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Black carbon – Possibilities to reduce emissions and potential effects

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Preface

This is the final report from the research investigation ”Black Carbon – possibilities to reduce emissions and potential effects”.

The aim of the study is to obtain an overall assessment of the opportunities and costs for reducing emissions of "soot" (black carbon - BC) in Sweden. It should also address the potential positive effects of such measures for health, ecosystems and climate from a Swedish and Arctic perspective.

Another target is to identify scientific and technological needs (such as methods for emission estimates and emission measurement) needed to implement mitigation measures and assess its impact.

The purpose is that Sweden actively should be able to contribute in the expert group under the UN-ECE Convention of Long Range Transboundary Air Pollution (CLRTAP), to assess the possibilities and effects of including BC in the new Gothenburg Protocol. The Arctic council have as well established a task force studying the effects of BC on the Arctic climate and effects of emission reductions of BC.

This report also presents a selection of abatement measures available for reduction of BC in Sweden. Their cost effeciciency is discussed.

Content

1 Glossary

Term	Explanation
Elemental carbon, EC	All carbon in elemental form. Measured as the carbon that does not oxidize below 550-600^{o}C?
Black carbon, BC	Light absorbing carbon, measured by optical methods. Includes EC, but may also include some light absorbing OC. Absorption efficiency coefficient obtained from literature or in-situ comparison with EC measurements are normally used to estimate the mass concentration of BC
Black Smoke, BS	The oldest standardized concept of surface blackening determined by optical measurements of change in light reflection on a white surface. It was used instead of measurements of PM using a standardized dust sample as reference to transfer the optical measure into a mass concentration. It cannot be compared with present PM measurements.
Char	Solid residue after gasification, in the initial stage of combustion of carbonaceous materials.
Carbonate carbon, CC	Inorganic carbon, present as CO3. Usually minor fraction that may be neglected.
Organic carbon, OC	Organic carbon, OC is the carbon that is not classified in the analysis as EC or CC
Organic matter, OM	OC multiplied 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.
PMx	Particulate matter including all particles with an aerodynamic diameter less x µm (defined as particles passing a inlet with 50% efficiency at x µm)
POC	Particulate Organic Carbon
POM	Particle Organic Matter, includes other elements than carbon.
Soot	Generic concept of remains of incomplete combustion
Total carbon, TC	Sum of EC and OC on carbon mass basis. Usually measured by same thermal method as EC.
TSP	Total Suspended Particle Mass. The diameter of the particles included in TSP is not well defined due to wind speed dependent sampling efficiency inlet, but it usually varies between 50 and 100 µm.
GAINS	GAINS - Greenhouse Gas and Air Pollution Interactions and Synergies, is an integrated assessment model and the main model used in the international air pollution negotiations with under the Convention of Long Range Transport of Atmospheric Pollutants within OECD.
SLCF	Short lived Climate Forcing components, which is methane, ozone and particles including soot.

2 Summary

The present report emerge from the Swedish EPA project ”Black carbon – possibilities to reduce emissions and potential effects” to obtain an overall assessment of the opportunities and costs for reducing emissions of "soot" (black carbon - BC) in Sweden and its effects on health, ecosystems and climate. The basic analytical methods and techniques are described and reviewed. Existing and upcoming standards are described. The national BC emission inventory has been evaluated through a thorough basic review of the underlying data and processes as well as comparison with other inventories. The report identifies scientific and technological needs (such as methods for emission estimates and emission measurement) needed to implement mitigation measures and assess its impact.

The following major conclusions emerge from this report concerning BC and Organic Carbon (OC);

Standardized sampling, measurement and analytic methods for BC and OC are underway. Some major networks have already developed standardized methods giving high quality data. A more general standardization will ensure comparability between networks. So future measurements will have less uncertainty and data should be comparable. However this also means that historic data always shall be used with caution.

The total BC and OC emissions reported by different inventories agree fairly well, e.g. results from the GAINS scenario estimates and national inventory agree within 30 – 40 % but estimates of major source types can differ with more than a factor 2. This must be investigated as such errors can affect the mitigation policy. Investigations have been started.

There is a great need for national projections for 2020 and 2030 for BC but also the other related climate forcing air pollutants. Other climate forcing air pollutants are besides BC and other particle components and ozone. Besides that they affect climate they have a short life time in the atmosphere, thus called Short Lived Climate Forcing compounds (SLCF). Included in the SLCFs are also methane as it affects ozone chemistry even though it has an intermediate atmospheric life time. Inventories and projections on national policy implementation plans have to be developed keeping in mind that climate and health effects depend not on one component only, e.g. soot but rather a mix of different components. The climate effects can be best reduced by a decrease of CO_2 and SLCF, while health effects can be reduced by reduced emissions of particles and ozone precursors. The inventories thus have to include the emissions of all these components for all available reduction technologies to facilitate the development of the best abatement strategy. The analysis shows that all techniques involving combustion should be reviewed concerning emissions of all mentioned components.

