fireplace	Open fire place and other stove	638	35 g/GJ (5% of PM _{2.5})
DK	Open fireplace	Other stove, incl open fireplaces	740	10% of TSP
NO	Open fireplace	Open fireplace	802 (16,435 g/kg)	1,414 g/kg (9% of PM _{2.5})
SE	Open fireplace	Wood logs	150	7% of PM _{2.5}

*FI emission factors are calculated Implied emission factors.

**NO emission factor for PM_{2.5} recalculated for comparison from g/kg to g/GJ using heating value of 16.8 GJ/ton.

Table 14. Emission factors for PM_{2.5} and BC for stoves using biomass in the Nordic countries

	Category	Technology	EF PM _{2.5} (g/GJ)	EF BC
DK	Stove	Old stove, stove pre-1990	930	15% of TSP
FI	Stove	Iron stoves conventional	113	27 g/GJ (24% of PM _{2.5})
NO**	Stove	Stove old technology (before 1998)	1,036 (21,565 g/kg)	0.96 g/kg (5–7% of PM _{2.5})
DK	Stove	New stove, with DS mark 1990–2005	740	15% of TSP
NO	Stove	Stove new technology (after 1998)	614 (12.73 g/kg)	0.86 g/kg (5–7% of PM _{2.5})
DK	Stove	Modern stove, conforming with Danish legislation (2008)	608	15% of TSP
FI	Stove	Iron stoves modern	72	17 g/GJ (24% of PM _{2.5})
DK	Stove	Eco labelled stove	206	15% of TSP
SE	Stove	Stove wood logs	100	10% of PM _{2.5}
FI	Stove	Kitchen range	53	34 g/GJ (64% of PM _{2.5})
DK	Stove	Pellet boilers/stoves	29	29% of TSP
SE	Stove	Stove pellets	30	15% of PM _{2.5}
FI	Stove	Masonry Heaters Conventional	138	47 g/GJ (34% of PM _{2.5})
FI	Stove	Masonry Heaters Modern	49	19 g/GJ (39% of PM _{2.5})
FI	Stove	Masonry Ovens	48	15 g/GJ (31% of PM _{2.5})
FI	Stove	Sauna stoves	470	182 g/GJ (39% of PM _{2.5})
FI	Stove	Sauna stove modern	204	91 g/GJ (44% of PM _{2.5})

*FI emission factors are calculated implied emission factors.

**NO emission factor for PM_{2.5} recalculated for comparison from g/kg to g/GJ using heating value of 16.8 GJ/ton.

As is evident from the tables, the emission factors vary widely, both between technologies and also between countries for supposedly similar technologies. As the structure and details in the national PM and BC emission inventories are heterogenic in the way they specify emissions from old and new appliances, different technologies and the way of use of the appliances, it is not unambiguous to compare their emission levels. However, as a common feature it can be concluded that old stoves

and manually fed appliances are in all countries estimated to generate the highest specific emissions while automatically fed units and pellets technologies have low emission factors.

In the current Nordic inventories, manually fed old stoves are estimated to emit 750–1,000 g PM_{2.5}/GJ and the same emission levels are used also for new manually fed stoves in Denmark and Norway. In Sweden and Finland the emission level for old boilers is 150–630 g PM_{2.5}/GJ while the level for modern boilers in Finland is 17 g PM_{2.5}/GJ. Emission factors for pellet boilers and stoves in all countries are around 30 g PM_{2.5}/GJ.

In the Arctic ACAP-project “Reduction of Black carbon emissions from residential wood combustion in the Arctic”, (ACAP, 2014) it is concluded that BC emission factors in the Arctic (including Nordic) countries have been established based on relatively few measurements and varying methods, that emission factors vary widely, that different technology categories in the national inventories make direct comparison between the technology specific emission factors challenging, and that the BC emission factors indicate significant potential for emission reduction if switching from old to advanced technology. These conclusions are well in line with the results above.

Calculated Implied Emission Factors (IEF) for PM_{2.5} for the total residential biomass combustion in the Nordic countries (Table 15) show that Norway has the highest “national” IEF, followed by Denmark. Sweden has the lowest IEF while Finland has a somewhat higher. In Figure 37 the biomass fuel consumption and the resulting estimated emissions of PM_{2.5} as reported in national inventories are presented as a total for each country.

Table 15. Calculated implied emission factors for the total residential biomass combustion in the Nordic countries (2011 or 2012)

Country	Activity (TJ)	Emissions of PM _{2.5} (Gg)	IEF (g/GJ)
DK	32,976	14.1	428
FI	68,737	12.1	176
NO*	25,812	21.3	825
SE	45,895	5.3	116
Total	173,605	52.8	304

*Activity recalculated from 1,536,455 ton, using the heating value 16.8 GJ/ton. IEF=13.85 g/kg.

Figure 36. Residential biomass fuel consumption and emissions of $PM_{2.5}$ in the Nordic countries

The obvious differences in the relation between biomass fuel use and resulting emissions of $PM_{2.5}$ between the countries are of course partly due to the varying stock and use of combustion technologies, but also to the different emission measurement methods underlying the national emission factors, where one reason for generally lower emission factors for $PM_{2.5}$ in Sweden may be that the emission factors are based on hot flue gas measurements while the Danish, Finnish and Norwegian emission factors are based on diluted sampling. Differences may also be due to the even more uncertain assumptions e.g. on firing habits and operation and maintenance taken into account in the national emission factors. For example in Finland the emission factors include specific assumptions on the share of both “bad combustion” time and magnitude of emissions by appliance type, the sector where the appliance is used as well as the development of the technologies over time.

There are also, most likely, real differences between the countries in how firing is generally performed, due to differences in the most commonly used combustion technologies and in national traditions. The purpose of firing (e.g. main heating source or supplementary heating) impacts the selection of type of appliance. All these factors will also influence the emissions.

5.4 Emission factors for PM_{2.5} and BC from the EMEP/EEA Guidebook

The EMEP/EEA Air Emission Inventory Guidebook¹⁶ was updated in 2013 to include emission factors for BC. In Table 16 emission factors from the Guidebook for PM_{2.5} and BC for residential sources burning wood are presented. In the table uncertainties are also given as the 95% confidence interval for each emission factor. BC emission factors are presented in % of PM_{2.5}. The emission factors for residential plants burning wood in the Guidebook take into account the whole combustion cycle, and are based on diluted sampling measurements. In the Guidebook extensive references to literature sources for all emissions factors are given, but they are not repeated here.

¹⁶ <http://www.eea.europa.eu/publications/emep-eea-guidebook-2013>

Table 16. Emission factors and 95% confidence intervals for PM_{2.5} and BC for residential combustion sources burning wood from EMEP/EEA Air Pollutant Emission Inventory Guidebook (2013). Tier 1=non-technology specific, general emission factors to be used when detailed technologies are not known. Tier 2=more detailed, technology specific emission factor

Table*	NFR**	Tier	Technology/fuel	Pollutant	Value	Unit	95% confidence interval	
							Lower	Upper
3–6	1.A.4.b	1	biomass (<50 kW)	PM2.5	740	g/GJ	370	1,480
				BC	10	% of PM2.5	2	20
3–14	1.A.4.b.i	2	open fireplaces burning wood	PM2.5	820	g/GJ	410	1,640
				BC	7	% of PM2.5	2	18
3–17	1.A.4.b.i	2	conventional stoves burning wood and similar wood waste	PM2.5	740	g/GJ	370	1,480
				BC	10	% of PM2.5	2	20
3–18	1.A.4.b.i	2	conventional boilers < 50 kW burning wood and similar wood waste	PM2.5	470	g/GJ	235	940
				BC	16	% of PM2.5	5	30
3–23	1.A.4.b.i	2	energy efficient stoves burning wood	PM2.5	370	g/GJ	285	740
				BC	16	% of PM2.5	5	30
3–24	1.A.4.b.i	2	advanced / ecolabelled stoves and boilers burning wood	PM2.5	93	g/GJ	19	233
				BC	28	% of PM2.5	11	39
3–25	1.A.4.b.i	2	pellet stoves and boilers burning wood pellets	PM2.5	29	g/GJ	9	47
				BC	15	% of PM2.5	6	39

*Table number in the EMEP/EEA Air Pollutant Emission Inventory Guidebook (2013).

** NFR=Nomenclature For Reporting used in the emission reporting tables submitted to CLRTAP.

None of the Nordic countries use emission factors for PM_{2.5} directly taken from the EMEP/EEA Guidebook. It is regarded as good practice to use national information, if available, in developing an inventory. All of the Nordic countries thus make use of national information on PM_{2.5}, sometimes in combination with Guidebook data, depending on national conditions and circumstances. For BC, Denmark used emission factors from GAINS in the first inventory carried out in 2010. From 2015 BC will be included in the Danish annual inventories and the BC inventory will be based on the information in the EMEP/EEA Guidebook. Sweden in its present BC inventory has used factors for BC directly from the EMEP/EEA Guidebook, while Norway and Finland to a larger degree use nationally derived factors for BC for residential combustion.

5.5 Available emission measurements for PM_{2.5} and BC from residential biomass combustion in the Nordic Countries

5.5.1 *Measurements in Finland*

In Finland emissions from residential combustion have been studied over a long period, especially during the last decade by several universities and research institutes. The Finnish Funding Agency for Innovation TEKES, for instance, in the beginning of the 2000s funded a programme to study small particle emissions from wood combustion. The programme focused on the impact of sampling and measurement techniques on the results and the differences between different measurement methods. In the other components of the work emission models and national emission factors were developed. Further needs for measurements have been identified e.g. related to samples from the different combustion cycles (including EC).

The emission measurements from domestic combustion applications have included both laboratory and field measurements. Measurements in Finland use dilution sampling (UEF, 2014). University of Eastern Finland (UEF) maintains a collection of measurements results from over 10 years. The data covers measurement results both for normal combustion conditions, where the combustion cycle is carried out according to appliance specific instructions, and for conditions modified for “bad” combustion. Parts of the measurement results are available through the online database PUPPO.¹⁷

5.5.2 *Measurements of TSP and BC from wood combustion in the residential sector, Norway*

In 2012/2013 SINTEF Energy Research carried out a project for the Norwegian Environment Agency, in collaboration with SINTEF NBL (Norwegian Fire Research Laboratory) and University of Eastern Finland (UEF), where the amount of elemental carbon (EC), OC and total amount of particles (TSP) emitted from Norwegian wood stoves were measured (Seljeskog, Goile *et al.*, 2013). Seljeskog and Goile *et al.* (2013) presents emission factors of EC, OC and total amount of particles as

¹⁷ <http://wanda.uef.fi/pupo/>

grams per kilo wood burned for combustion in closed stoves with old technology, and in closed stoves with new technology.

Emission factors for these compounds were established by performing experimental measurements on two selected representative stoves, A) Closed stove – old technology (produced before 1998) and B) Closed stove – new technology (produced after 1998). The two selected closed wood stoves were the old and new model of the Jøtul F3 series. The intention was to develop emission factors for EC, OC and TSP as grams per kilo fired dry wood. In Norwegian primary households, these two types of stoves represent 96% of all wood combustion.

The wood stove experiments were performed according to the Norwegian national standard for testing closed wood heaters and smoke emission, NORSK STANDARD NS3058/NS3059. The combustion experiments were carried out by SINTEF Energy Research AS, and the Norwegian standard for stoves was used. A thermal-optical method was selected to provide results for the two components EC and OC. UEF made OC/EC analyses of the filter samples with an OC/EC analyzer manufactured by Sunset Laboratory Inc., following the NIOSH 5040 analysis protocol.

The Norwegian standard for closed wood stoves has been developed with the intention to reflect a typical Norwegian household wood stove operation. The Norwegian Standard requires four tests at four different burnings rates. The stoves are tested under less favourable combustion conditions with reduced burning rates lower than 1.25 g/kg. This leads to much higher emissions than what the stove is optimized for. A dilution tunnel captures condensed particles in addition to solid particles.

Emission factors for both normal firing and firing without night firing (smouldering fire) were proposed, see Table 17.

No measurements were made on open fire places. BC and OC from open fire places were estimated as shares of $PM_{2.5}$. Table 17 shows the shares of $BC/PM_{2.5}$ and $OC/PM_{2.5}$ taken from IIASA.

Table 17. Emission factors for fuelwood, g/kg dry matter. Normal firing and firing without night firing (applied in larger cities)

Source	TSP	PM _{2.5}	EC/BC	OC	Source
Open fireplace*	17.3	16.4	9 % of PM _{2.5}	48 % of PM _{2.5}	IIASA 2012
Small stove, old technology - with night firing	22.7	21.6	0.96	16.74	Seljeskog, Goile <i>et al.</i> 2013
Small stove, old technology - without night firing	17.4	16.5	1.01	12.89	Seljeskog, Goile <i>et al.</i> 2013
Small stove, new technology – with night firing	13.4	12.7	0.86	10.47	Seljeskog, Goile <i>et al.</i> 2013
Small stove, new technology – without night firing	12.2	11.6	0.9	9.26	Seljeskog, Goile <i>et al.</i> 2013

Source for emission factors TSP and PM_{2.5} for open fireplace; Sandmo, T., K. Flugsrud, *et al.* (2014).

5.5.3 Sweden

In Sweden no measurements of BC from residential combustion have been made, but a lot of work regarding emissions from wood burning was performed and reported during the years around 2005–2007 (Johansson *et al.*, 2006, Paulrud *et al.*, 2006, Ryde and Johansson, 2007, Todorovic *et al.*, 2007). In later years additional work has been published (e.g. Bäfver *et al.*, 2011, Boman *et al.*, 2011). Swedish measurement experts have also participated in international efforts in comparing emission measurement standards and resulting emission factors for particulate matter (e.g. Nussbaumer *et al.*, 2008). Recently (2013–2014) additional test measurements of PM were performed on assignment from the Swedish Energy Agency on eleven modern pellets boilers, nine modern wood log boilers and two wood stoves (Energimyndigheten, 2014). The tests were performed in lab, using the measurement standard EN-303-5 (hot flue gas measurements). The PM emissions from the pellets boilers ranged from 16–162 mg/m³, with an average of 62 mg/m³ and a median value of 44 mg/m³. For the wood boilers the range of emissions of PM was 26–65 mg/m³, with an average of 36 and median 30 mg/m³. For the two wood stoves, the emissions of PM were 53 and 137 mg/m³ respectively. These tests indicate that for new, modern wood boilers the level of PM emissions is as low as for pellets boilers, or even lower in some cases.

All of the Swedish PM emission measurements have been performed in hot flue gases, except in the work by Ryde and Johansson (2007) where PM measurements in hot flue gases and in dilution tunnel were compared. Field measurements were performed in the studies by Johansson *et al.* (2006) on wood boilers, and in Paulrud *et al.* (2006) on wood fuelled stoves and inserts, while the other studies were lab measurements.

The comparison between dilution tunnel measurements and hot flue gas measurements on two wood stoves (Ryde and Johansson, 2007) showed ratios of 4.3 and 4.1 as an average of four tests on each stove. Ryde and Johansson also made a comparison for a wood boiler at nominal effect, where the measurements in the dilution tunnel were 2.2 times higher than the hot flue gas measurements, as an average of four tests. The measurement standards used in the study were Swedish standard SS028426 (hot flue gas measurement) and Norwegian standard NS 3058-2 (dilution tunnel).

In the field measurements on wood boilers by Johansson *et al.* (2006), particulate matter was sampled on a filter within the chimney (hot flue gases). The sampling covered the whole combustion cycle and the measured PM emissions from 13 boilers without accumulator tank (not fulfilling Swedish BBR-requirements, see explanation below Table 18) ranged from 73–260 g/GJ with a median and average of 150 g/GJ. For 19 measurement cases on wood boilers with accumulator tank (fulfilling Swedish BBR-requirements) the PM emissions ranged from 26–450 g/GJ with an average of 150 and median 120 g/GJ. These emission factors are well in line with those used for estimating PM_{2.5} emissions from wood boilers in the national Swedish emission inventory (150 g/GJ).