It is clearly shown that regulation of SLCF can give co-beneficial effects on climate, health and ecosystem. However it cannot replace the abatement of long-lived climate forcers but rather increase the climate response to the abatements. The reductions needed for 2050 and beyond have to be large. Combustion is the basic process in the major common sources

for CO_2, O_3-precursors and particles including BC. Combustion has to be questioned as a part of future sustainable transport systems, energy and heat production.

The Swedish abatement costs for different SLCF abatement options varied strongly, in the hypothetical scenarios. However the same abatement options show up as the most cost effective in all scenarios. The three most cost effective options covered about 30% of the present emissions. The most cost effective measures found, e.g. decreasing BC emissions from power production and renewing of domestic fuel wood boilers, are found to be in the same range as CO_2 ETS price projected for Sweden in 2020. The cost estimates were in line with other studies. Still, the measures studied represent only a very small fraction of all options available to reduce BC emissions. The cost effectiveness of more alternatives in both the mobile and stationary sectors should be assessed. Fuel efficiency improvements, fuel shifts, as well as scrapping schemes are all potentially interesting options. In conclusion, the options analyzed in this study are found to be effective complements, both from health and climate point of view.

3 Soot - definitions and abundance

3.1 Definitions

Soot, Black Carbon (BC), Elemental Carbon (EC) and Black Smoke (BS) are all concepts of carbonaceous remains from pyrolysis in combustion of carbonaceous material, e.g. wood, coal or oil. The generic concept for this material is Soot and it is easily recognized as it is strongly blackening when smeared out on a white surface. Further it is very adhesive and sticks strongly to a surface. The most striking property is the light absorbing properties of soot. It is one of the stronger light absorbing materials found, certainly the most used. It is not one chemical substance but rather a varying mixture of different chemical substances, varying from pure graphite to different organic compounds often of aromatic character, e.g. polycyclic aromatic hydrocarbons.

Another property is that soot is not easily oxidized, e.g. rather high temperatures are needed to vaporize soot compared with other carbonaceous compounds.

The concepts BC, EC and BS have emerged from the different measurement techniques that are based on the different properties of soot to determine the abundance of soot. If the amount of soot is determined by measuring its light absorption the notion Black Carbon, BC, is used. Elemental Carbon, EC, is determined by techniques based on oxidizing all non light absorbing carbonaceous compounds prior to the analysis of the remaining carbon. Black Smoke, BS is the oldest standardized technique for measuring soot based on measuring the changing light reflection on a white filter surface. By a standardized reference sample a relation was found between the total mass and the change in light reflection. Unfortunately this relation is not valid for anything else than the reference sample and cannot be used for any other sample. Thus the BS measurements cannot directly be compared with EC, BC or any measurement of Particulate Mass (PM), even though there may be a very good correlation between BS and BC at some sites for certain time periods (e. g. Quincey et al., 2011).

Besides soot, today either measured as EC or BC, carbon exists in the atmospheric aerosol as Organic Carbon, OC, or Inorganic Carbon, IC. IC is essentially carbonates, often abundant in low concentrations so the carbonaceous aerosol is dominated by EC (BC) and OC. The OC is a most complicated mixture of smaller and larger organic molecules of which only a minor fraction has been chemically identified. An understanding of the complexity can possibly be conveyed by mentioning that the emissions of organic compounds from the biosphere to the global atmosphere have been estimated to be about 1500 Mtons per year acting as huge source for aerosol formation. For Europe the emission is about 10-30 Mton/y. The European anthropogenic emissions are estimated to be in the same range. These compounds are most likely oxidized by reactions with ozone, hydroxyl and nitrate radicals. A significant fraction of the reaction products, perhaps 10%, forms condensable organic compounds, i.e. particulate organic matter (POM). However the chemical pathways are not well known. Soot is a strong chemical absorbent, i.e. it is absorbing and binding vapors very efficiently. So soot is always containing OC, due to it has absorbed organic compounds already either at the source or later

during its atmospheric transport. This means that the properties of the soot particles affecting their influence on different climate important processes change drastically during their atmospheric transport.

3.2 Abundance

BS levels have dropped by more than a factor of 10 between 1965 and 1995 in Stockholm and Gothenburg (Johansson and Hansson, 2007). This is due to both decreased local and regional emissions, but not only related to reduced soot emissions since BS is more a measure of PM than BC as it also of depend strongly on the concentration of other components. In cities in Sweden, local emissions from vehicle exhaust and wood burning contributes to substantially increased soot concentrations (Johansson and Hansson, 2007). In recent years concentrations of black smoke (BS[1]) have been 2.5-10 times higher in urban background compared to at rural stations. At street level concentrations of BC (black carbon[2]) are 10-20 times higher as compared to urban background (Krel et al., 2011). There are no BS measurements at street level in Sweden. As for $PM_{2.5}$ and PM_{10} local source contributions are relatively much smaller due to the important contribution from secondary PM (such as organics, nitrates, sulphates etc). Measurements at different traffic sites show a strong correlation between BC and NO_X (Krecl et al., 2011). In Stockholm and at other sites were non-exhaust PM is an important source, correlations between PM_{10} and BC concentrations are usually very small. Mean BC/$PM_{2.5}$ ratios are larger at traffic sites in Stockholm (26%-38%) compared to rural sites (4-10%) (Krecl et al., 2011). This means that NO_X most likely is a much better proxy for BC than PM at least in urban environment dominated by traffic emissions.