The fuel quality (wood species, fuel wood storage, moisture, etc) and how the whole firing cycles were managed were documented (Johansson *et al.* 2006). There were various fuel wood species and variations in the handling of the ignition phase as well as how much and when additional wood logs were added during the firing cycle. Wood fuel moisture was between 10–29% with an average and median of around 15%. During the study it was noted that all operators involved had good firing habits, firing with small batches, and it was concluded that all operators that participated in the study were interested and knowledgeable. In Paulrud *et al.* (2006) a similar study as in Johansson *et al.* (2006) focused on stoves and inserts, including field emission measurements, documentation of firing habits and conditions during measurement, as well as a broader survey. The survey covered questions on the type of combustion equipment, how often and how it is used, the type of wood and how the firewood is stored. The results of the measurements for whole firing cycles showed that emissions of PM ranged from 22–110 g/GJ, with an average of 61 g/GJ for stoves, and 26–180 g/GJ with an average of 94 g/GJ for inserts. The fuelwood consisted of birch or mixed wood with moisture contents between 10–18%. The Swedish national emission factor for PM_{2.5} from stoves is 100 g/GJ which is in accordance with the reported measurement results in Paulrud *et al.* (2006).

In the study by Todorovic *et al.* (2007) a synthesis and assessment of emission factor results from several earlier measurements are made. In the report also information from the chimney sweepers register was used to make assumptions on the types of biomass combustion technologies and their extent of use in order to estimate emissions of PM in Sweden. In the assessment, it was assumed that 5% of the boilers without accumulator tank were fired with restricted air supply. In Table 18 the underlying activity data and emission factors for the assessment is presented. Table 19 presents the resulting estimated “national” emission factors, given for an assumed average combustion equipment stock, calculated from the information in Table 18, combined with a synthesis and assessment of the emission factors for all the SLCPs (Todorovic *et al.*, 2007). The derived “national” emission factor for PM, as a combination of fuel use in 6 different defined technologies, is 74 g/GJ, which is even lower than the calculated “national” IEF of 116 g/GJ (Table 15) based on the 2011 residential biomass combustion emissions in the Swedish national inventory.

Table 18. Number of combustion appliances of different types in Sweden (before 2007), estimated consumption of biomass (TJ/year), and emission factors for PM (Todorovic *et al.*, 2007)

	IBGP	IBGB	IBGA	BGA	PE	TLE+LLE	Total
Number of appliances	7,500	142,500	10,000	70,000	67,000	84,000+ 61,1000	992,000
Share (%)	0.76	14	1.0	7.1	6.8	8.5+62	100
TJ biomass/year	900	17,000	1,200	6,700	6,500	7,700	40,100
Share of biomass (%)	2.2	43	3.0	17	16	19	100
Average EF for PM (g/GJ)	1,300	120	95	44	28	58 (LLE)	
EF max-min for PM (g/GJ)	350–2,200	73–260	87–100	11–450	10–66	22–180 (LLE)	

IBGP, not approved according to building rules (BBR), without accumulator tank, restricted air supply.

IBGB, not approved according to building rules, without accumulator tank, firing with many small batches of wood.

IBGA, not approved according to building rules, with accumulator tank.

BGA, approved according to building rules, with accumulator tank.

PE, pellets.

TLE, heavy local space heaters.

LLE, light local space heaters.

Table 19. Estimated national emission factors for residential biomass combustion, based on an assumed average combustion equipment (Todorovic *et al.*, 2007)

Pollutant	Emission factor (g/GJ)
CO	2,300
NMVOC	110
CH ₄	110
PM	74

5.6 Conclusions regarding residential biomass combustion

In 2011 the emissions of $PM_{2.5}$ from residential combustion in the Nordic countries was about 64 Gg or 47% of the total Nordic $PM_{2.5}$ emissions. For BC the estimated emissions was 10 Gg, 45% of Nordic total emissions. Residential combustion is thus the major single Nordic source of $PM_{2.5}$ and BC emissions. Individual national conditions may however differ as for example in Norway, where heating in households contributed to 23% of total BC emissions in 2011.

All Nordic countries, except Iceland, have developed emission inventories for $PM_{2.5}$ and BC from residential biomass combustion. Conditions regarding residential biomass combustion are, however, more differentiated than might be expected for the neighboring Nordic countries. This is also highlighted in Levander and Bodin (2014) where it is stated that the market for domestic heating products shows a great diversity of products across the Nordic countries, and that due to various national, cultural, and local conditions, space heating demands have been met in many different ways in the Northern countries. The types and uses of combustion appliances are quite different between all countries, where Norway primarily use stoves, Denmark a combination of stoves and boilers, Sweden has the highest share of boilers and Finland is the only country with significant use of masonry heaters and sauna stoves, in addition to boilers and other stoves. These differences are also reflected in the inventory methodologies in the countries, where different structuring and detail are applied for technologies and emission factors in the emission calculations.

A further differentiation is in the measurement methodologies underlying the national emission factors for $PM_{2.5}$ (and BC) where Denmark, Norway and Finland have used dilution tunnel measurements while the Swedish emission factors are based on hot flue gas measurements. These two principally different measurement methods do not, especially in case of incomplete combustion conditions, give the same results as PM from the dilution tunnel measurement also include particles formed as semi volatile gases are condensed, adding to the PM mass.

In order to ensure comparability between PM (and BC) emission inventories in the future there is a need to establish a common emission measurement method for deriving emission factors, since measured differences of in the order of 2–4 in the studies referred above, and a factor of up to 10 in worst cases, obviously makes it challenging to compare results. The consistency of emission factors for $PM_{2.5}$ are of critical

importance in estimating BC if BC is calculated based on emission factors given as a share of PM_{2.5}.

The assessment and comparison of the nationally used emission factors for PM_{2.5} show that emission factors vary widely, both between technologies but also between countries for supposedly similar technologies. These differences can be attributed partly to the non-comparable measurement methods underlying the emission factors, but also to assumptions made regarding firing habits, fuel quality etc., which influences emissions and emission factors. It is also not unlikely that conditions influencing emissions, like for example firing habits, in reality are different in the Nordic countries.

Given the variations in combustion technology stock, emission measurement methodology and other important influencing factors (as assumptions or in reality), a straightforward comparison between the countries is not easily accomplished.

It is clear is that in general information on emission factors for BC is scarce, with a few exceptions (e.g. recent results from measurements on Norwegian stoves, under Norwegian conditions, and measurements in Finland). The Nordic BC emission inventories, at present, to a large extent rely on information on BC as a fraction of emitted PM_{2.5} from the EMEP/EEA Guidebook, which represents the currently best available collected knowledge. Using emission factors from the Guidebook will give results that are acceptable, but as has been discussed above, conditions differ in the Nordic countries and it is unclear how well country specific conditions and circumstances are reflected in the factors presented in the Guidebook. As residential biomass combustion is such a dominating source of PM_{2.5} and BC emissions in the Nordic countries, the present uncertainties need to be reduced in order for the inventory results to serve as a sufficiently reliable basis for policy development and actions.

The objective of this project is to improve the Nordic emission inventories of primarily BC (and PM_{2.5}) by performing emission measurements, in order to create an improved basis for development of emission factors. For technologies using pellets the emission factors agree fairly well, as combustion conditions in pellets technologies are more controlled and foreseeable than when using wood logs. For most other biomass technologies than pellets combustion, the reported data on technology use, emissions factors and estimated emissions from the countries need to be carefully assessed in order to design a measurement program that will benefit the Nordic BC (and PM_{2.5}) emission inventories by improved emission factors.

Emission factors, valid on the national scale, should be derived based on representative emission measurements for national conditions. The background analysis shows that there is a need to improve or adapt national information to be able to make more use of the available emission factors from the other Nordic countries and from the EMEP/EEA Guidebook. This could include for example a more detailed knowledge of combustion technologies in use, and assessments of the influences of national firing habits etc. This type of information is country specific and must be treated outside this project.

6. Non-road and on-road diesel vehicles in the Nordic countries

6.1 Important diesel vehicles emission sources in the Nordic countries

Road traffic vehicle types, diesel fuel consumption and estimated PM_{2.5} and BC emission from road traffic in the Nordic countries are presented in Table 20. In the table also the implied emission factors for PM_{2.5} are calculated. The differences between the countries for the same vehicle types can be due to different age profiles and Euro standard mix of the vehicle fleet, but also due to different emission factors used in the countries.

Table 20. Road traffic vehicle types, diesel fuel use, estimated emissions of PM_{2.5} and BC and calculated IEF for PM_{2.5}

Country	Technology, Road traffic, diesel	Activity (TJ)	Share of activity	Emissions of PM _{2.5} (Gg)	Share of PM _{2.5} emissions	PM _{2.5} IEF (g/GJ)**	Emissions of BC (Gg)	Share of BC emissions
Denmark	Passenger cars	41,837	40%	0.54	44%	12.9	0.54	40%
Denmark	Light duty vehicles	22,539	22%	0.42	34%	18.6	0.41	31%
Denmark	Heavy duty vehicles	39,810	38%	0.27	22%	6.8	0.40	29%
		104,186		1.23		11.8	1.35	
Finland	Passenger cars	39,818	38%	0.84	44%	21.1		
Finland	Light duty vehicles	16,220	16%	0.50	26%	30.8		
Finland	Heavy duty vehicles	47,720	46%	0.57	30%	11.9		
		103,758		1.92		18.5		
Norway	Passenger cars	851,595*	38%	0.39	35%	10.6. (0.46**)	0.28	36%
Norway	Light duty vehicles	469,156*	21%	0.43	39%	21.3 (0.92**)	0.30	39%
Norway	Heavy duty vehicles	924,678*	41%	0.30	27%	7.4 (0.32**)	0.19	24%
		2,245,429*		1.11		11.4 (0.49**)	0.77	
Sweden	Passenger Car	40,837	31%	0.33	26%	8.1	0.27	33%
Sweden	Light duty vehicles	19,112	15%	0.35	28%	18.3	0.28	33%
Sweden	Heavy duty vehicles	70,257	54%	0.57	46%	8.1	0.27	33%
		130,206		1.25		9.6	0.82	

*Activity in ton.

**kg/ton.

Non-road diesel vehicles, their use of fuel and corresponding estimated emissions of PM_{2.5} and BC, as well as calculated implied emission factors (IEF) in the Nordic countries is presented in Table 21. The differences in IEFs may be due to different types and age classes of vehicles in use in the countries, but also due to different emission factors.

Table 21. Non road diesel vehicles fuel consumption and resulting PM_{2.5} and BC emissions

Country	Technology	Activity (TJ)	Emissions of PM _{2.5} (Gg)	IEF (g/GJ)	Emissions of BC (Gg)	IEF BC (% of PM _{2.5})
Denmark	Non road diesel	34,870	1.40	40.1	0.93	67%
Finland	Non road diesel	31,635	0.91	28.9		
Norway	Non road diesel	22,664 (525,845*)	2.55	112.3 (4.84*)	1.19	47%
Sweden	Non road diesel	44,144	1.44	32.6	0.77	53%

*Activity in ton, IEF in kg/ton.

6.2 Factors influencing uncertainties for diesel vehicles combustion sources

Diesel fuelled road transport vehicles and non-road mobile machinery are the most important mobile (land based) sources of PM_{2.5} and BC emissions. The uncertainties of the emission estimates rely on the uncertainties of the activity data and the emission factors used.

For road transport, activity data are often well described in the Nordic countries. Fleet numbers split into detailed vehicle layers (e.g. fuel type, engine size, first registration year, emission legislation standard) are in many cases available from national vehicle registers. However, in some cases the emission legislation standard needs to be estimated by referring vehicle type and first registration year to the relevant emission legislation directive class.

Mileage numbers are often available from road administration statistics, at least in time series per vehicle type. Further, detailed mileage numbers for specific statistical year(s) are in some cases known from national vehicle inspection data, and vehicle age-mileage distribution keys can then be derived for vehicle types or sub types in these cases. For other years, the vehicle type specific mileage data can be broken down further into vehicle layers by using the vehicle age-mileage distribution function in question, and subsequently scale specific mileage

numbers in order to reach the total mileage per vehicle type known from the statistics. Emission factors for PM and BC fractions of PM are generally well described for road transport and detailed according to the vehicle layers defined in the national road transport models.

For non-road mobile machinery, the machinery stock composition is less certain compared to the fleet description available for road transport. For non-road machines fully detailed statistical registers are not present. Instead inventory compilers need to construct their own stock composition matrix per equipment type e.g. from total machinery numbers, annual new sales and assumed engine life times. Assumptions also need to be made on engine size, annual working hours per year and engine load factors based on key expert judgment.

PM emission factors for non-road machinery are derived from relatively small numbers of measurements, and in addition measurement data for modern engine types are in some cases not presently available. Instead emission factors are constructed by multiplying the present emission factor with scaling ratios obtained from emission directive values. For non-road engines emission data for BC are very scarce. Hence, due to the engine similarities between non road and road transport engines, the source for non-road BC emission information are in many cases road transport. BC emission data are chosen by selecting emission data from a road transport vehicle type with a similar engine emission technology level.

6.3 Emission measurement methods for diesel exhaust emissions

PM in the exhaust from road vehicles and non-road vehicles are normally measured following the methods stipulated in the exhaust emission regulations, i.e. through gravitational methods after dilution. Filters are then analysed for BC and/or EC. When using diesel of road quality the difference between BC and EC will be small.

6.4 Emission factors for PM_{2.5} and BC from mobile diesel combustion in the Nordic emission inventories

In Table 22 calculated implied emission factors from the Nordic national emission inventories for diesel vehicles and machinery are presented. The differences between the countries for the same vehicle types can be

due to different existing age profiles and Euro standard mix of the vehicle fleet, but also due to different emission factors used in the countries.

Table 22 A. Emission factors for PM_{2.5} and BC for diesel vehicles and machinery in the Nordic countries

Technology		Based on which model/measurement method/cycle	Implied emission factor (IEF) PM _{2.5} (g/GJ)	Reference	BC (%)
DK	Passenger cars	GB COPERT IV	12.9	EMEP/EEA (2013), Danish IIR	81.8
DK	Light duty vehicles	GB COPERT IV	18.6	EMEP/EEA (2013), Danish IIR	78.5
DK	Heavy duty vehicles	GB COPERT IV	6.8	EMEP/EEA (2013), Danish IIR	66.5
DK	0801 Military	Derived from road	11.8	Danish IIR	75.7
DK	0802 Railways	Danish Railways	24.2	Danish IIR	73.7
DK	0806 Agriculture	GB non road	39.3	EMEP/EEA (2013), Danish IIR	50.0
DK	0807 Forestry	GB non road	23.4	EMEP/EEA (2013), Danish IIR	50.0
DK	0808 Industry	GB non road	47.5	EMEP/EEA (2013), Danish IIR	50.0
FI	Passenger cars	LIPASTO/LIISA	21.1	Finnish IIR 2014	
FI	Light duty vehicles	LIPASTO/LIISA	30.8	Finnish IIR 2014	
FI	Heavy duty vehicles	LIPASTO/LIISA	11.9	Finnish IIR 2014	
FI	Railways	LIPASTO/RAIL	29.0	Finnish IIR 2014	
FI	Commercial / industry	TYKO	26.8	Finnish IIR 2014	
SE	Passenger cars	HBEFA	8.0	Boström <i>et al.</i> , 2004b	64
SE	Light duty road vehicles	HBEFA	17.0	Boström <i>et al.</i> , 2004b	75
SE	Heavy duty road vehicles	HBEFA	6.1	Boström <i>et al.</i> , 2004b	70
SE	Railways	AD from Statistic Sweden	95.7	Boström <i>et al.</i> , 2004b	64
SE	Off-road; industry	National off-road model	26.1	Boström <i>et al.</i> , 2004b	75
SE	Off-road; farming	National off-road model	31.9	Boström <i>et al.</i> , 2004b	70
SE	Off-road; forestry	National off-road model	21.2	Boström <i>et al.</i> , 2004b	65

*unit conversion from kg/tonne to g/GJ using the factor 43.1 GJ/tonne for diesel.