For sites impacted by wood burning there is much higher correlation between BC and PM_{10} and $PM_{2.5}$ concentrations (Johansson et al., 2004; Krecl et al., 2007; Krecl et al., 2008). Also OC concentrations are substantially higher in urban areas as compared to rural background due to local source contributions, but there are less data on OC. EC/OC ratios have been shown to vary from 0.68 (road tunnel), 0.36 (street canyon Stockholm), 0.15 urban background (Stockholm), 0.11(urban background in Lycksele and Växjö) to 0.17 for a rural site (Aspvreten) (Johansson et al, 2004). But these ratios from different sites are based on measurements during different periods and relatively short measurement campaigns. There is need for long term data on OC and BC concentrations in Swedish cities. Such data are necessary for assessments of abatement measures and analysis of health and climate impacts.

4 Methods for BC / OC analysis

4.1 - Established methods for measuring BC/OC emissions

A guide on how to measure EC and OC in suspended particles in ambient air is under development within CEN/TC264, the European committee for standardization responsible for standardization of air quality measurements. The work builds on measurements and methods

[1] Sampling of particles, reflectance measurements, and calculation of BS index were done according to specifications of the SS-ISO 9835, which is the Swedish version of the international standard ISO9835 (1993).
[2] Measured as the attenuation of light transmitted through particles that are continuously collected on a filter

already published in the literature. Another prerequisite is the measurements should be suitable for ambient particles less than 2.5 µm in size and deposited on a filter in accordance with the EU-Directive for air quality, 2008/50/EG.

The guide for EC/OC measurements, "*Ambient air – Guide for the measurement of EC and OC deposited on filters*" exists so far in a draft form and describes the analytical methodology to determine the EC/OC after sampling on quarts fibre filter in accordance with EN 14907 for $PM_{2.5}$. In the sampling process particles are collected, however organic gases can be absorbed or semi volatile OC are partially desorbed, introducing uncertainties in the result already in the sampling. Further only a part of the filter is analyzed. The same method can also be used for other particle size fractions, but some of the mentioned artifacts might be larger for other size fractions.

The analytical method is based on exposing the sample to increasing temperatures and an oxygen free atmosphere such that the OC is volatilized while the EC remains. Thereafter the sample is exposed to higher temperature in an oxygen atmosphere facilitating total volatilization. The CO_2 emitted from this process is measured which can be transformed in to the carbon content in either fraction, EC or OC. The main differentiation between EC and OC is that OC usually vaporize at lower temperatures than EC when heated in an oxygen free atmosphere. Monitoring of the optical transmission or the reflectance during the measurement allows for correction due to unwanted pyrolysis during heating of the sample in thermal-optical methods. Thermal methods often use extraction of part of the OC prior to the thermal steps in order to reduce the unwanted pyrolysis. The difficulties in preventing pyrolysis or estimating the degree of pyrolysis introduce uncertainties in the analysis in terms of the EC/OC ratio. IC in the samples can be quantified separately by acidification of the sample followed by release of CO2, it is, however very imprecise and presence of carbonates in the sample increases uncertainty in the EC/OC or EC/TC quantification. Another factor that can bring a bias is presence of oxides in the sample (e.g. vanadium oxide abundant in exhaust from combustion of residual fuel) which can decrease the EC/OC ratio. The analytical instrumentation for the thermal-optical method is commercially available.

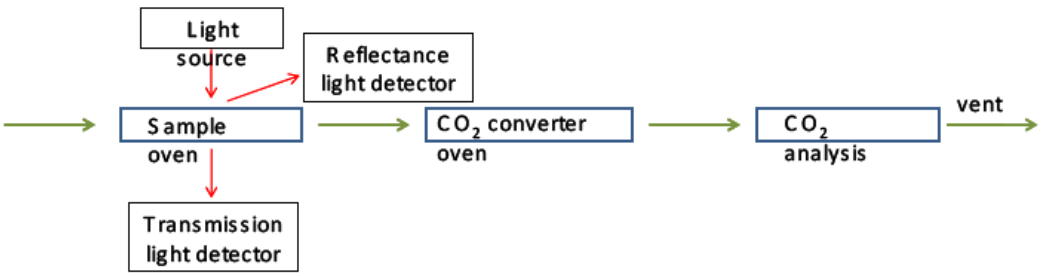

Figure 1 — Simple scheme of a thermal-optical analyser

There are several different protocols having somewhat different temperatures steps, time on each step and gas mixtures. Those considered in the standardization for measurements in the ambient air are NIOSH, IMPROVE and EUSAAR2. For direct measurements on emission sources, especially mobile, are standardized VDI thermal methods (VDI, 1996). A workshop at EU Joint Research Centre in Ispra, Italy resulted in an overview of measurements of EC/OC globally. This report serves as reference in the work with CEN/TR-method (EUR 23992 EN _JRC Scientific and Technical Reports *Measurement of Elemental and Organic Carbon in Europe.* Office for Official Publications of the European Communities, Luxembourg, 2009 (ISBN 978-92-79- 11294-2)).

The EU FP6 Infrastructure project European Supersites for Atmospheric Aerosol Research (EUSAAR), see www.eusaar.net, has developed standardized sampling, analysis and evaluation procedures for both EC and BC. The EC analytical procedure is the one now discussed in CEN, see above. There are several different optical instrumental approaches to measure BC which has been investigated and standardized. The standardization efforts in EUSAAR aimed not only at getting comparable data between similar instruments but also to get comparable BC values for all different instrument types.

There are several fundamental difficulties with all the measurement techniques used, as soot is not a unique chemical compound but rather a property of a mixture of compounds formed in combustion of organic material. This property is then converted into mass with different techniques, which usually are based on certain assumptions. The light absorption property of soot has relevance for the direct influence on climate while rather other properties of soot cause the effect on health and its indirect influence on climate through cloud formation. It is therefore most important to develop and agree on standardized sampling, analytical and evaluation procedures to facilitate a well based understanding of the abundance and variation of soot in the environment. As all historical data emerge from non-standardized, often indirect measurements, e.g. light reflection measurement transferred to mass, these have to be viewed in this context irrespective of it is emission or ambient measurements.

5 Methods for estimating BC/OC emissions

Different methods have been used to obtain emission estimates of BC/OC. Basically emissions are estimated either from specific emission factors for different fuels used by different types of machines in different sectors, or based on $PM_{2.5}$ or PM_{10} emission inventories with estimated BC and OC fractions of PM emitted. The latter seems to be the most common method to obtain BC/OC emissions.

A general way of estimating emissions is by multiplying the magnitude of an activity with a relevant emission factor:

E =AD x EF, where E=emissions, AD=activity data, EF= emission factor,

This means that the quality and representativeness of the activity data as well as of the emission factors used are important for the resulting estimated emissions.

5.1 Specific BC/OC emission factors

Kupiainen and Klimont (2007) present measurements of specific emission factors for most combustion and non-combustion related anthropogenic sources of BC and OC. Here we shortly discuss emission factors for vehicle exhaust and residential wood burning as they are responsible for a large fraction of the total BC and OC emissions in Europe. In this discussion it should be noted that BC, e.g. in Kupianen and Klimont (2007), has been used irrespective of the analytical method, i.e. BC has been used even though the analytical method used was thermo-optical. We have thus chosen to keep this notion in this chapter.

For vehicle exhaust BC and OC emissions depend on vehicle type, fuel and after treatment. Typical BC emission factors for heavy duty diesel vehicle exhaust are 45-150 mg/vkm (20%-60% of $PM_{2.5}$) without exhaust after treatment and 9-18 mg/vkm (50%-70% of $PM_{2.5}$) with after treatment (Kupiainen and Klimont, 2007). Lowest emissions of a few mg per vehicle kilometer are seen for light duty vehicles with after treatment. This variation makes it necessary to carefully consider the vehicle composition when emissions of BC and OC are to be estimated. Catalysts are more efficient in reducing OC emissions as compared to BC.

For residential wood burning the BC and OC emission factors depend on a range of factors such as type of appliance, type of firewood, moisture content and burn rates. The range of experimentally determined emission factors for biofuels extend over more than one order of magnitude (e. g. Kupiainen and Klimont, 2007; Junker and Liousse, 2008). For studies of emissions from residential wood burning cited in Kupiainen and Klimont (2007), emission factors for BC range from 0.043 to 3.5 g BC-C/kg wood and 0.25 to 7.3 g OC-C/kg wood. These large ranges reflect the variability seen depending on type of appliance, firewood and other conditions. In general, the OC/BC ratio increases for less efficient burning conditions (low burn rate, high moisture contents of the firewood etc). An important complication when comparing reported emission factors is due to application of different methodologies. This is particularly important for residential biomass appliances and involves both different analytical methods for BC and OC quantification, different sampling conditions (e.g. whether OC includes condensable organic compounds or not) and different parts of the burning cycle (e.g. whether it includes the start-up phase or not).

5.2 Using PM emission estimates to estimate BC/OC emissions

Another approach than using specific emission factors for BC and OC is to start from estimated emissions of particulate matter and then apply different fractions of BC and OC depending on fuel/sector etc. This is motivated since, the total BC and OC emission is constrained by the amount of PM emitted. This means that the PM and BC emission data is consistent but it does not mean that the resulting BC emission data is more exact or correct.

This approach is encumbered with uncertainties coupled to the PM emission sampling methodology. There are several standards for sampling of PM in terms of sample dilution and temperature program and these standards may have great effect on mass of condensable PM that is measured. While measurements of e.g. road vehicle sources are standardized both in terms of PMx, BC and OC, other sources, as e.g. non-road vehicles, are not entirely and

several standards can be in use. Combination of the EC/PM ratios and the PMx inventory in the second case needs to be done with caution as combination of the two parameters measured with different standards may bring a large error into the calculation.