Table 23 B. Emission factors for PM_{2.5} and BC for diesel vehicles and machinery in the Nordic countries

Technology		based on which model/measurement method/cycle	(IEF) PM _{2.5} kg/tonne	Reference	BC (kg/tonne) and % of PM _{2.5}
NO	Passenger cars	HBEFA (INFRAS 2009) Auto diesel	0.46 (10.6 g/GJ)	The Norwegian emission Inventory 2013, rap 30/2013	0.325 (71%)
NO	Light duty road vehicles	HBEFA (INFRAS 2009) Auto diesel	0.92 (21.3 g/GJ)	As above	0.644 (70%)
NO	Heavy duty road vehicles	HBEFA (INFRAS 2009) Auto diesel	0.32 (7.4 g/GJ)	As above	NO
NO	Railways	Auto diesel	3.8 (88.1 g/GJ)	As above	46% of PM _{2.5}
NO	Motorized equipment	Auto diesel Light fuel oil	3.8- 6.75 (83.5–157 g/GJ)	As above	41% of PM _{2.5}
NO	Small boats 4 stroke	Auto diesel	4 (92.8 g/GJ)	As above	41% of PM _{2.5}

*unit conversion from kg/tonne to g/GJ using the factor 43.1 GJ/tonne for diesel.

6.5 Emission factors for BC for diesel vehicles and machineries from the EMEP/EEA Guidebook

The EMEP/EEA Air Emission Inventory Guidebook includes emission factors for PM_{2.5} as well as for BC as a fraction of PM_{2.5}. The emission factors are presented as different Tiers, depending on how detailed underlying information that is available. For road traffic, for example, there are default emission factors for BC as a fraction of PM_{2.5} (Table 24), where disaggregation is only made on passenger cars, light duty or heavy duty diesel vehicles. If information is available on the existing vehicle fleet divided in Euro classes, more detailed emission factors should be used, as given in Table 25. In the Guidebook there is extensive referencing to underlying literature.

Table 24. Road traffic diesel, Tier 1 BC emission factors as fraction of PM_{2.5}

Tier 1 BC fractions of PM	
Vehicle category	f-BC
Diesel passenger cars	0.57
Diesel light duty vehicles	0.55
Diesel heavy duty vehicles	0.53

Source: Table A4-4 in EMEP/EEA Guidebook. (EMEP/EEA, 2013).

Table 25. More detailed emissions factors for EC from diesel vehicles, based on Euro standard classification

Vehicle category	Euro standard	EC/PM _{2.5} (%)	Uncertainty (%)
Diesel PC and LDV			
	Conventional	55	10
	Euro 1	70	10
	Euro 2	80	10
	Euro 3	85	5
	Euro 4	87	5
	Euro 3–5 DPF w. fuel additive	10	50
	Euro 3–5 Catalyzed DPF	20	50
Diesel HDV			
	Conventional	50	20
	Euro I	65	20
	Euro II	65	20
	Euro III	70	20
	Euro IV	75	20
	Euro V	75	20
	Euro VI	15	30

EMEP/EEA, 2013.

For non-road machinery, Table 26, Table 27 and Table 28 provide emission factors for BC to be used depending on detail in available national information regarding the fleet of non-road machinery (EMEP/EEA

Guidebook, 2013). In the Guidebook even higher technological detail is available as Tier 3 emission factors.

Table 26. Non- road machinery, diesel, BC-fractions based on detailed technologies

Table D.1 Proposed f-BC fractions as input for aggregated Tier 1 and 2 for non-road engines				
Technology	Diesel < 130kW		Diesel >=130 kW	
	f-BC	+/- (%)	f-BC	+/- (%)
<1981	0.55	10	0.5	20
1981–1990	0.55	10	0.5	20
1991-Stage I	0.55	10	0.5	20
Stage I	0.8	10	0.7	20
Stage II	0.8	10	0.7	20
Stage III	0.8	10	0.7	20
Stage IIIA	0.8	10	0.7	20
Stage IIIB, no DPF	0.8	50	0.7	20
Stage IIIB, DPF	0.15	50	0.15	20
Stage IV, no DPF	0.8	50	0.7	30
Stage IV, DPF	0.15	50	0.15	30

EMEP/EEA, 2013.

Table 27. Non-road machinery, diesel, BC-fractions based on sector of use of machinery

Table D.2 Tier 1 BC fractions of PM for non road diesel engines	
Category	f-BC
Agriculture	0.57
Forestry	0.65
Industry	0.62

Based on implied factors from Danish inventory. (EMEP/EEA, 2013).

Table 28. Non-road machinery, diesel, BC- fractions based on technology and sector of use

Table D.3 Tier 2 BC fractions of PM for non road diesel engines			
Category/technology	Agriculture	Forestry	Industry
<1981	0.55	0.55	0.55
1981–1990	0.55	0.55	0.55
1991-Stage I	0.54	0.54	0.55
Stage I	0.79	0.78	0.80
Stage II	0.77	0.76	0.80
Stage IIIA	0.70	0.70	0.70

EMEP/EEA, 2013.

6.6 Conclusions regarding mobile diesel vehicles and machinery

In 2011 the $PM_{2.5}$ emissions (including road abrasion) from road traffic in the Nordic countries was about 17 Gg or 13% of the total. For BC, where data are available for Denmark, Finland Norway and Sweden, the contribution from road traffic to the BC emissions was about 20%. For non-road mobile machinery the $PM_{2.5}$ emissions from the Nordic countries was 8 Gg (6% of the total) and the BC emissions about 3.5 gG (16% of the total). The emissions of BC from the road sector are relatively well characterized. For the non-road mobile machineries there are very few measurements and the emission inventories normally rely on BC fractions for PM from similar road diesel engines. However, also the PM emission factors must be considered as uncertain for non-road mobile machinery. In inventories the emission factors are normally related to the legal limits for PM emissions which are measured in engine bench tests with test cycles comprising of a number of stationary points. Thus, these emission factors will not account for cold starts or transient operation. Further, also the number and age of machines and engine load factors are factors that are not well characterized. For PM emissions the use of particle filters gives large differences in emissions and the use of these filters are not well described in the emission inventories.

7. Shipping

7.1 Important national and international shipping emission sources in the Nordic area

According to the definitions of the UNECE and UNFCCC conventions, international shipping emissions include the emissions from fuels used by vessels of all flags that are engaged in international water-borne navigation. These activities include journeys that depart in one country and arrive in a different country, and may take place at sea, on inland lakes and waterways and in coastal waters. International shipping fuel consumption excludes the consumption of fuels by fishing vessels, which is defined by the UNECE and UNFCCC conventions as being part of the national navigation total.

National shipping are activities taking place within a country, and are included in the national total estimates in the reporting to the conventions. The total Nordic emissions of PM_{2.5} from national shipping amounted to 3.5 Gg in 2011. From international shipping, the emissions of PM_{2.5} are higher, around 10 Gg (see chapter 3.6).

Table 29. National Danish shipping activities and emissions of PM_{2.5} and BC as reported to CLRTAP

Country	Technology	Fuel type	Activity (TJ)	Emissions of PM _{2.5} (Gg)	Share of PM _{2.5} emissions	Emissions of BC (Gg)	Share of BC emissions
Denmark	0803 Inland waterways	Diesel	1,002	0.096	24%	0.037	34%
Denmark	080402 National sea traffic	Diesel	2,903	0.062	16%	0.027	25%
Denmark	080402 National sea traffic	Residual oil	2,353	0.102	26%	0.004	4%
Denmark	080403 National fishing	Diesel	6,466	0.137	35%	0.040	37%
				0.397		0.109	

Table 30. National Finnish shipping activities and emissions of PM_{2.5} as reported to CLRTAP

Country	Technology	Fuel type	Activity (TJ)	Emissions of PM _{2.5} (Gg) 2012	Share of PM _{2.5} emissions
Finland 2011	Leisure boats	LIGHT FUEL OIL (S=0.0915%)	576	0.025	5.8%
Finland 2011	Leisure boats	MOTOR GASOLINE (S=0.001%)	1,627	0.191	44.5%
Finland 2011	Icebreakers	HEAVY FUEL OIL (S<1%)	637	0.033	7.7%
Finland 2011	Icebreakers	LIGHT FUEL OIL (S=0.0915%)	473	0.026	6.0%
Finland 2011	Fishing vessels	LIGHT FUEL OIL (S=0.0915%)	1,501	0.033	7.6%
Finland 2011	Ferryboats	LIGHT FUEL OIL (S=0.0915%)	257	0.006	1.3%
Finland 2011	Passenger ships	HEAVY FUEL OIL (S<1%)	84	0.002	0.5%
Finland 2011	Passenger ships	LIGHT FUEL OIL (S=0.0915%)	368	0.010	2.4%
Finland 2011	Cargo ships	HEAVY FUEL OIL (S<1%)	183	0.007	1.6%
Finland 2011	Cargo ships	LIGHT FUEL OIL (S=0.0915%)	1,697	0.066	15.5%
Finland 2011	Cruisers	LIGHT FUEL OIL (S=0.0915%)	123	0.003	0.6%
Finland 2011	Working boats	LIGHT FUEL OIL (S=0.0915%)	1,270	0.028	6.4%
				0.429	

Table 31. National Norwegian shipping activities and emissions of PM_{2.5} as reported to CLRTAP

Country	Technology	Fuel type	Activity (tonne)	Emissions of PM _{2.5} (Gg)	Share of PM _{2.5} emissions
Norway	National fishing	Marine gas oil/diesel	406,693	0.865	40%
Norway	National fishing	Heavy distillate	49,850		
Norway	National fishing	Heavy fuel oil	2,617		
Norway	National navigation	Marine gas oil/diesel	474,048	1.230	60%
Norway	National navigation	Heavy distillate	59,776		
Norway	National navigation	Heavy fuel oil	56,566		
				2.16	

Table 32. National Swedish shipping activities and emissions of PM_{2.5} as reported to CLRTAP

Country	Technology	Fuel type	Activity (TJ)	Emissions of PM _{2.5} (Gg) 2012	Share of PM _{2.5} emissions
Sweden	Navigation_Domestic	Diesel Oil	1,322	0.021	4%
Sweden	Navigation_Domestic	Domestic Heating Oil	712	0.011	2%
Sweden	Navigation_Small boats	Gasoline	1,065	0.096	19%
Sweden	Navigation_Domestic	Residual Oil	3,226	0.336	66%
Sweden	Fishing	Diesel Oil	1,664	0.038	7%
Sweden	Military use_Navigation	Diesel Oil	345	0.006	1%
				0.508	

7.2 Specific emission inventory studies for shipping made in the Nordic area

The later year's availability of AIS data for ship tracking has made it possible to set up detailed ship type or even ship specific emission inventories with a high temporal and spatial resolution.¹⁸ Such AIS based inventories have been made in Denmark, Finland, Norway and Sweden for navigation in the Baltic Sea, North Sea and the Arctic. During the later years, the Arctic area has also become the target for spatially distributed emission inventories set up by researchers in other countries. Although the studies generally tend to focus on the more traditional emission components associated with navigation activities like NO_x, SO₂, particulates as well as fuel consumptions and CO₂, a few of the works cited below comprise emission calculations for SLCP's also.

In the following these targeted shipping emission inventories are briefly described in terms of methodology used, ship types included and pollutants covered. Due to differences in e.g. inventory calculation methods, input activity data, emission factors and sea area covered no attempts are made to compare the emission results between models. Also it should be made clear that these inventory models are not set up to produce national and international navigation emission estimates according to UNECE and UNECE convention definitions (c.f. chapter 6.1), and hence no comparison is made between the individual model results and reported estimates for the Nordic countries. For more information about the shipping emission inventories described below, please refer to the references.

In *Denmark* an AIS based inventory was made for the waters around Denmark for the years 2007, 2011 and 2020 (Olesen *et al.*, 2009). The inventory combined AIS signals from ships, ship specific technical data, ship engine power demand (function of installed engine power and sailing speed) and engine power related emission factors. The calculations comprised the emissions of CO₂, NO_x, SO₂, VOC, TSP, PM₁₀ and PM_{2.5}, and estimates were given for the ship types: bulk carriers, ro-ro cargo, container ships, tankers, fishing vessels and other ships, and for flag nations as well.

Also in Denmark, an emission inventory was made for shipping in the Arctic area above 58.95 N based on terrestrial and satellite sampled AIS

¹⁸ AIS (Automatic Information System) is an automatic vessel tracking system used onboard ships to identify and locate vessels by means of an electronic interchange of, among others, geo positioning data with other nearby vessels.

data (Winther *et al.*, 2014). Prior to inventory input, the raw AIS data were grouped into grid cells and stratified according to ship types and ship length intervals, average sailing speed and distance. The inventory then combined the aggregated AIS data with ship engine power demand (function of ship type and length) and engine power related emission factors. The emission inventory comprised SO₂, NO_x, CO, NMVOC, PM, BC and OC (organic carbon) and the greenhouse gases CO₂, CH₄ and N₂O. The emissions were calculated per ship type for the baseline year 2012 and the forecast years 2020, 2030 and 2050, also in order to assess the emission consequences of future diversion shipping routes in the Arctic due to a possible decline in polar sea ice extent.

In *Finland*, Johansson *et al.* (2013) estimated the navigation emissions of SO_x, NO_x, CO₂, CO and PM_{2.5} in the northern European Emission Control Area (ECA) for the years 2009 and 2011 using the Finnish Ship Traffic Emission Assessment Model (STEAM) developed by the Finnish Meteorological Institute (FMI). The inventory combined AIS signals from ships with ship specific technical data, ship engine power demand (function of installed engine power, sailing speed and e.g sea waves) and engine power related emission factors. The emission estimates were distributed into the vessel types: passenger ships, cargo ships, container ships, tankers and other (primarily small) vessels. Sub-estimates were reported for the Baltic Sea and North Sea, respectively, and for flag nations as well. Emission projections were also made by Johansson *et al.* (2013) to study the impact of the reduced fuel sulphur content in heavy fuel oil to be used by maritime vessels in 2015. Earlier emission calculations in Finland were made with the same model for the inner part of the Baltic Sea and the years 2006–2009 (Jalkanen *et al.*, 2013).

In *Norway*, DNV estimated the emissions of SO_x, NO_x and PM from shipping in the Nordic Region in 2011 (DNV, 2012). The study was made on behalf of the Nordic Council of Ministers in order to assess the baseline emissions from shipping in the Nordic region, as well as their reduction potential and possible control mechanisms. The inventory area comprised all Nordic national waters (excluding the waters around Iceland and Shetland) and the entire Baltic region. Ship type specific emission results were obtained by using AIS signals from ships, ship technical data, ship engine power demand (function of installed engine power and sailing speed), and engine power related emission factors.

In *Norway*, several works have so far been using AIS data from ships as ship traffic input basis for sea management plans and different risk assessment studies for Norwegian waters or the adjacent North Sea and Arctic sea areas. Although being very advanced in their ship traffic de-

scription, none of these AIS based studies have, however, included published estimates for ship traffic emissions.

As a part of the management plan for the Barents Sea and the marine area outside Lofoten, the Norwegian Coastal Administration (von Quillfeldt, 2010) made up the sailed distance per ship type and size class, distributed into transit traffic, internal ship traffic, and traffic from outside the Barents Sea to/from ports in the area. The ship traffic data basis was AIS data received from land base stations, statistical data for relevant ports and satellite tracking signals from fishing vessels.

In an assessment of risk of oil spill for the coastal areas of mainland Norway, including Nordland, Troms and Finnmark, made on behalf of the Norwegian Coastal Administration, DNV (2010) used AIS data to geospatially map the ship traffic for the year 2008, split into ship types and ship dead weight classes. The report then described risk assessment indicators for 38 coastal segments in three different future scenarios for ship traffic management in 2025.

Caused by the increasing ship traffic in the Arctic – and due to that the northernmost sea and coastal areas have become increasingly accessible for maritime traffic – the Norwegian Ministry of Foreign Affairs formed a working group in order to study the impact on Norwegian interests in relation to trade, environment and foreign politics (Vold *et al.*, 2013). In the working group report, the ship traffic was mapped for the Arctic area in 2012, based on AIS data from land based stations, satellite receivers and other sources of ship traffic information.

In a study made by Dalsøren *et al.* (2013) the environmental impacts of the expected increase in sea transportation was examined. Emission inventories for SO₂, NO_x, CO, NMVOC, PM, BC and OC and the greenhouse gases CO₂, CH₄ and N₂O were set up for the year 2000 for Norwegian coastal ship traffic, and forecasts were made for 2015 for oil and gas transport from ships from Norway and northwest Russia, and shipping along the Northern Sea Route.