In the EUCAARI (EU FP6 Integrated Project, European Integrated project on Aerosol Cloud Climate Air Quality Interaction, see www.atm.helsinki.fi/eucaari/) emission inventory representative EC and OC fractions are selected and applied to ~200 individual GAINS PM source categories and separated in < 1μm, 1-2.5 μm and 2.5-10 μm size classes. Size-differentiated EC and OC fractions were obtained from literature e.g., Kupiainen et al. (2004), Bond et al., 2004; Streets et al., 2001) and Schauer et al. (2006). As shown in Figure 2 most EC and OC are in the fine particle fraction, but the super micron fraction may not be neglected. Figure 3 shows the total organic fraction of $PM_{2.5}$ for different source sectors expressed as organic matter (OM). Organic matter is total mass of the organic compounds while OC is the mass of only the carbon in the organic compounds emitted. For industrial and non-industrial combustion (including residential wood and coal burning) the large non-organic matter fraction is due to mineral ash. The dominance of OM in $PM_{2.5}$ emissions from

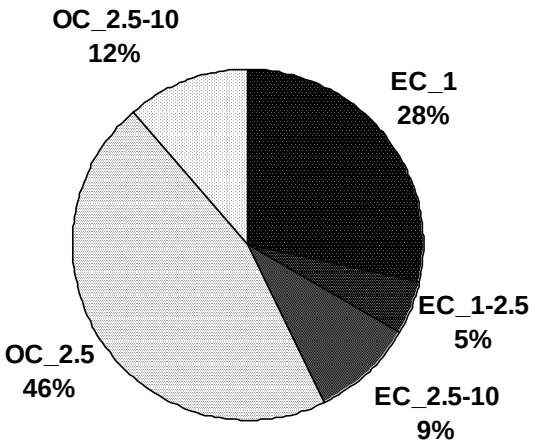

Figure 2. Carbonaceous aerosol < 10 μm (as TC) by compound and size class (van der Gon et al, oral presentation at the EUCAARI meeting in Helsinki, 2009).

road transport may be exaggerated due to missing contributions from emissions of non-exhaust material, such as suspension of road dust. It is likely that the share of EC and OM (organic matter) in the coarse fraction of PM_{10} is not negligible. For example, Sillanpää et al. (2006) report between 0.96 and 5.5 % EC of the coarse PM for six cities in Europe and 9.4 to 27 % OM.

Total $PM_{2.5}$ emissions for UNECE Europe excluding international shipping amounts to 3.4 Mt and about half of this is carbonaceous aerosol (organic matter). Primary sources of non-carbonaceous particles are combustion in industries and residential combustion, comprising fly ash and suspended product particles. The largest OC source in Europe is residential combustion of wood and coal. EC emissions are dominated by road transport (diesel) and non-road transport (diesel and fuel oil). Total carbonaceous aerosol for Europe in 2005 amounts to ~2 Mt/yr of which ~10% is due to international shipping.

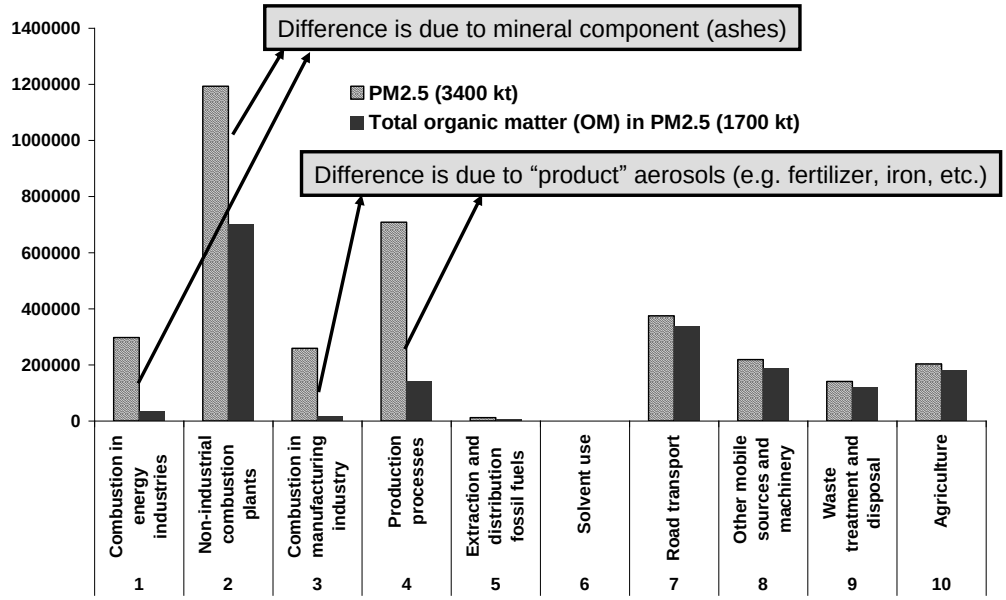

Figure 3. Total organic fraction of $PM_{2.5}$ for different source sectors in Europe according to the EUCAARI inventory 2005 (van der Gon et al., unpublished, 2009).

5.3 Estimating Swedish Emissions

The Swedish estimates of the BC and OC emissions are based on estimated fractions of officially reported national emissions of particulate matter. In the Swedish national air pollutant inventory emissions of $PM_{2.5}$, PM_{10} and TSP (Total Suspended Particulates) is estimated and reported to CLRTAP (Convention on Long Range Transboundary Air Pollution). The inventory is performed in accordance with the Guidelines for reporting (UNECE, 2003) and the EMEP/EEA Emission Inventory Guidebook (EEA, 2009). The national inventory is performed and reported on an annual basis and covers several air pollutants from various anthropogenic sources (IIR and IIR Annexes, Swedish EPA, 2011).

5.3.1 Activity data

The activity data used in the national inventory are for the energy sector (stationary and mobile combustion of fuels) based on official statistics on fuel consumption, collected and compiled by Statistics Sweden.

The main source of information for stationary combustion in energy production and in manufacturing industries is the quarterly fuel statistics collected by Statistics Sweden. The quarterly fuel statistics is done as a postal sample survey sent to all working units[3]. Data are collected from all companies in electricity and heat production, all companies in the pulp and paper industry and all companies in the manufacturing industry with more than nine employees and annual fuel combustion of more than 325 tonnes oil equivalents. All data are on facility level and by fuel (Swedish EPA, 2011, IIR. Annex 2).

[3] A company may consist of several working units, that is could be located in several places (factories).

The response rate to the quarterly fuel statistics is almost 100 % for the heat and electricity production sector (ISIC 40) and about 90 % for industries. The non-respondents among the industries are often small companies, which mean that much more than 90% of consumed energy is covered in responses to the survey. To compensate for companies not included in the sample and companies not responding to the survey, all fuel consumption is enumerated with an enumeration factor which is produced based on information from the most recent total survey (which is performed intermittently) (Swedish EPA, 2011, IIR. Annex 2).

For stationary combustion within other sectors (e.g. residential and other small scale combustion), activity data from the annual energy balances is used in order to ensure that all activities are covered and no activities are double-counted. The energy balances are based on a number of surveys (Swedish EPA, 2011, IIR. Annex 2). Sectors covered in these underlying surveys are one- and two dwelling statistics, holiday cottage statistics, multi-dwelling statistics, surveys for commercial and institutional statistics, and surveys made in the construction sector, in all companies with less than 10 employees and in the agriculture and in forestry sectors. The energy balances are used since none of the underlying surveys cover all emission sources in the different sub-sectors. In the energy balances, complementary calculations are made at Statistics Sweden in order to obtain full coverage and avoid double counting. Data for residential and other small scale combustion has been verified against the underlying surveys and the coherence was good for biomass fuels and oils (Swedish EPA, 2011, IIR. Annex 2).

5.3.1.1 Detailed description of activity data for residential and other small scale combustion

The sample survey for one-and two dwellings is conducted annually to collect data on the use of electricity and heat for a total of 7,000 one- and two-dwellings. The survey is based on a random sample from a real estate assessment. The real estate assessment includes all dwellings with an economic value higher than 50,000 SEK. Activity data in the inventory is taken from reports prepared by Statistics Sweden[4]. Data is on the national level by fuel type and of relatively good quality.

Every third year, a postal survey collects data from agricultural properties. The sample in this sector is 3,000 objects. Activity data in the inventory is taken from yearly reports prepared by Statistics Sweden[4]. Data is on national level by fuel type and considered to be of relatively good quality.

Holiday cottages are defined as residences with no permanent residents. Energy consumption in holiday cottages has been surveyed only three times in the last thirty years, 1976, 2001 and 2002. In 2002, Statistics Sweden carried out a stratified sample survey to house owners, covering 1,500 of the estimated 750,000 holiday cottages in Sweden 2001[5]. Results show that electricity and biomass combustion are the two main sources of heating in holiday cottages[6].

[4] Statistics Sweden EN20SM, 1990-2009.
[5] Statistics Sweden, 2002
[6] Biomass consumption in holiday cottages amounts to ≈6 % of the total biomass consumption in NFR 1A4b, residential plants.

A survey covering commercial and institutional combustion is a sample survey carried out each year, covering the use of electricity and heat of about 8,000 premises. Data is on national level by fuel type and of relatively good quality.

Data used in the inventory for stationary fuel consumption in the construction sector, in all companies with less than 10 employees, in agriculture and in the forestry sectors is taken from Statistics Sweden. The fuel consumption for the construction sector is based on a survey from 2005[7]. Data on fuel consumption in the agricultural sector is based on two intermittent surveys, for gardening[8] and agriculture[9] and the fuel consumption in the forestry sector has been studied thoroughly in 2007[10]. The fuel consumption in small companies (9 employees or less) is estimated using a model where fuel consumption for companies with 10-49 employees is taken from the industrial energy statistics and the average use of fuel per employee is calculated. Data for these sub sectors is on national level and by fuel type. The total estimated consumption for the sectors is checked against fuel deliveries, so that possible errors only occur in the allocation between these sectors (Swedish EPA, 2011, IIR. Annex 2).