In Sweden a model has been set up which enable the calculation of emissions from shipping based on AIS data. The shipping emission model is an integrated part of the comprehensive Swedish air quality management system Airviro. An application of the Airviro system, called Shipair, has been developed for the Baltic Sea (Segersson, 2013). The Shipair model use AIS data from the international AIS database operated by Helcom together with ship specific technical data and emission factors compiled by the Swedish Maritime Administration. The AIS data cover the Baltic Sea area and the North Sea up to the southern coast of Norway and the ship specific technical data consist of e.g. installed en-

engine power, design speed, operational specific auxiliary engine loads. The shipair model and model results can be distributed into ship types and the navigation operational modes cruise, manouvring and hotelling. The model comprise the emissions of NO_x, SO_x, PM_{2.5}, NMVOC, CO₂, NH₃, CH₄, N₂O, CO, and the PM description will in the near future be refined to fractions of SO₄, H₂O (bound), EC, OC and BC.

For the whole *Arctic* region, during recent years, a few studies have been setting up geographically distributed emission inventories in order to better examine the environmental consequences of shipping emissions in the Arctic.

Corbett *et al.* (2010) produce 5x5 km gridded emission inventories of CO₂, SO₂, NO_x, CO, NMVOC, PM, BC and OC for 2004 and the forecast years 2020, 2030 and 2050 for different vessel categories, taking into account shipping growth, possible emission control measures and the opening of diversion routes for shipping in the Arctic area, as a consequence of expected melting of sea ice due to climate changes. The study considers Business-As-Usual (BAU) and High Growth (HiG) shipping activity scenarios based on the Second International Maritime Organization Greenhouse Gas Study 2009 (Second IMO GHG Study 2009) (Buhaug *et al.*, 2009).

Peters *et al.* (2011) examine the future emissions from shipping and petroleum activities in the Arctic for the years 2030 and 2050 by setting up a 1x1 degree emission inventory model and use the inventory results as an input for further chemical transport, radiative transfer and climate modeling. The inventory set up by Peters *et al.* (2011) comprise the emissions of SO₂, NO_x, CO, NMVOC, PM, BC and OC and the greenhouse gases CO₂, CH₄ and N₂O.

Emissions from navigation in the Arctic Area in 2004 have also been estimated in the Arctic Marine Shipping Assessment (AMSA) report (Arctic Council, 2009). The AMSA inventory comprises the emissions of SO_x, NO_x, CO, PM, BC as well as fuel consumption by vessel category.

7.3 Emission measurement methods and emission factors for shipping

Conventionally PM emissions are measured from the stack or exhaust pipe as “primary emissions”. They are defined as PM (total particulates), PM₁₀ (particles with aerodynamic size < 10 µm or PM_{2.5} (fine particles, < 2.5 µm), at temperatures above the dew point of condensable matter in the emission. There are several European or US standards for undiluted stationary source emissions measurements e.g. ISO9096, VDI 2066,

EN13284-1, EPA17, EPA201a, EPA5 standards (Table 33). Since 1996 another kind of definition for marine PM emission has been adopted, in which exhaust is sampled as diluted and quenched (Bastenhof 1995, ISO8178:1996). The purpose of this procedure is to partly take into account the liquid and condensable constituents of “particle emission”.

PM emission factors found in the literature are basically based on these two approaches of PM determination (1) PM measured from the hot stack of typically 300–400 °C or (2) the more recent emission standard ISO8178, which is based on exhaust “quenching”, i.e. dilution and cooling.

Due to the various PM-definitions and sampling conditions, results given as PM emissions in the literature are variable. While this is so, BC is a fixed emission and can, due to the various PM-concepts, not be defined as a fixed proportion of PM.

Measurement methods and emission factors from shipping are further elaborated in Annex A.

Table 33. Various approaches for the concept of PM from stationary emission sources

PM method	US EPA 40 CFR 50 Appendix B	ISO 8178	ISO 9096	EN-13284-1 & VDI 2066	EPA 17	EPA Method 201/201A	EPA Method 202	EPA/CARB Method 5
Description/ application area	Ambient air	Reciprocating IC engines; test bed/at site	Stationary sources	Stationary source, (wet) flue gas; test bed/at site	Stationary sources	Stationary sources	Downstream EPA 201/201A sampling	Stationary sources
Measured quantity	Suspended particulates	PM _{tot}	PM _{tot}	Dust load up to 50 mg/m ³	PM _{tot}	PM ₁₀ & PM _{2.5}	Condensable PM	PM _{tot}
Dilution	as in ambient air	diluted, Dr >4, non-isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic
Cyclone	no	no	no	for > 10µm	no	for > 10µm	for > 10µm	No
Filter position*	air	OS	IS/OS	IS/OS	IS	IS	IS	OS
Sampling T	25°C	42-52°C	stack T/160°C	160-180°C	stack T	stack T rinse of tubing added to PM	≤ 30°C	120°C rinse of tubing added to PM
Impingers for volatile PM		no	no	no	optional	no	yes, dry	optional, wet 0°C

7.3.1 *PM emission factors*

While NO_x and SO_x emission factors from ocean-going vessels are relatively well-understood, PM emission factors are much more uncertain due to limited data, diversity of emission sources and variability in the measurement techniques. The most widely cited “historical” emission tests, which have formed the basis for many PM emission factor estimations are those of Wright (1997) and Lloyd’s (1995).

As there is so far no legislation or regulations for marine PM emissions, quite a diversity of ways of defining PM emission factors for ship exists, as discussed above. Additionally, PM emissions can be calculated based on fuel sulphur content (TEMA2000, Saiyasitpanich *et al.*, 2005) or fuel type (Lloyd’s, 1995). Emission factors are also dependent on engine load (EPA 2000) or engine type (TEMA2000). The basis for reported PM emission factors is unfortunately not always clear or reported.

7.3.2 *Current knowledge of soot emission factors EF_{soot} from shipping*

The problems in determining BC emissions and emission factors from sea traffic are revealed by the recent and still on-going work within the international maritime organisation IMO. Its sub-committee on Bulk Liquids and Gases (BLG) decided late 2012 to establish a correspondence group to develop a definition, to consider measurement methods and to identify and collate possible control measures regarding Black Carbon emissions (BLG 17/18). The outcome of the work so far was reported in October 2013, but there is no conclusion by the group in any of the above issues. The work will continue in the first session of the newly organised sub-committee of IMO, that for the Pollution, prevention and response (PPR-1) in February 2014.

In Table 34 below is a collation of current values published for soot emission factors (EF_{soot}) from marine engines and large commercial vessels. The designations for the soot definitions, which are based on the measuring principle, are according to (Petzold *et al.*, 2013). Elemental carbon (EC) is pure inorganic graphitic carbon, typically sampled on a filter. Equivalent elemental carbon (eBC) represents light absorbing carbon in the emission, which is measured by light attenuation/extinction. Refractory elemental carbon, rBC, denotes carbon measured by its thermal resistance, typically using methods based on laser induced incandescence (LII). In the IMO correspondence group no definition or measurement principle has so far been favoured over the others. Only obsolete methods based on ethalometry and opacimetry were discarded.

Other variables that affect the EF_{soot} are for example: (a) if the measurement is made from the exhaust pipe or from the ambient plume, (b) if the engine is slow speed 2-stroke or medium speed 4-stroke, (c) the type of operation of the engine etc. The EF_{soot} are also functions of both engine load and fuel quality.

Due to the multitude of variables and uncertainties that affect the published EF_{soot} s from marine traffic a detailed conclusive break-down of the data in Table 34 is not possible. Only some coarse guidelines can be given. In the estimations of the EF_{soot} , medium speed engine traffic (MSD) and slow speed engine traffic (SSD) should be differentiated. According to data in Table 34, the soot emission formation from these engine types as a function of engine load are principally different. With MSDs the soot emission factor tends to rise steadily with lowered engine load. For the SSDs there is no general trend in relation to load, and the soot emission factor is relatively constant irrespective of load.

Accurate and justified values for shipping EF_{soot} , based on direct determination of BC in the marine emission can be evaluated only after decision on the definition for BC (associated with the decision of the approved measurement methods).

In Table 34, if the original EF_{soot} was presented in unit (m)g/kg fuel in the literature cited, it is converted into (m)g/kWh by dividing by 5 for 100–50% loads and by 4 for lower loads.

Table 34. Soot emission factors EF_{soot} from the literature

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ¹⁾	Technique of measu- rement	EF _{soot} mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
HSD ^{***)}	engine			Cummins QSK 19-M	1	4	0.375	95 75 50 25 idle		engine-out engine-out	automotive fuel	1.3 ppm	EC	TOT	circa 56 circa 83 circa 67 circa 27 circa 167	Jayaram <i>et al.</i> 2011
MSD	test engine	constant		1 cylinder	1	4	0.4	100 75 25 10	750	engine-out	HFO MGO	2.2 <0.1	BC	MAAP	4.8-0.9 (HFO-MGO) 10.1-1.3(HFO-MGO) 22.9-4.3 (HFO-MGO) 126-32.5(HFO-MGO)	Petzold <i>et al.</i> 2010
MSD	test engine	constant	1995	Wä 4R32LN 4 cylinder	1	4	1.6	100(high) 75(high) 50(med) 25(med) 10(low)	750	engine-out	LFO HFO1 HFO2 LFO HFO1 HFO2 LFO HFO1 HFO2	<0.1 <0.9 2.4 <0.1 <0.9 2.4 <0.1 <0.9 2.4	EC EC EC eBC eBC eBC "BC" "BC" "BC"	1)TOT 2) FSN 3)Total C- org. solubles	15-20/28-43/150/high/med/low 10-20/30-60/210- 250/high/med/low 10-20/15-60/60- 180/high/med/low 7-12/20-40/140- 150/high/med/low 12-13/24-51/260/high/med/low 18-21/33-43/182/high/med/low 25-35/42-75/310/high/med/low 55-80/120- 210/800/high/med/low 55-130/140- 230/570/high/med/low	Ristimäki <i>et al.</i> 2010
MSD	engine at vessel	propeller curve	1989	12V ZA 40X	2	4	7.2	27	360 (510 nom)	engine-out	MDO	0.48	EC BC	TOT MAAP	60-100 30-40	Lappi <i>et al.</i> 2013
MSD	test-rig engine			MAN B&W 9L58/64	1	4	10.625	100 110 85 50 25 10		engine-out	HFO	2.21	eBC EC	MAAP solvent extrac- tion+TA (no PyC correction)	BC 15/70 EC 14/40 11/36 15/30 45/76 92/129	Petzold <i>et al.</i> 2010
MSD	test-rig engine	Propulsion mode variable rpm		Multicylinder 1MW/cylinde r air-cooled, TC	1	4	ca 15	100(load100) 75(82) 50(63) 25(40)	514 468 411 324	engine-out engine-out engine-out engine-out	HFO LFO	0.83 0.1	eBC	FSN	11-15 14-16 23-29 143-155	Sarvi <i>et al.</i> 2008

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ¹⁾	Technique of measu- rement	EFsoot mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
MSD	test-rig engine	Generator mode constant rpm		Multicylinder 1MW/cylinde r air-cooled, TC	1	4	ca 15	100 75 50 25	514 514 514 514	engine-out engine-out engine-out engine-out	HFO LFO	0.83 0.1	eBC	FSN	9-11 15-16 27-30 54-55	Sarvi <i>et al.</i> 2008
MSD	test bed			MAN B&W 7- cylinder	1	4	ca 8	85-100		engine-out	HFO	2.21	EC	solvent extrac- tion+TA (no PyC correction)	35	Petzold <i>et al.</i> 2008
MSD	crude oil tanker aux. engine			Wärtsilä Vasa 6R22/26	(1)	4	0.9	75 50 25	1200	engine-out	MGO	0.06	EC	TOT	6 8 17	Agrawal <i>et al.</i> 2008
MSD	research vessel	Controlla- ble pitch propeller variable speed	1967	no TC (blo- wer)	1 (?)	2	1.64	(100) (61) (19) (1.4)	185 lower >lower >>lower	plume	MGO, MDO	0.1	rBC rBC eBC eBC	SP2 SP-AMS PAS PSAP	70**) 80 35 10	Cappa <i>et al.</i> 2013
SSD	test bed	variable speed	2007	4RTX-3 Wärtsilä TC common rail slide vessel	1	2	8.5	100 75 50 25 1	105 95.4 83.3 66.1 22.6	engine-out	MDO	0.155	EC	Coulo- metry (no PyC correction)	45 30 23 8 128	Kasper 2007
SSD	Post- Panamax class container ship	variable speed	1998	12k90MC MAN	1	2	54.84	90 75 50 25 13	94 lower >lower >>lower >>>lower	engine-out	HFO	3.01	EC	TOT	8 7 8 9 12	Miller <i>et al.</i> 2012
SSD	Panamax ship	variable speed		Sulzer 9RTA84C	1	2	36.74	1 0.125	102	engine-out	HFO	3.14	EC	TOT TOT	X 1.7*x	Khan <i>et al.</i> 2012
SSD	Crude oil tanker main engine	variable speed		Sulzer 6RTA72		2	15.75	85 75 50 25 13	90 lower >lower >>lower >>>lower	engine-out	HFO	2.85	EC	TOT	~20 ~25 ~20 ~20 50	Agrawal <i>et al.</i> 2008

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ¹⁾	Technique of measu- rement	EF _{soot} mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
SSD	vessel					2		57		engine-out			EC	TOT	7	Murphy <i>et al.</i> 2009
SSD	vessel					2	20.2	84	97	engine-out?	HFO	1.9– 1.97	EC		26	Moldanova <i>et al.</i> 2009
SSD	Container PanaMax	variable speed (ISO 8178 E-3)			1	2	50.27	70 63 52 27 8	101.8 98.1 91 73 49.2	engine-out engine-out engine-out engine-out engine-out	HFO	2.05	EC	TOT	17 20 17 16 29	Agrawal <i>et al.</i> 2008 ¹
SSD	Post- Panamax class container ship	variable speed	1998	12k90MC MAN	1	2	54.84	90 75 50 25	94 88 78 33	engine-out engine-out engine-out engine-out	HFO	3.01	EC	TOT	6.8 5.8 6.3 8.5	Agrawal <i>et al.</i> 2010
SSD	test engine			4T50ME-X 4 cylinder	1	2	7.08	75	123	engine-out	HFO MGO		EC	Solvent extrac- tion+TA (no PyC correction)	40 23	Internal report MAN
SSD (& MSD)	container vessel			MAN B&W	1 (1)	2 (4 for AE)	46.96 (AE 2.4 MW)	85		plume	HFO	2.45	eBC	PSAP	35±9	Petzold <i>et al.</i> 2008
SSD (& MSD)	container ship	Propeller curve?	2008	12RT-flex96C	1 (3)	2 (4 for AE)	68.6 (AEs 3x3.BMW)			plume	HFO MGO	3.15 0.07	eBC eBC		higher EF _{BC} expected lower EF _{BC} expected	Lack <i>et al.</i> 2011
SSD (& MSD?)	cargo & tankers	?			MEs +AEs boilers	2 (4 for AE)				plume	MDO? MDO?	0.55 0.4	eBC	MAAP	24 30	Diesch <i>et al.</i> 2013
SSD	tanker		1982		1	2	8.2	cruise		plume	MGO		eBC	white light attenuati- on	36	Moldanova <i>et al.</i> 2009

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ^{*)}	Technique of measu- rement	EFsoot mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
SSD	Tankers	propeller		various	MEs + AEs	2+AEs		cruise		Plume		> 0.5%	eBC	PAS	76	Lack <i>et al.</i> 2009
SSD	container	curve		various	+ boilers	2+AEs		cruise				> 0.5%	eBC	PSAP	160	
SSD	cargo	propeller		various		2+AEs		cruise				> 0.5%			80	
SSD	carrier	curve		various		2+AEs		cruise				> 0.5%			76	
MSD	bulk carrier tug boats	propeller curve propeller curve ?				4				plume		< 0.5%	eBC		194	
SSD	ocean- going vessels (n=71)			various	MEs + AEs + boilers					plume	HFO MDO/MG O	higher S lower S	rBC eBC	SP2, SP- AMS, PAS, PSAP	66**) 42	Buffaloe <i>et al.</i> 2013

*) The designations are according to Petzold et al 2013 except for "BC" which denotes Total C-SOF (Soluble Organic Fraction).