5.3.1.2 Detailed description of activity data for mobile combustion

For mobile combustion sources data on fuel use for each fuel type is collected on the national level by Statistics Sweden. This information is used in combination with information for individual sources, eg railways, military use, road traffic, off-road vehicles and machinery, to allocate the national fuel consumption between the different mobile categories (Swedish EPA, 2011, IIR. Annex 2). For some of these sources detailed information is available while for others estimates are based on special studies made by SMED (Svenska MiljöEmissionsData, www.smed.se) in the framework of inventory improvements (e.g Fridell, Jernström and Lindgren, 2008, for off-road vehicels and machinery). The Transport Authority uses the ARTEMIS model (Swedish EPA, 2011, IIR. Annex 2) to calculate emissions from road traffic. From this model, a bottom-up national estimate of road traffic fuel consumption is calculated and used together with the available information for other sources, as input data in the balancing of the top-down national fuel consumption information.

5.3.1.3 Data used for emissions from Industrial Processes

For the sector Industrial Processes, covering emissions arising from all processes not defined as combustion for energy purposes, emission data for the inventory are to a large extent collected and compiled from the facilities annual environmental reports to the supervising authorities. The use of activity data for emission calculations is limited. It is however common to calculate $PM_{2.5}$ as a fraction of reported TSP or PM_{10} since $PM_{2.5}$ is rarely reported in the Environmental reports. The environmental reports are annually uploaded to SMP, Svenska Miljörapporteringsportalen hosted by the Swedish Environmental Protection Agency (Swedish EPA, 2011).

[7] Statistics Sweden, 2005
[8] Statistics Sweden, JO36SM, 1991, 94, 97, 2000, 2003, 2006, 2010
[9] Statistics Sweden, JO63SM, 1995, 2003, 2008
[10] Swedish Energy Agency, ER 2007:15. Energianvändningen inom skogsbruket 2005

5.3.2 Emission factors for PM2.5

The emission factors used in the Swedish inventory for estimating $PM_{2.5}$ are either nationally derived and documented, or taken from tabulated emission factors in the inventory guidelines or from other literature sources considered to be relevant for Swedish conditions. One primary condition for the emission factors used in the national emission inventory is that they should reflect the condition on the national level as closely as possible. This means that generalizations and assumption are necessary. The emission factors are usually derived based on results from emission measurements, which in reality may differ substantially. From this variable information, expert judgments based on general knowledge of "real" conditions has to be made. Examples of the variability of results from emission measurements from small-scale combustion in Paulrud et al (2006) are presented in table 1.

Table 1. Example of the variation in emission measurements of PM from small scale wood combustion (Paulrud et al. 2006).

Fuel/appliance	PM mg/MJ	Reference
Wood boiler	26-450	Johansson, 2005
Wood boiler	23-2200	Johansson, 2003
Wood boiler	30-700	SNV, 1983
Wood stove	22-181	Paulrud, 2006
Wood stove	7-173 (PM2.5)	Heberg, 2002
Wood stove	37-350	Boman, 2005
Wood stove	120-320 (PM2.5)	MacDonald, 2000
Wood Stove	30-55 (PM2.5)	Johansson, 2004
Wood Stove	10-1000	SNV, 1983
Wood stove	200-5500	Glasius, 2005
Wood stove	100, 90 (PM1)	Ohlström, 2005
Pellets burner	12-65	Johansson, 2003
Pellets burner	10-60 (PM2.5)	Johansson, 2004
Pellets burner	35, 25 (PM1)	Ohlström, 2005
Pellets boiler	30-40	SNV, 1983
Pellets boiler	15, 10 (PM1)	Ohlström, 2005
Pellets stove	30-60 (PM2.5)	Johansson, 2004
Pellets stove	11-81	Boman, 2005
Pellets stove	17-46	Boman, 2005
Open fire place	170-780 (dilution tunnel)	Purvis, 2000
Open fire place	100-150	SNV, 1983
Open fire place	130-1200	Dasch, 1982
Open fire place	150-420 (PM2.5)	McDonald, 2000
Open fire place	330-630 <PM10	Schauer et al 2001.
Open fire place	180-760 (PM2.5)	Fine, 2001
Wood chips boiler	30-1600	SNV, 1983
Wood chips boiler	20, 10 (PM1)	Ohlström, 2005
Wood chips boiler	50, 30 (PM1)	Ohlström, 2005

The national emission factors for $PM_{2.5}$ used in the Swedish national inventory for combustion of fuels in stationary and in mobile sources are presented in Annex 1. The tables on emission factors in the Annex 1 also shows the level of detail of the individual sources

that are treated separately in the emission calculations, and also the documented literature sources used for the emission factors.