**) Average of the 4 measurement methods.

***) HSD=high speed diesel, MSD= medium speed diesel, SSD=slow speed diesel.

7.4 Emission factors for PM_{2.5} and BC from shipping in the Nordic emission inventories

In the tables below, the emission factors for PM_{2.5} and BC used in the Nordic emission inventories are presented (Table 35 – Table 39).

Table 35. Danish emission factors for PM_{2.5} from shipping

Country	Technology	Fuel type	National or international (memo items in NFR)	Implied emission factor (IEF) PM _{2.5} (g/GJ)
Denmark	0803 Inland waterways	Diesel	National	95.5
Denmark	080402 National sea traffic	Diesel	National	21.2
Denmark	080402 National sea traffic	Residual oil	National	43.3
Denmark	080403 National fishing	Diesel	National	21.2
Denmark	080404 International sea traffic	Diesel	International	21.2
Denmark	080404 International sea traffic	Residual oil, SS/MS	International	43.3

Table 36. Finnish emission factors for PM_{2.5} from shipping

Country	Technology	Fuel type	National or international (memo items in NFR)	Implied emission factor (IEF) PM _{2.5} (g/GJ)
Finland	International navigation 1A3di(i)	Light Fuel Oil (S=0.0915%)	International	21.8
Finland	National navigation 1A3dii	Heavy Fuel Oil (S<1%)	National	40.8
Finland	National navigation 1A3dii	Light Fuel Oil (S=0.0915%)	National	30.0
Finland	National navigation 1A3dii	Motor Gasoline (S=0.001%)	National	11.8

Table 37. Swedish emission factors for PM_{2.5} from shipping

Country	Technology	Fuel type	National or international (memo items in NFR)	Emission factor (EF) PM _{2.5} (g/GJ)
Sweden	Fisheries	Diesel Oil	National	23
Sweden	Bunkers, Navigation/Shipping	Diesel Oil	International	16
Sweden	Bunkers, Navigation/Shipping	Residual Fuel Oil	International	104
Sweden	Domestic navigation	Diesel Oil	National	16
Sweden	Domestic navigation	Residual Fuel Oil	National	104
Sweden	Small boats	Gasoline	National	90

Table 38. Norwegian emission factors for PM_{2.5} from shipping

Country	Technology	Fuel type	National or international (memo items in NFR)	Emission factor (EF) PM _{2.5} (g/tonne)*
Norway	National fishing	Marine gas oil/diesel	national	1.5
Norway	National fishing	Heavy distillate	national	5.1
Norway	National fishing	Heavy fuel oil	national	5.1
Norway	National navigation	Marine gas oil/diesel	national	1.5
Norway	National navigation	Heavy distillate	national	5.1
Norway	National navigation	Heavy fuel oil	national	5.1

Table 39. Danish emission factors for BC/EC from shipping

Country	Technology	Fuel type	National or international (memo items in NFR)	BC/EC (% of TSP)
Denmark	0803 Inland waterways	Diesel	National	37.0
Denmark	080402 National sea traffic	Diesel	National	31.0
Denmark	080402 National sea traffic	Residual oil	National	12.0
Denmark	080403 National fishing	Diesel	National	31.0
Denmark	080404 International sea traffic	Diesel	International	31.0
Denmark	080404 International sea traffic	Residual oil	International	12.0

The emission factors for BC for shipping activities used in the Swedish inventory are those presented in the EMEP/EEA Guidebook.

7.5 Emission factors for BC for shipping from the EMEP/ EEA Guidebook

The EMEP/EEA Guidebook presents several tables which contain information on BC as fraction of PM_{2.5} for various shipping activities. Below is an overview of relevant studies referred to in the Guidebook (Table 40) and where information on BC-fractions for shipping can be found in the Guidebook (Table 41).

Table 40. Overview of BC fractions for shipping from relevant studies as presented in the EMEP/EEA Guidebook

Reference	Vessel	Fuel ^a	Engine ^b	Stroke	Size (kW)	Sampling	f-BC
Petzold <i>et al.</i> (2004)		HFO	SS				0.07
Kasper <i>et al.</i> (2007)	Tanker	HFO	SS	2-stroke	8500		0.17
	Tanker	MDO	SS	2-stroke	8500		0.17
Lack <i>et al.</i> (2009)		HFO	SS			Plume	0.12
		MDO	MS			Plume	0.40
		MDO	HS			Plume	0.22
		MDO a/g				Plume	0.31
Lack <i>et al.</i> (2011)		HFO	SS			Plume	0.06
		MDO	SS			Plume	0.33
Agrawal <i>et al.</i> (2008a)	Container	HFO	SS	2-stroke	50270	8178-1	0.013
Agrawal <i>et al.</i> (2008b)	Tanker	HFO	SS	2-stroke	15750	8178-1	0.011
Agrawal <i>et al.</i> (2010)	Container	HFO	SS	2-stroke	54840	8178-4	0.003
Murphy <i>et al.</i> (2009)	Container	HFO	SS	2-stroke	54849	8178-1	0.003
Petzold <i>et al.</i> (2010)		HFO	MS	4-stroke	10000		0.026

^a: HFO = heavy fuel oil; MDO = marine diesel oil.

^b: SS = slow speed; MS = medium speed; HS = high speed.

Table 41. Information on where to find BC-data in the EMEP/EEA Guidebook

Table no.	Tier	Detail	BC:PM data source
3-1	1	HFO	Present note; f-BC = 0.12
3-2	1	MGO	Present note; f-BC = 0.31
3-3	1	Gasoline (boats)	Winther et al. (2011); f-BC = 0.05
3-4	2	Engine type x Fuel type	Present note; HFO: 0.12, MGO: 0.31
3-5	2	Boats (D/G2/G4) x Fuel type	Winther et al. (2011); diesel: 0.55, gasoline: 0.05
3-9	3	Phase x Engine type x Fuel type	Present note; HFO: 0.12, MGO: 0.31
3-10	3	Phase x Engine type x Fuel type	Present note; HFO: 0.12, MGO: 0.31
3-11	3	Boats (D/G2/G4) x Vessel type x Fuel type	Winther et al. (2011); diesel: 0.55, gasoline: 0.05

7.6 Conclusions regarding shipping

The emissions of PM_{2.5} from shipping with 3.5 Gg and 10 Gg for the Nordic countries in 2011 from national and international shipping, respectively, must be considered as a significant source. For BC the Nordic national shipping contributed 1.3 Gg in 2011, or 6% of aggregated Nordic emissions. There are however large differences between the Nordic countries, where national shipping in Norway contributes ~17% of national Norwegian BC emissions, in Sweden ~6%, and in Denmark and in Finland ~1%. There is less data reported in the inventories for international shipping, Denmark and Sweden report 0.58 and 0.86 Gg BC respectively. The quality of the data for shipping is hampered by a number of difficulties. One should also note that the emissions in the reporting for international shipping typically is based on fuel sale statistics in the respective countries and thus does not reflect the emissions on the territorial water, nor by the country's fleet.

The measured emissions of PM_{2.5} will depend on a number of factors such as fuel quality, engine type, operational mode, engine maintenance and engine load. For example, the measured PM will depend strongly on the sulphur content in the fuel and also on if the fuel is a distillate or residual oil. There are also different measurement methods where there will be a large difference between in stack sampling and diluted sampling.

For BC the situation is not better. There are not much data available and there are a number of different BC instruments that will give different results. When expressing BC as a fraction of PM one must use different fractions for diluted and in-stack measurements since the BC should be relatively insensitive to if dilution is made, while other types of particles (sulphates, organic compounds etc) will be significantly influenced.

8. Conclusions and discussion on measurement strategy

The ultimate objective of the measurements to be performed in the next phase of this project is to improve the estimates of BC emissions in the Nordic countries. This background analysis has focused on four important Nordic emission sources of BC and PM_{2.5}; residential biomass combustion, on-road and non-road mobile sources, and shipping. For the coming measurement program we propose to focus on residential biomass combustion. The reasons for this are discussed in the sections below.

In general, 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 (Arctic Council Task Force on Short-lived Climate Forcers (2011)). Emissions from source categories aside from on- and off-road mobile sources are however 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 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 (Arctic Council Task Force on Short-lived Climate Forcers (2011)).

8.1 On-road mobile sources

For on-road mobile sources, future reductions in PM/BC emissions by implementation of EURO-standards are expected, and the BC emissions are comparatively well characterized. The same EURO standards also exist in other countries, why increased knowledge from other non-Nordic investigations can be used in the Nordic countries. No measurements on road diesel vehicles are therefore foreseen in the measurement program in this project.

8.2 Non-road mobile sources

For the non-road mobile machineries there are very few measurements and the emission inventories normally rely on BC fractions of PM from similar road diesel engines. However, also the PM emission factors must be considered as uncertain for non-road mobile machinery. In inventories the emission factors are normally related to the legal limits for PM emissions which are measured in engine bench tests with test cycles comprising of a number of stationary points. Thus, these emission factors will not account for cold starts or transient operation. Field measurements to capture real time conditions would be desirable, but there are substantial discussions needed regarding how to perform such measurements in order to achieve enough representative results for use in national inventories. This would most likely be too large an undertaking for the measurement program in this project.

8.3 Shipping

Shipping must be considered as a significant source of PM_{2.5} and BC emissions, even though complete data is not reported from all the Nordic countries. For shipping the measured emissions of PM_{2.5} will depend on a number of factors such as fuel quality, engine type, operational mode, engine maintenance and engine load. There are also different measurement methods where there will be a large difference between in stack sampling and diluted sampling. For BC the situation is not better. There are not much data available and there are a number of different BC instruments that will give different results. Work is going on internationally regarding shipping emissions, for example discussions on the definitions of BC (IMO, see chapter 7.3.2).

For shipping, emissions are not expected to significantly decrease in the future. There is however a lack of agreement in the international community on the definitions of BC, as well as on standardised BC measurements, which means that it is still uncertain how a relevant measurement program for shipping emissions should be designed. In order for measurement results to be generally accepted as reliable enough to be used in official emission inventories they would need to be based on accepted definitions and methods, which at present are not available. Emission measurements from shipping are therefore not prioritised for measurements within this project.

8.4 Residential biomass combustion

Residential biomass combustion is a dominating source for BC and PM_{2.5} emissions in the Nordic countries. Emissions are expected to increase, or at least no to decrease, and thus to become of relatively even higher importance in the future.

The main conclusions and gaps of knowledge from the background analysis presented in this report regarding residential biomass combustion, its emissions of BC and PM_{2.5}, the measurement methodologies and emission factors are summarised below.

Emissions

- Residential biomass combustion is a significant source for BC and PM_{2.5} emissions in the Nordic countries, contributing more than 40% of the total Nordic emissions.
- Emission reporting of PM_{2.5} (and BC) from residential biomass combustion is not comparable between the Nordic countries, partly due to different measurement methodologies underlying the national emission factors (hot flue gas, dilution tunnel).

Measurements

- Nordic national information on BC is scarce and there is a general lack of BC emission measurements, except from recent measurements on old and new stoves in Norway, and measurements in Finland.
- Presently there is no defined measurement standard prescribed as a basis for PM_{2.5} emission factor development within the CLRTAP convention (or EU). Different countries use different measurement standards from tradition. The applied emission measurement standards and combustion cycle during tests have a considerable influence on the estimated emission data for PM. Thus, results are not necessarily comparable between the literature sources covered in preparation of the 2013 update of the Guidebook. It is stated in the EMEP/EEA Guidebook (EMEP/EEA, 2013) that recent studies based on diluted flue gas sampling were prioritised when updating the Guidebook. In addition, emission data that includes the whole combustion cycle were prioritised as the emission during ignition, part load and burnout are much higher than at full load conditions.
- The fact that emission factors for PM are based on different, but official, emission measurement standards (hot flue gases or diluted) that may give significantly different results raises the question on what is

needed and wanted from the point of view of the potential use of data from national emission inventories. Reported emission data may be used for modelling purposes, in assessments of compliance, comparability and health impact etc. Depending on the purpose the requirements may differ. For comparability and compliance purposes, the important issue is to base the estimates on comparable measurement standards, irrespective of standard. For modelling purposes and in assessment of health effects, it seems that results from diluted sampling would be favored, since those data are considered to better reflect real conditions in the atmosphere after an emission has occurred. These are also relevant questions to be taken into consideration for the measurement strategy within this project.

Emission factors

- At present, both results on EC (Elemental Carbon) and BC are used interchangeably for emission factor development, even though they strictly do not represent identical particle fractions. The possible errors introduced by these assumptions are, however, probably minor compared to other uncertainties in national emission inventories.
- There are uncertainties when using emission factors for BC expressed as a fraction of $PM_{2.5}$. The problem arises when emission factors for $PM_{2.5}$ are not well defined as with or without condensable organic matter included in the mass. The fraction of BC will be different depending on if condensable organic matter is included in the $PM_{2.5}$ mass or not. BC is theoretically already present in hot flue gases, even though some addition of mass could occur at dilution and condensation. For specific emission factors for BC (e.g. in the unit g/GJ) this problem does not exist. Care should however be taken not to report inconsistent data for $PM_{2.5}$ and BC if specific emission factors from different measurements or literature sources are used.
- Many national specific emission factors exist in the Nordic countries, but it is not always that national activity data (e.g. stock of combustion technologies in use), or knowledge on for example combustion practices are available to make full use of existing information. There is work to be done in the countries to adapt national information to already available emission factors. A more comparable disaggregation of emission sources would also facilitate the use of harmonised emission factors. National activities and analysis outside this project to collect suitable national information are necessary.

For residential wood combustion it is clear that in general information on emission factors for BC is scarce, with a few exceptions. In the Finnish and Norwegian emission inventories national emission factors for BC are used where available, while the Danish and Swedish BC emission inventories, at present, rely on information on BC as a fraction of emitted PM_{2.5} from the EMEP/EEA Guidebook, which represents the currently best available collected knowledge. Using emission factors from the Guidebook will give results that are acceptable, but as has been discussed above, conditions differ in the Nordic countries and it is unclear how well country specific conditions and circumstances are reflected in the factors presented in the Guidebook. As residential biomass combustion is such a dominating source of PM_{2.5} and BC emissions in the Nordic countries, the present uncertainties need to be reduced in order for the inventory results to serve as a sufficiently reliable basis for policy development and actions. As conditions are different in different countries, we would not necessarily expect possible future results from investigations in non-Nordic countries to be representative and usable for Nordic conditions. The measurement program in this project should therefore prioritise residential wood combustion.

In the report on residential wood combustion from ACAP (2014) it is considered that a common framework for estimating and reporting emissions of BC from residential wood burning would be of great use. The suggestions for further work in ACAP (2014) include the following; to describe and recommend measurement methods and test conditions, to recommend methodologies for collecting wood consumption data, and in order to overcome the challenge of comparing different technology categorization in the countries inventories, to develop a better understanding of the country specific technology categories and their combustion characteristics. This is well in line with the results in the background analysis presented in this report.

9. Discussion on design of measurement program for BC from residential wood burning

Emission measurements from residential combustion are rather complicated regarding BC (and PM) emissions. Measurement results are at the moment not available for several appliance types and different operational procedures, and there are also different sampling and analysis methods for PM/BC. The focus of this project is to increase the knowledge on BC-emissions to improve national Nordic emission inventories. The aim of the measurement program will thus be to increase the knowledge on the most important variables and reduce the uncertainties, while we do not expect to be able to solve all problems.

The first step in a development of a measurement program focused on BC and PM_{2.5} emissions from residential wood combustion would ideally be to nationally investigate which available emission factors from the other Nordic countries would be representative of the national emissions, maybe after additional data collection and/or assumptions regarding national conditions. If already available emission factors are judged to be generally representative, measurements for those technologies and conditions would not need to be included in the measurement program. For e.g. residential wood combustion in stoves, it would be reasonable to find out whether the nationally measured Norwegian BC emission factors for wood combustion can be used in the other Nordic countries. However, according to Finnish expertise (Lamberg, pers. comm.) who was involved in the measurements for Norway, the Norwegian BC factors are probably not representative for Finnish conditions as the stove type measured for Norway is rare in Finland and the Norwegian common operational practices do not correspond to how stoves are used in Finland.

There are several decisions that need to be made in designing a relevant measurement program to improve the Nordic knowledge on emissions of BC and PM_{2.5} from residential biomass combustion. They include:

- which technologies should be selected for the measurement program
- which measurement, sampling and analysis methods should be used
- how to account for possible difference between lab measurement and field measurements, i.e how to take into account the impact from operational practices etc., for example “good” and “bad” firing habits.

Technologies

The current understanding of the commonly used appliances and factors impacting the actual emission levels in the countries does not allow selecting clear example cases representative for all Nordic countries. The combustion technologies where knowledge is scarce and which have a significant contribution to emissions should be prioritised for measurements. These have to be defined in the Nordic (and country specific) context. Also modern types of appliances, which presumably will increase in importance in the future, should be included even if they are relatively low-emitting. For modern technologies it is possible that test protocols from equipment producers are available (at least regarding PM but not for BC) that would be sufficient as an indication for standard combustion conditions.

Measurement and sampling methods

Measurements should preferably be made where both hot flue gas and diluted sampling is performed to assess differences in results. If choices have to be made, diluted sampling should be prioritised. A whole combustion cycle should be sampled since this reflects real emissions better than some shorter sampling. In the report from ACAP (2014) it is suggested (among other things) that it would be desirable to conduct measurements of PM_{2.5}, BC and OC including parallel measurements with different methods, both in the laboratory and the field.

The selection of analysis method(s) for BC needs to be discussed.

Lab measurements and/or field measurements, firing habits

Field measurements of course better reflect real time conditions, but to achieve a large enough basis to be able to generalise to the national (or Nordic) level, a vast measurement program would need to be designed. Ideally field measurements would be carried out in each participating country to study the actual emission levels from practical wood combustion events in the selected appliances. Measurements would be carried out under authentic conditions without giving beforehand instructions on the use of the appliance, the fuel quantity/quality, the operational procedure nor the beforehand maintenance.

In practice it is probably more reasonable to focus on a well-designed measurement program with lab measurements as a basis to answer some of the questions, and to verify those measurements by a suitable number of field measurements to capture some of the variations introduced by field conditions. An alternative to field measurements would be to simulate “real world conditions” in the lab environment.

In the measurement program it is important to capture the influence on the resulting emissions from common “real world” combustion practices, as these may give emissions that are significantly different from the standard combustion conditions recommended from the equipment producer or given in the measurement standards. To be able to systematically document and evaluate the differences, firing conditions representing common operational practices that deviate from the recommendations or standard measurements could be simulated under well controlled measurements in a lab.

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Sammanfattning

Emissionsinventeringar av kortlivade klimatpåverkande luftföroreningar (SLCP), och framför allt av Black Carbon (BC), är osäkra och inte alltid jämförbara. Tillförlitliga emissionsinventeringar är viktiga som underlag för att ta fram och följa upp strategier och åtgärder för minskade utsläpp. I denna rapport presenteras de nordiska ländernas emissioner och emissionsinventeringar av SLCP och de viktigaste utsläppskällorna och deras utveckling över tiden. Rapporten diskuterar också kunskapsluckor, faktorer som bidrar till osäkerheten i uppskattningarna, samt möjligheter till förbättrade emissionsberäkningar.

SLCP är en grupp ämnen som innefattar BC, marknära ozon (O_3), metan (CH_4) och hydrofluorkolväten (HFC). O_3 bildas i atmosfärskemiska reaktioner där CH_4 , kväveoxider (NO_x), kolmonoxid (CO), flyktiga organiska ämnen (NMVOC) och solljus ingår.

Det finns ett ökande intresse, särskilt för BCs roll i klimatiförändringarna och möjligheterna att bromsa den pågående globala temperaturökningen genom att minska utsläppen av BC och andra SLCP. Utsläppsminskningar av SLCP kan också ha en regional påverkan på klimatiförändringen. Dessutom har de negativa effekterna på människors hälsa från exponering för partiklar länge varit kända. Reducerade utsläpp av BC skulle därmed kunna påverka både klimatiförändringar och bidra till minskade negativa effekter på människors hälsa.

I maj 2012 antogs ett reviderat Göteborgsprotokoll under UNECE CLRTAP (FN:s Ekonomiska Kommission för Europa, Konventionen om långväga gränsöverskridande luftföroreningar). Det reviderade protokollet innehåller tak för nationella utsläpp av $PM_{2,5}$ (partiklar $<2.5 \mu m$) och för SO_2 , NO_x , NH_3 och NMVOC. BC är en komponent i $PM_{2,5}$ och i den reviderade protokollstexten finns en rekommendation att när åtgärder för att minska utsläpp av $PM_{2,5}$ genomförs ska de källor med de största andelen av BC i $PM_{2,5}$ prioriteras.

För att kunna bedöma och rapportera emissionsförändringar på ett konsekvent och korrekt sätt, behövs ökad kunskap och förbättrade metoder för emissionsinventeringar. Den övergripande målsättningen för det aktuella projektet är att förbättra de nordiska emissionsinventeringarna av SLCP, med fokus på BC. Som ett första steg har denna Bakgrundsanalys genomförts för att bedöma och sammanfatta nuvarande

kunskap, och samtidigt lägga grunden för ett emissionsmätprogram som ska genomföras i den andra fasen av projektet. Eftersom BC är en komponent i emitterad $PM_{2.5}$ är tillförlitliga emissionsinventeringar av $PM_{2.5}$ en viktig grund för att uppskatta utsläpp av BC. $PM_{2.5}$ ingår därför i analyserna i detta projekt.

Nationella officiella emissionsinventeringar för luftföroreningar och växthusgaser, inklusive $PM_{2.5}$ och CH_4 samt CO och NMVOC (som bidrar till ozonbildning) rapporteras årligen från de Nordiska länderna till internationella konventioner. BC är ännu inte en del av rapporteringsprogrammet, men det kommer att ingå som frivillig rapportering till CLRTAP inom en snar framtid. Alla nordiska länder utom Island har dock redan utvecklat preliminära emissionsinventeringar av BC. Tidsserien för uppskattade nordiska aggregerade utsläpp av BC presenteras i figuren nedan.

Beräknade nordiska utsläpp av BC (Gg), 2000–2011

De nordiska emissionsinventeringarna visar att den största källan till utsläpp av BC och $PM_{2.5}$ är förbränning i bostadssektorn, vilken bidrar till mer än 40 % av de nordiska BC och $PM_{2.5}$ utsläppen. Betydande bidrag kommer från vägtrafiken (ca. 20 % under senare år) och andra mobila fordon och maskiner (ca. 15 %). Den nordiska inrikes sjöfarten bidrog ca 6 % till de aggregerade nordiska utsläppen av BC år 2011. Det finns dock stora skillnader mellan de nordiska länderna, där den nationella sjöfarten i Norge bidrar med ca. 17 % av de nationella norska BC

utsläppen, 6 % i Sverige, och 1 % i Danmark och Finland. Alla länder rapporterar inte BC från den internationella sjöfarten i inventeringarna.

De aggregerade nordiska utsläppen av CH₄ domineras av jordbruks- och avfallssektorerna. Dessa sektorer tillsammans bidrar med mer än 85 % av de totala utsläppen av CH₄.

De aggregerade nordiska utsläppen av NMVOC visar en nedåtgående trend med 45 % minskning mellan 2000–2011. Medan NMVOC från förbränning av bränslen minskat i storleksordningen 65–70 %, är källkategorin "lösningsmedel och produktanvändning" fortsatt hög och stabil över tiden. Förbränning av biomassa bidrar ca 15 % till nordiska NMVOC-utsläpp.

De största bidragande källorna till utsläpp av CO under senare år har varit förbränning i bostadssektorn samt vägtrafik.

Bakgrundsanalysen har identifierat tre viktiga nordiska källor till emissioner av BC och partiklar (PM_{2,5}) och fokuserar på förbränning av biomassa i bostadssektorn, dieselfordon (både vägtrafik och arbetsmaskiner), samt sjöfart.

Förbränning av biomassa i bostadssektorn, småskalig förbränning

Småskalig förbränning av biomassa skiljer sig mer än kanske förväntat mellan de nordiska länderna. Beståndet av förbränningsutrustning och användningsmönster skiljer sig mellan länderna, t.ex. används främst kaminer i Norge, i Danmark är både kaminer och pannor vanliga, Sverige har den högsta andelen av pannor och Finland är det enda landet med betydande användning av murade värmekällor (masonry heaters) och vedeldade bastuaggregat, förutom pannor och kaminer. Dessa skillnader återspeglas också i inventeringsmetoder i länderna, där olika indelning och detaljnivå tillämpas avseende teknologier och emissionsfaktorer i emissionsberäkningarna.

En ytterligare skillnad är de mät- och provtagningsmetoder som använts för att ta fram emissionsresultat som ligger till grund för nationella emissionsfaktorer för PM_{2,5} (och BC). Danmark, Norge och Finland har använt resultat från provtagning i spädda rökgaser medan de svenska emissionsfaktorerna baseras på provtagning i varma rökgaser. Dessa två principiellt olika metoder, båda standardmetoder, ger oftast inte jämförbara resultat, särskilt inte vid förhållanden med ofullständig förbränning. PM från provtagning i spädtunnel inkluderar förutom fasta partiklar också partiklar som bildas när semivolatila ämnen i rökgaserna kondenserar i spädtunneln, dvs. partikelmassan ökar. Skillnader i resultat mellan prov-

tagning i varma rökgaser och i spådtunnel rapporteras i litteraturen ofta vara i storleksordningen 2–4 gånger, och en faktor på upp till 10 i värsta fall. Detta gör naturligtvis att det är svårt att jämföra resultaten.

En genomgång och jämförelse av nordiska nationella emissionsfaktorer för $PM_{2,5}$ visar att de varierar kraftigt, både mellan teknologier men också mellan länderna för liknande typer av förbränningsutrustningar. Dessa skillnader kan delvis hänföras till de icke jämförbara mät- och provtagningsmetoder som emissionsfaktorerna baseras på, men också till nationella antaganden beträffande eldningsvanor, bränslekvalitet etc, vilket påverkar de beräknade utsläppen. Det är inte heller osannolikt att förhållandena, som till exempel eldningsvanor, i verkligheten är olika i de nordiska länderna.

För biomassaförbränning i bostadssektorn är information om emissionsfaktorer för BC generellt knapphändig, med vissa undantag (t.ex. resultat från mätningar på norska kaminer enligt norska förhållanden, och mätningar i Finland). I de norska och finska emissionsinventeringarna används nationella emissionsfaktorer för BC, där sådana finns tillgängliga, medan de danska och svenska emissionsinventeringarna för BC för närvarande förlitar sig på information om BC som en andel av emitterad $PM_{2,5}$ från EMEP/EEA Air Pollutant Emission Inventory Guidebok (2013).

Sammanfattning och viktigaste slutsatser, BC och $PM_{2,5}$ från förbränning av biomassa i bostadssektorn

Emissioner

- Förbränning av biomassa i bostadssektorn är en viktig källa till emissioner av BC och $PM_{2,5}$ i de nordiska länderna, som bidrar med mer än 40 % av de totala nordiska utsläppen.
- Emissionsrapporteringen av $PM_{2,5}$ (och BC) från förbränning av biomassa i bostadssektorn är inte jämförbar mellan de nordiska länderna, delvis på grund av de olika mät- och provtagningsmetoder som ligger till grund för nationella emissionsfaktorer (varma rökgaser, spådtunneln).

Emissionsmätningar

- Nordisk nationell information om BC är knapphändig och det finns en brist på emissionsmätningar av BC, utom från gamla och nya kaminer i Norge, och mätningar i Finland.

- För närvarande finns det ingen definierad mätstandard som ska användas som bas för utveckling av emissionsfaktorer för PM_{2,5} inom CLRTAP (eller EU). I EMEP/EEA Guidebook (2013) anges att nya studier baserade på provtagning i spädda rökgaser prioriterades vid uppdatering av information i EMEP/EEA (2013).
- Rapporterade emissionsdata användas för olika syften, t.ex. för modellering, i bedömningar av kravuppfyllelse, för jämförelser mellan länder och i bedömning av hälsoeffekter. Beroende på syftet kan kraven på underliggande mätförfarande för redovisade emissionsdata skilja. För jämförbarhet och kravuppfyllelse är det viktigt att beräkningarna är baserade på emissionsfaktorer från jämförbara mätningar (mätstandarder), oavsett standard. För modelleringsändamål och för bedömning av hälsoeffekter tycks resultat från provtagning i spädda rökgaser vara att föredra, eftersom resultat från sådana mätningar anses bättre spegla faktiska förhållanden i atmosfären efter att ett utsläpp har skett.

Emissionsfaktorer

- Såväl mätresultat på EC (Elemental Carbon) som BC används för emissionsfaktorutveckling för BC, även om de strikt sett inte representerar identiska partikelfraktioner. De osäkerheter som introduceras är dock troligen små jämfört med andra osäkerheter i nationella emissionsinventeringar.
- Det finns osäkerheter när emissionsfaktorer för BC uttrycks som en andel av PM_{2,5}. Problemet uppstår när emissionsfaktorer för PM_{2,5} inte är väl definierad som med eller utan kondenserade organiska ämnen i partikelmassan. Fraktionen av BC kommer vara olika beroende på om kondenserbart organiskt material ingår i PM_{2,5}-massan eller inte.
- Ett antal nationellt framtagna emissionsfaktorer finns i de nordiska länderna. För att till fullo kunna utnyttja befintlig information behöver nationell kunskap om aktivitetsdata (såsom populationen och utnyttjandegraden av olika förbränningsteknologier, eller kunskap om förbränningsvanor) utvecklas och anpassas till redan tillgängliga emissionsfaktorer. En mer jämförbara uppdelning av utsläppskällor (förbränningsteknologier och förhållanden) skulle också underlätta användningen av harmoniserade emissionsfaktorer.

Mobila dieselfordon och maskiner

För dieselfordon i vägtrafik förväntas minskade utsläpp av PM och BC i framtiden till följd av succesiv implementering av EURO-standarder. Samma EURO standarder finns även i andra länder i Europa, varför framtida ökad kunskap från andra icke-nordiska undersökningar kan användas i de nordiska länderna. Inga mätningar på fordon inom vägtrafik förutses därför i det föreslagna mätprogrammet i detta projekt.

För arbetsmaskiner och andra dieseldrivna fordon som inte är avsedda för vägtrafik finns det mycket få resultat från mätningar och till emissionsinventeringar förlitar man sig normalt på BC fraktioner av PM från liknande dieselmotorer i vägtrafikfordon. I inventeringarna relateras normalt emissionsfaktorerna till de juridiska gränsvärdena för partikelutsläpp som mäts i motorbänkstester med testcykler bestående av ett antal stationära punkter. Dessa emissionsfaktorer tar således inte hänsyn till kallstarter eller transient drift. Fältmätningar för att fånga verkliga förhållanden skulle vara önskvärt, men det behövs omfattande diskussioner om hur sådana mätningar bäst skulle utföras för att erhålla representativa resultat anpassade för att använda i nationella emissionsinventeringar. Detta skulle vara ett alltför omfattande arbete för mätprogrammet i detta projekt.

Sjöfart

Fartygstrafik måste betraktas som en viktig källa till emissioner av PM_{2,5} och BC, även om fullständiga data inte rapporteras från alla de nordiska länderna. För sjöfarten beror de uppmätta utsläppen av PM_{2,5} på ett antal faktorer såsom bränslekvalitet, motortyp, driftläge, motorunderhåll och motorbelastning.

Arbete pågår internationellt gällande sjöfartens utsläpp, till exempel diskussioner om mätstandarder och definitionerna av BC. Eftersom det för närvarande inte finns några accepterade överenskommelser bör resurser inte läggas på mätningar av utsläpp från fartyg inom detta projekt. Risker finns att eventuella framtagna resultat i ett senare skede inte skulle betraktas som representativa för att förbättra de nationella nordiska BC inventeringarna.

Strategi för emissionsmätningar av BC från småskalig biomassaförbränning i den andra fasen av projektet

Eftersom förbränning av biomassa i bostadssektorn är en sådan dominerande källa till PM_{2,5} och BC-utsläpp i de nordiska länderna, måste nuvarande osäkerheter och kunskapsluckor minskas för att inventeringsresultaten ska fungera som ett tillräckligt tillförlitligt underlag för policyutveckling och åtgärder. Mätprogrammet i detta projekt bör därför prioritera att förbättra de nordiska emissionsfaktorerna för BC (och PM_{2,5}) för biomassaförbränning i bostadssektorn, med hänsyn tagen till nordiska förhållanden.

I utvecklingen av mätprogrammet kommer de typer av förbränningsutrustning som ger ett betydande bidrag till utsläppen i de nordiska länderna och där kunskapen är knapp att prioriteras. Mätresultat är för tillfället inte tillgängliga för flera typer av teknologier och olika driftsförhållanden. Det kommer inte att vara möjligt att lösa alla problem, utan snarare att öka kunskapen om vissa av de viktigare faktorerna, såsom effekterna av mätstandard på mätresultaten och bidragen från olika användningsmönster till utsläppsnivåerna.

Fältmätningar skulle naturligtvis bättre spegla verkliga förhållanden, men för att uppnå ett tillräckligt stort underlag för att kunna generalisera till den nationella (eller nordiska) nivån, skulle ett omfattande mätprogram behöva utformas. Vi föreslår att fokusera på ett väl utformat mätprogram med laboratoriemätningar som bas för att svara på några av frågorna, och komplettera dessa med mätfall som simulerar typiska driftsförhållanden och eldningsvanor som förekommer i verkligheten.

Annex A

Shipping, measurement methods, PM and BC emission factors

Concept of PM emission

Conventionally PM emissions are measured from the stack or exhaust pipe as “primary emissions”. They are defined as PM (total particulates), PM₁₀ (particles with aerodynamic diameter < 10 µm or PM_{2.5} (fine particles, < 2.5 µm), at temperatures above the dew point of condensable matter in the emission, applying one of the several European or US standards for undiluted stationary source emissions: ISO9096, VDI 2066, EN13284-1, EPA17, EPA201a, EPA5 standards. From 1996 on another definition for marine PM emission has been adopted, in which exhaust is sampled as diluted and quenched (Bastenhof, 1995, ISO8178:1996). The purpose of this procedure is to take partly into account the liquid and condensable constituents of “particle emission”. The Dilution ratio (Dr) requirement in this procedure is at least 4 (Dr 4). The emissions in this case result in variable amounts of condensed liquid matter (PM) on the filter. This condensed matter has different properties as a pollutant than just the solid matter that is defined by the in-stack standards. For example, the ISO9096 and EPA5a standards define the sampling temperature such (>160 °C), that evaporation of sulphuric acid (H₂SO₄) from PM is confirmed. On the other end of a “PM” definition, capturing condensable organic and inorganic matter at 0 °C (CPM), results from applying the combination of EPA202 standard (EPA202, 2010) and EPA201a (EPA201a, 2010). EPA201a+EPA202 is probably the most comprehensive definition for exhaust PM. Principles of the most common PM sampling standards applicable to marine engine exhausts are compiled in Table 42.

The status of exhaust “PM” as it is released into ambient air (as primary PM, not aged), i.e. the combination of liquid aerosols + solid nuclei coated with liquid matter, is somewhere between the non-volatile in-stack PM measurements and that of EPA201a+EPA202, as the EPA202 sampling is performed at a moderate ambient temperature of 30 °C. Due to the impreciseness of the source-base PM emission concept it is not possible to define

BC emission as a fixed proportion of PM. BC is a fixed emission while PM can be very variable, depending on the definition and sampling conditions.

Although there are uncertainties regarding the concept of PM emissions, it is important to characterize the primary particulate forming potential of the source emission as comprehensively as possible. After release into air, the time, meteorology and the background environment control the ageing of the emission, not just the primary emission itself. Chemical and physical properties of PM_{2.5} may vary greatly, as well as the formation of liquid secondary aerosols in the atmosphere. Depending on these factors, chemical and physical transformations of solid, liquid and gaseous emissions take place in innumerable ways. Secondary particles can also remain in the atmosphere for days to weeks, dilute and travel through the atmosphere hundreds or thousands of kilometres.

Table 42. Various approaches for the concept of PM from stationary emission sources

PM method	US EPA 40 CFR 50 Appendix B	ISO 8178	ISO 9096	EN-13284-1 & VDI 2066	EPA 17	EPA Method 201/201A	EPA Method 202	EPA/CARB Method 5
Description/ application area	Ambient air	Reciprocating IC engines; test bed/at site	Stationary sources	Stationary source, (wet) flue gas; test bed/at site	Stationary sources	Stationary sources	Downstream EPA 201/201A sampling	Stationary sources
Measured quantity	Suspended particulates	PM _{tot}	PM _{tot}	Dust load up to 50 mg/m ³	PM _{tot}	PM ₁₀ & PM _{2.5}	Condensable PM	PM _{tot}
Dilution	as in ambient air	diluted, Dr >4, non-isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic	undiluted, isokinetic
Cyclone	no	no	no	for > 10µm	no	for > 10µm	for > 10µm	No
Filter position*	air	OS	IS/OS	IS/OS	IS	IS	IS	OS
Sampling T	25°C	42-52°C	stack T/160°C	160-180°C	stack T	stack T rinse of tubing added to PM	≤ 30°C	120°C rinse of tubing added to PM
Impingers for volatile PM		no	no	no	optional	no	yes, dry	optional, wet 0°C

Dependence of PM emission quantity and quality on method of determination

PM emission factors found in the literature are basically based on either of two approaches of PM determination, (1) PM measured from the hot stack of typically 300–400 °C or (2) the more recent emission standard ISO8178, which is based on exhaust “quenching”, i.e. dilution and cooling. The hot stack measured PM constitutes only those components of emission aerosol that are not evaporable at the high temperature of sampling. This includes the oxidation and sulphation products of the fuel “ash” and metals, as well as products of incomplete combustion, i.e. soot and the most difficulty volatilised organic compounds. The amount of organic carbon (OC) is dependent on the sampling temperature, and can make up the major part of the carbon even at sampling at 300–400 °C, depending on the fuel type.

The ISO8178 standard is the currently accepted method for conducting PM emissions testing on marine vessels and engines, as it has been widely adopted for marine exhausts. One basic limitation is that the standard is valid for fuels of less than 0.8% sulphur content only. Testing with typical MDOs (Marine Diesel Oil) or residual oils (RO) with higher sulphur content result in more variability in emission rates (Bastenhof 1995, Lappi & Turunen 2009). According to ISO8178, PM is composed of all emission components that are solid or condensed on the sampling filter at 42–52 °C, after dilution of the exhaust with any acceptable air/exhaust ratio $\geq 3/1$.

Evidently these two PM emission concepts may yield widely different emission rates and emission factors. PM according to ISO8178 is not unambiguously defined, as the PM amount depends on the rate of dilution and the concentrations and vapour pressures of volatile constituents (volatile organic carbon compounds (VOCs) and H_2SO_4 (+ H_2O) in the exhaust), see Figure 37 (Ristimäki *et al.* 2010). PM measured by hot-stack methods is strictly not unambiguous either, but more specific.

Figure 37. Dependence of PM emission rate on dilution ratio according to ISO8178:2006 standard. Engine operate at high load (Ristimäki et al. 2010)

Examples of results using the two different PM emission sampling concepts are shown Figure 38 (Lappi & Turunen 2009). Due to the high sampling temperature of around 350 °C the measured in-stack PM is free of volatile matter, while the ISO8178 PM contains 85% volatiles and 15% non-volatiles. As the dilution ratio is increased (towards infinity) the ISO8178 based PM emission converges towards the in-stack PM emission results. The ISO8178 standard seems to have been rather commonly applied for fuels of higher S content, regardless of the fuel sulphur limitation in the standard. As long as the measurement method is not harmonized, e.g. requiring a constant dilution ratio, the ISO8178 PM emission factors are not comparable, and thus not an appropriate basis for emission inventories. The solid in-stack PM measurements is the most precise measure, valid for PM comparisons. It does not include the volatile share of the emission (VOCs and sulphuric acid) (Figure 38). The ash contents in Figure 38 is calculated from fuel ash, while the H₂O content is the equilibrium concentration of hydration water attached to H₂SO₄ at standard conditions of determination (RH50, T23 °C).

Relative amounts of various chemical constituents in the PM of a typical MGO (Marine Gas Oil), MDO and RO emission, determined according to ISO8178, are shown in Figure 39. Proportions of the volatiles are dependent on the selected dilution ratios. The fuel ash based ash emission calculations lack components from lubrication oil. It is estimated though,

that fuel ash gives a fairly good estimate for the quantity of the inorganic load in the emission.

Figure 38. Relative filter based PM emission rate depending on sampling method. Exhaust volume basis. TSP in-stack = EPA Method 17, ISO9096 or respective, ISO8178:2006 with dilution ratio (Dr 18). (Lappi & Turunen, 2009)

Figure 39. Proportions of PM constituents from MGO, MDO and RO. Dr:s according to ISO8178 were 7, 11 and 18, respectively. Collection temperature was circa 50 °C

An image summarizing the effect of engine load and PM dilution ratio Dr (ISO8178) on PM emission factors is shown in Figure 40 for HFO (Heavy Fuel Oil) with high sulphur. Dilution ratio at “close to infinity” corresponds to the in-stack PM emission rate that contains no volatiles. Depending on engine load and PM sampling conditions emission rates may vary 5 –fold. The Lloyd’s relative value, which is based on fuel sulphur content only, is close to the higher end of the emission values (TEMA2000).

Figure 40. Dependence of PM emission factor on engine load and dilution ratio (ISO8178). Data calculated from the source (Lappi & Turunen 2009)

There is only a little difference between emission rates of PM, PM₁₀ and PM_{2.5} and PM₁ from marine engines. From HFO (2.5% S, < 0.07% ash) about 90% of PM is PM₁, and 90–95% is PM_{2.5} at high load. For a good quality distillate fuel the spread of PM size classes is wider (Figure 41). As the load is decreased the share of smallest particles, PM₁, increases, as more and more new liquid aerosol appears in the emission. In Entec (2007) the share of PM_{2.5} has been estimated to be 90% and the share of PM₁₀ 95% of total particle mass based emission, consistent with the experimental results presented in Figure 40.

Figure 41. PM mass size distribution of RO, MDO and MGO emissions from high load operation (Lappi & Turunen 2009)

Some general recommendations regarding measurement standards have been given in the literature. Bastenhof (1995) for example, concluded that in cases where PM limits are officially applied (as in case of power plants), it would be wise to continue the in stack methodology rather than changing to the ISO8178 standard for high sulphur fuel emissions. Furthermore, the international council for combustion engines, CIMAC, that represents main parties working with large power plants and marine engines, so far recommends the use of the ISO9096 standard also for marine engines, operating on any fuel quality, in order to achieve consistent measurement results and to enable comparison to other stationary land based sources, where the ISO9096 is the predominant method (CIMAC 2007).

PM emission factors

While NO_x and SO_x emission factors from ocean-going vessels are relatively well-understood, PM emission factors are much more uncertain due to limited data, diversity of emission sources and variability in the measurement techniques. The most widely cited “historical” emission tests, which have formed the basis for many PM emission factor estimations are those of Wright (1997) and Lloyd’s (1995).

As a result of the lack of legislation or regulations for marine PM emissions there is quite a diversity of ways of defining PM emission fac-

tors for ship, as discussed earlier. Additionally, PM can be calculated based on fuel sulphur content (TEMA2000, Saiyasitpanich *et al.*, 2005), fuel type (Lloyd's, 1995), in combination with engine load (EPA 2000) or engine type (TEMA2000). The basis of published PM emission factors is not always clearly reported. Notable is, for instance, that the earlier data of (Cooper 2002, Cooper 2003, Cooper 2004) are significantly lower than those of other studies. The possible reason could be that PM measurements have been made "undiluted", directly from the hot stack, and thus free from volatile matter.

Additional, critical perspectives to the ocean-going vessel PM emission factors have been given (CARB 2007). The analysis showed no significant difference between emission factors for auxiliary engines and the main low speed engines, for load factor, installed power, or model year when emission factors were normalised by power, except for low loads. Increase in PM emission factors at low loads, of 10–25%, have been identified for all marine fuel types (Sierra 2000, Lappi & Turunen 2009), the relative change being significant, and the highest changes for the best quality MGOs with < 0.1% S content. For this fuel even a 10-fold rise was found compared to emissions at 50–100% loads (mg/kWh). For fuels with < 1% S the difference in EF_{PM} (mg/kWh) was 2–3 fold.

According to CARB (2007) only a weak relationship was found between fuel sulphur content and PM emission factors for a set of engines (Figure 42). In our study, however, this relationship was very clear, especially at high loads of 50–100% (Lappi & Turunen 2009). Thus, it must be kept in mind, that the relationship between fuel sulphur content and PM emissions is very dependent on the PM sampling conditions and standards. In CARB (2007) it was estimated that the PM emission factor at 1.5% S level would be reduced by about 30%, to 1 g/kWh, compared to the 1.5 g/kWh estimated for HFO with 2.5% S. There was no statistically significant difference between distillate and low sulphur HFO PM emission factors.

The most important confounding factor in the emission factor data found by CARB (2007) was the differences in the measurement methodologies between the different studies. This analysis however lacked the very significant variability factor (besides fuel S content and sampling lines), of dilution ratio, the significance of which was exemplified in Figure 37.

Figure 42. Emission factor by fuel sulphur content. Several engines, sources, fuels and running modes (CARB 2007)

Based on the data set above and that of ENVIRON (2002) a theoretical assessment of the decreasing contribution of PM sulphate in total PM as fuel sulphur content decreases has been conducted. Differentiated and linear interpolation was made for high and low sulphur fuels, separately. These different estimates for the PM – fuel S relationships are shown in Figure 43.

Figure 43. Fuel sulphur – PM emission factor relationships (ENVIRON 2002, CARB 2007)

As PM and SO₂ emission factors are dependent on the fuel sulphur level, calculation of emissions in emission inventories require information about the fuel sulphur levels associated with fuel type, as well as which fuel types are used by propulsion and auxiliary engines. Based on a recent US survey, average fuel sulphur level for residual marine (RM, RO) was found to be between 2.5–2.7% S. For emission inventories, a sulphur content of 1.5% was used for MDO, while a more realistic value for MDO used in the US appeared to be 0.4% S. In the coming SECA environment in 2015, < 0.1% S shall be used, and from 2020/2025 on < 0.5% S globally. The effect of the scrubbers on PM emission is to a large extent still unavailable. Assumptions should also be provided on the mixes of fuel types used for propulsion and auxiliary engines by ship type. Slow speed Ocean Going Vessels (OGVs) vs. vessels with medium speed 4-stroke MEs (Main Engines) should be differentiated.

The quite recent PM₁₀ emission factors defined by EPA (US EPA 2009) rely on fuel S level, fuel consumption (BSFC, Brake Specific Fuel Consumption) and SO₄ conversion % according to the following equation for PM_{EF}.

$$PM_{EF} = PM_{Nom} + [(S_{Act} - S_{Nom}) \times BSFC \times FSC \times MWR \times 0.0001] \text{ where:}$$

- PM_{EF} = PM emission factor adjusted for fuel sulphur.
- PM_{Nom} = PM emission rate at nominal fuel sulphur level, = 0.23 g/kW-hr for distillate fuel, 1.35 g/kW-hr for residual fuel.
- S_{Act} = actual fuel sulphur level (w-%).
- S_{Nom} = nominal fuel sulphur level (w-%), = 0.24% for distillate fuel, 2.46% for residual fuel.
- BSFC = fuel consumption (SFOC, Specific Fuel Oil Consumption), g/kWh, = 200 g/kWh in this analysis.
- FSC = % of sulphur in fuel converted to direct sulphate PM, = 2.247% in this analysis.
- MWR = molecular weight ratio of sulphate PM to sulphur = 224/32 = 7 used for this analysis.

PM₁₀ is defined as engine exhaust (aerosol) emission on filter, obtained from either a full or partial flow dilution system, using min. Dr 5. This PM measurement method, according to US EPA (2012), is optional until 01.01.2015, after which it will become mandatory in the US. Noticeable is that prospects for the formation of sulphate PM may be increasing, as in earlier EPA regulations from year 1998 the estimated SO₂ to SO₃ con-

version % in marine engine was 1.3% (US EPA 1998), while it is 2.25% in the equation above. The effect of SO_4 on PM emissions is very intensive, 7 times the plain sulphur concentration, as 132% hydration water is attached to H_2SO_4 molecules at the conditions of PM determination, under the assumption that all SO_4 is in free acid form.

At present, both the “established” European and US procedures for PM sampling from ship emissions are based on diluting and cooling of the exhaust. According to ISO8178 the minimum dilution ratio Dr is 4 and for the US EPA 40 CFR 1065 (US EPA 2012) the minimum primary Dr is 2 and minimum total Dr is 5–7. In certain US waters the PM procedure becomes mandatory in 2015, in European ECA areas there is no PM emission legislation so far.

The US emission inventories, aiming at designating the US coastline up to 200 nautical miles as an ECA area, are based on the STEEM emission inventory model. The inventory estimates include emissions for nitrogen oxides (NO_x), particulate matter ($\text{PM}_{2.5}$ and PM_{10}), sulphur dioxide (SO_2), hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2). The PM inventories include directly emitted, primary PM only, although secondary sulphates and nitrates are taken into account in the air quality modelling (US EPA 2009).

Current knowledge of soot emission factors EF_{soot} from shipping

The problem with determining BC emissions and emission factors from sea traffic is evident by the recent and still on-going work within the international maritime organisation IMO. Its sub-committee on Bulk Liquids and Gases (BLG) decided late 2012 to establish a correspondence group to develop a definition, to consider measurement methods, and to identify and collate possible control measures regarding Black Carbon emissions (BLG 17/18). The outcome of the work so far was reported in October 2013, but there is yet no conclusion by the group in any of the above issues. The work will continue in the first session of the newly organised sub-committee of IMO, that for the Pollution, prevention and response (PPR-1), in February 2014.

In Table 43 below is a collation of current values published for soot emission factors (EF_{soot}) from marine engines and large commercial vessels. The designations for the soot definitions, which are based on the measuring principle, are according to (Petzold *et al.*, 2013). Elemental carbon (EC) means graphitic carbon, typically on a filter sample. EC is pure inorganic carbon not originating from any other carbonaceous con-

stituents. Equivalent elemental carbon (eBC) represents light absorbing carbon in the emission, the amount of which is dependent on the principle of the measurement of the light attenuation/extinction (e.g. absorption, transmission, reflectance) and its correctness (e.g. selection of exposure wavelengths, treatment of scattering and other unfavourable side phenomena and correctness of calibration, like defining the specific absorptivity of the soot, viz. mass absorption coefficient (MAC). Refractory elemental carbon, rBC, denotes carbon measured by its thermal resistance, typically using methods based on laser induced incandescence (LII). In the IMO correspondences group, so far, no definition or measurement principle was favoured over the other. Only obsolete methods based on ethalometry and opacimetry were discarded.

In addition to the above method of measurement itself and its development stage, there are unfortunately very many other variables that affect the non-coherence of the available EF_{soot} s in Table 43. They are related at least to the following factors: the position from which the measurement is made (either from the source like the exhaust pipe or from the ambient plume), if the engine is slow speed 2-stroke or medium speed 4-stroke, the type of operation of the engine (“propulsion mode” (variable speed of rotation of the engine) or “generator mode” (constant speed of rotation of the engine)), the age, i.e. emission category of the engine, the accuracy of information of the emission source(s) in plume measurements (it can be any combination of the main engine(s), auxiliary engine(s) and/or boilers), and the accuracy of the information of the powering/fuel consumption of the vessel at the moment of the measurement. The EF_{soot} s are natural functions of both engine load and fuel quality.

For EC there are two methods of determination: Thermal Optical Transmittance (TOT) according to the NIOSH 5040 or its modification (Birch & Cary 1996, Peterson & Richards 2002), or the “in-house” modification of Germanischer Lloyd of the German standards VDI 2465 Blatt 1 & Blatt 2 (Lauer *et al.*, 2008). For eBC one method is the filter smoke number (FSN) measurement that is based on reflectance of visible light from the blackened filter, and which is a very commonly used indicator of smoke formation in diesel engine development and operation. The other, and more specific and “scientific” methods used are based on absorption of visible light or its selected wavelength(s) (MAAP, PAS, PSAP, PASS). For rBC LII based methods of SP2, SP-AMS were applied in few instances.

Basically three research groups have performed multi studies of soot emissions from ships or ship engines with their usual methodologies. These are those of Petzold *et al.* (2008, 2011, 2013), which have determined the EC according to the above mentioned German standards from engine-out emissions of medium speed diesel engines (MSD), that of Lack *et al.* (2008, 2009, 2011) who measure eBC and rBC from the air released plume in-situ with optical methods, and that of Agrawal *et al.* (2008, 2008a, 2010) who have measured EC from engine-out exhausts of both MSDs and slow speed diesel engines (SSD) by application of the TOT method. Other reported studies are single efforts.

Due to the multitude of variables and uncertainties that affect the published EF_{soot} s from marine traffic a detailed conclusive break-down of the Table 43 data is not possible. Only some coarse guidelines can be given. In the estimations of the EF_{soot} s, medium speed engine traffic and slow speed engine traffic shall be differentiated. According to Table 43, trends of soot emission formation from these engine types as a function of engine load are principally different. With MSDs the soot emission factor tends to rise steadily with lowered engine load. For the SSDs there is no general trend with load, and the soot emission factor is relatively constant irrespective of load; in one case the factor decreased with decreased engine load. If EC determination is used as the basis for EF_{soot} , correction for the pyrolysed carbon during the thermal analysis is a prerequisite for correct results. Methods like that published in the standard VDI 2465 Blatt 2, or based on the coulometric applications are not reliable. This is especially important regarding results that are obtained from high sulphur fuels like HFO and ROs. With plume measurement results care must be taken to have correct source apportionment of the emission sources in use in the vessel, as well as reliable power/fuel consumptions as the basis for EF_{soot} calculations.

Soot emission factors from marine exhausts are presented in Figure 44. The figure shows the differences in EFs obtained with different methods. Noticeable is that EC emission of the MGO was higher than those of MDO (HFO 1) and residual oil (HFO 2) at moderate or high loads (Ristimäki & Lappi 2011).

Figure 44. Emission factors for elemental carbon EC from a MSD marine engine (Ristimäki & Lappi 2011). The reference values of Agrawal et al. (Agrawal et al. 2008a) are respective EC values from a SSD engine, those of Lack et al. (2011), different, viz. eBC from plume measurements of OGVs

In agreement with the approach of the BC correspondence group of IMO, it seems plausible that accurate and justified values for shipping EF_{sootS} , that are based on direct determination of BC in the marine emission, can be evaluated only after decision on the definition for BC (associated with the decision of the approved measurement methods), as the EF_{soot} is highly dependent on these.

In Table 43, if the original EF_{soot} was presented in the unit (m)g/kg fuel, it is converted into (m)g/kWh by dividing by 5 for 100–50% loads and by 4 for lower loads.

Table 43. Soot emission factors EF_{soot} from the literature

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ¹⁾	Technique of measu- rement	EF _{soot} mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
HSD ^{***)}	engine			Cummins QSK 19-M	1	4	0.375	95 75 50 25 idle		engine-out engine-out	automo- tive fuel	1.3 ppm	EC	TOT	circa 56 circa 83 circa 67 circa 27 circa 167	Jayaram <i>et al.</i> 2011
MSD	test engine	constant		1 cylinder	1	4	0.4	100 75 25 10	750	engine-out	HFO MGO	2.2 <0.1	BC	MAAP	4.8-0.9 (HFO-MGO) 10.1-1.3(HFO-MGO) 22.9-4.3 (HFO-MGO) 126-32.5(HFO-MGO)	Petzold <i>et al.</i> 2010
MSD	test engine	constant	1995	Wä 4R32LN 4 cylinder	1	4	1.6	100(high) 75(high) 50(med) 25(med) 10(low)	750	engine-out	LFO HFO1 HFO2 LFO HFO1 HFO2 LFO HFO1 HFO2	<0.1 <0.9 2.4 <0.1 <0.9 2.4 <0.1 <0.9 2.4	EC EC EC eBC eBC eBC "BC" "BC" "BC"	1)TOT 2) FSN 3)Total C- org. solubles	15-20/28-43/150/high/med/low 10-20/30-60/210- 250/high/med/low 10-20/15-60/60- 180/high/med/low 7-12/20-40/140- 150/high/med/low 12-13/24-51/260/high/med/low 18-21/33-43/182/high/med/low 25-35/42-75/310/high/med/low 55-80/120- 210/800/high/med/low 55-130/140- 230/570/high/med/low	Ristimäki <i>et al.</i> 2010
MSD	engine at vessel	propeller curve	1989	12V ZA 40X	2	4	7.2	27	360 (510 nom)	engine-out	MDO	0.48	EC BC	TOT MAAP	60-100 30-40	Lappi <i>et al.</i> 2013
MSD	test-rig engine			MAN B&W 9L58/64	1	4	10.625	100 110 85 50 25 10		engine-out	HFO	2.21	eBC EC	MAAP solvent extrac- tion+TA (no PyC correction)	BC 15/70 EC 14/40 11/36 15/30 45/76 92/129	Petzold <i>et al.</i> 2010
MSD	test-rig engine	Propulsion mode variable rpm		Multicylinder 1MW/cylinde r air-cooled, TC	1	4	ca 15	100(load100) 75(82) 50(63) 25(40)	514 468 411 324	engine-out engine-out engine-out engine-out	HFO LFO	0.83 0.1	eBC	FSN	11-15 14-16 23-29 143-155	Sarvi <i>et al.</i> 2008

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ¹⁾	Technique of measu- rement	EFsoot mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
MSD	test-rig engine	Generator mode constant rpm		Multicylinder 1MW/cylinde r air-cooled, TC	1	4	ca 15	100 75 50 25	514 514 514 514	engine-out engine-out engine-out engine-out	HFO LFO	0.83 0.1	eBC	FSN	9-11 15-16 27-30 54-55	Sarvi <i>et al.</i> 2008
MSD	test bed			MAN B&W 7- cylinder	1	4	ca 8	85-100		engine-out	HFO	2.21	EC	solvent extrac- tion+TA (no PyC correction)	35	Petzold <i>et al.</i> 2008
MSD	crude oil tanker aux. engine			Wärtsilä Vasa 6R22/26	(1)	4	0.9	75 50 25	1200	engine-out	MGO	0.06	EC	TOT	6 8 17	Agrawal <i>et al.</i> 2008
MSD	research vessel	Controlla- ble pitch propeller variable speed	1967	no TC (blo- wer)	1 (?)	2	1.64	(100) (61) (19) (1.4)	185 lower >lower >>lower	plume	MGO, MDO	0.1	rBC rBC eBC eBC	SP2 SP-AMS PAS PSAP	70**) 80 35 10	Cappa <i>et al.</i> 2013
SSD	test bed	variable speed	2007	4RTX-3 Wärtsilä TC common rail slide vessel	1	2	8.5	100 75 50 25 1	105 95.4 83.3 66.1 22.6	engine-out	MDO	0.155	EC	Coulo- metry (no PyC correction)	45 30 23 8 128	Kasper 2007
SSD	Post- Panamax class container ship	variable speed	1998	12k90MC MAN	1	2	54.84	90 75 50 25 13	94 lower >lower >>lower >>>lower	engine-out	HFO	3.01	EC	TOT	8 7 8 9 12	Miller <i>et al.</i> 2012
SSD	Panamax ship	variable speed		Sulzer 9RTA84C	1	2	36.74	1 0.125	102	engine-out	HFO	3.14	EC	TOT TOT	X 1.7*x	Khan <i>et al.</i> 2012
SSD	Crude oil tanker main engine	variable speed		Sulzer 6RTA72		2	15.75	85 75 50 25 13	90 lower >lower >>lower >>>lower	engine-out	HFO	2.85	EC	TOT	~20 ~25 ~20 ~20 50	Agrawal <i>et al.</i> 2008

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ¹⁾	Technique of measu- rement	EF _{soot} mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
SSD	vessel					2		57		engine-out			EC	TOT	7	Murphy <i>et al.</i> 2009
SSD	vessel					2	20.2	84	97	engine-out?	HFO	1.9– 1.97	EC		26	Moldanova <i>et al.</i> 2009
SSD	Container PanaMax	variable speed (ISO 8178 E-3)			1	2	50.27	70 63 52 27 8	101.8 98.1 91 73 49.2	engine-out engine-out engine-out engine-out engine-out	HFO	2.05	EC	TOT	17 20 17 16 29	Agrawal <i>et al.</i> 2008 ¹
SSD	Post- Panamax class container ship	variable speed	1998	12k90MC MAN	1	2	54.84	90 75 50 25	94 88 78 33	engine-out engine-out engine-out engine-out	HFO	3.01	EC	TOT	6.8 5.8 6.3 8.5	Agrawal <i>et al.</i> 2010
SSD	test engine			4T50ME-X 4 cylinder	1	2	7.08	75	123	engine-out	HFO MGO		EC	Solvent extrac- tion+TA (no PyC correction)	40 23	Internal report MAN
SSD (& MSD)	container vessel			MAN B&W	1 (1)	2 (4 for AE)	46.96 (AE 2.4 MW)	85		plume	HFO	2.45	eBC	PSAP	35±9	Petzold <i>et al.</i> 2008
SSD (& MSD)	container ship	Propeller curve?	2008	12RT-flex96C	1 (3)	2 (4 for AE)	68.6 (AEs 3x3.BMW)			plume	HFO MGO	3.15 0.07	eBC eBC		higher EF _{BC} expected lower EF _{BC} expected	Lack <i>et al.</i> 2011
SSD (& MSD?)	cargo & tankers	?			MEs +AEs boilers	2 (4 for AE)				plume	MDO? MDO?	0.55 0.4	eBC	MAAP	24 30	Diesch <i>et al.</i> 2013
SSD	tanker		1982		1	2	8.2	cruise		plume	MGO		eBC	white light attenuati- on	36	Moldanova <i>et al.</i> 2009

Engine/ ship type	Engine or vessel	Engine speed (operation mode)	Year of ma- nuf.	Engine type & parame- ters	Number of MEs (AEs) in use/tested	Stroke	Max. power MW	Power (load) % of max.	Engine speed l/min	Emission type ambi- ent/plume or engine-out	Fuel type	Fuel S %	Measu- red "soot" magni- tude ^{*)}	Technique of measu- rement	EFsoot mg/kWh (=mg/kg fuel*0.2 for 100-50%, *0.25 for 25-10% load)	Reference
SSD	Tankers	propeller		various	MEs + AEs	2+AEs		cruise		Plume		> 0.5%	eBC	PAS	76	Lack <i>et al.</i> 2009
SSD	container	curve		various	+ boilers	2+AEs		cruise				> 0.5%	eBC	PSAP	160	
SSD	cargo	propeller		various		2+AEs		cruise				> 0.5%			80	
SSD	carrier	curve		various		2+AEs		cruise				> 0.5%			76	
MSD	bulk carrier tug boats	propeller curve propeller curve ?				4				plume		< 0.5%	eBC		194	
SSD	ocean- going vessels (n=71)			various	MEs + AEs + boilers					plume	HFO MDO/MG O	higher S lower S	rBC eBC	SP2, SP- AMS, PAS, PSAP	66**) 42	Buffaloe <i>et al.</i> 2013

*) The designations are according to Petzold et al 2013 except for "BC" which denotes Total C-SOF (Soluble Organic Fraction).

**) Average of the 4 measurement methods.

***) HSD=high speed diesel, MSD= medium speed diesel, SSD=slow speed diesel.

Improved emission inventories of SLCP

Emission inventories of Short Lived Climate Pollutants (SLCP), and especially of Black Carbon (BC), are uncertain and not always comparable. Comparable and reliable emission inventories are essential when aiming for efficient strategies and policies for reduced emissions. This report presents the Nordic emissions and emission inventories of SLCP, the important emission sources and their development over time. It also discusses knowledge gaps, factors contributing to the uncertainties, and possibilities for improved emission estimates.

The overall objective of the three-year project is to improve the Nordic emission inventories of Short Lived Climate Pollutants (SLCP), with a focus on Black Carbon (BC). This report presents the results from the first phase of the project, an analysis of the present status of knowledge, with focus on BC and particulate matter (PM_{2.5}) emissions from residential biomass combustion, on-road and non-road diesel vehicles, and shipping. The next phase will draw on the results from this background analysis in designing and implementing an emission measurement program, where the objective is to expand the knowledge and develop well documented and reliable emission factors, primarily for BC, for use in future national emission inventories.

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