5.3.3 Emission factors for BC and OC

Emissions of BC and OC are calculated as a fraction of estimated emissions of particulate matter, PM. The International Institute for Applied System Analysis (IIASA) has compiled a comprehensive material on fractions of BC and OC for a number of emission sources. Below, table 2 presents examples of data from IIASA for small scale biomass (FWD) combustion, and compared with combustion of diesel oil (MD) for heating. The data by IIASA is derived from various sources in the international literature and can be seen as a compilation and harmonisation of existing information. It is however important to bear in mind that IIASAs objective is to use data that can be generally applicable for calculating national emissions for overall comparison between countries. For individual sources in individual countries the IIASA general data may not fully reflect the conditions.

Table 2. Examples of shares of different PM fractions in TSP (total suspended particles) from IIASA

Sector	**Fuel**	**$PM_{2.5}$**	**PM_{10}**	**BC**	**OC**
Domestic fireplace (DOM_FPLACE)	Fuelwood	93.0%	96.0%	11.5%	50.0%
Medium size boiler, automatic (DOM_MB_A)	Fuelwood	77.0%	89.0%	15.0%	15.0%
Medium size boiler, manual (DOM_MB_M)	Fuelwood	77.0%	89.0%	35.0%	25.0%
Single house boiler, automatic (DOM_SHB_A)	Fuelwood	93.0%	96.0%	35.0%	25.0%
Single house boiler, manual (DOM_SHB_M)	Fuelwood	93.0%	96.0%	30.0%	50.0%
Domestic stove (DOM_STOVE)	Fuelwood	93.0%	96.0%	20.0%	50.0%
Domestic sector (DOM)	Medium destillate	45.0%	55.0%	32.4%	8.1%

Fuelwood=FWD, wood and other biomass
Medium destillate=MD, Diesel/EO1

The Swedish emissions of BC and OC have thus been calculated based on reported national inventory data of $PM_{2.5}$ emissions, where source- and fuel specific fractions of BC and OC have been applied according to available information from IIASA.

5.4 Modeling of soot emissions and the effects

In the past there have been several attempts to model EC and OC over Europe. Deficiencies in emission data and formation of secondary organic aerosol have been identified when model results are compared with measurements (e. g. Simpson et al, 2007; Tsyro et al., 2007). Estimating and modelling present BC emissions are difficult and contain a number of steps as described above. Obviously modeling future emissions are even more difficult as it also including estimates of changes in energy use and changes in appliances. Below the steps included in these calculation is described for the GAINS model, giving an understanding for the necessity of supporting information and the difficulties in the calculations. In calculation

of the effects in the atmosphere knowledge is necessary about a chain of processes affecting the soot concentrations as dispersion, dry and wet deposition. OC and other gas emissions, gas phase chemistry, condensation on soot particles have also to be taken into consideration as soot contains not only EC/BC but also other compounds.

5.4.1 Emission modeling with GAINS

The Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS) model, developed by the International Institute for Applied System Analysis (IIASA) is used in UNECE CLRTAP to provide estimates on emissions of air pollutant (incl. BC) emissions and emission removal potentials in the European UNECE countries (Amann et al. 2004, 2008, 2011). The model calculates emissions, abatement costs and environmental impacts associated with economic activity and air pollution policies. Economic activity is in the model described as fuel use or production (inter alia), while air pollution policies are described as varying use of emission control options. The model data and methods are well documented, and the model has been peer-reviewed in 2004 and 2009. The model has an online functionality where external users can calculate emissions, abatement costs and environmental impacts for specified scenarios. All scenario data are open for public access http://gains.iiasa.ac.at/gains/EUR/index.login?logout=1&redirect=www .

Since 2007, IIASA has developed the possibility to calculate BC emissions for different scenarios (Kuupianien & Klimont 2007). Swedish GAINS modelling capacity has been established under the auspices of the Swedish Clean Air Research Programme (SCARP), financed by the Swedish EPA since 2006. In this report we have used this existing Swedish modelling capacity together with Swedish BC emission inventories to create an Alternative BC emission calculation in the GAINS model for Sweden in 2005.

In order to provide comparability with European estimates we have compared the Swedish BC emission inventories and the alternative BC emission calculation presented in this report with one of the latest GAINS model scenarios available. The "GOTH_PRIMESBL2009_baseline_rev1" scenario, hereafter called 'GAINS-Baseline' scenario is one of the scenarios used by IIASA to calculate Swedish emissions of air pollutants in 2020. This scenario serves as basis for Sweden and other European UNECE countries when IIASA develops more ambitious scenarios for Sweden. It is a part of the support to the CLRTAP negotiations, revising the Gothenburg protocol, to develop more ambitious scenarios for the parties of the CLRTAP. The revision of the Gothenburg protocol is ongoing and aims at prolonging the duration of the Gothenburg protocol, and to include control of PM emissions. The CLRTAP is currently also discussing the possibility to include BC as a pollutant of concern for the Gothenburg protocol.

Since this report focus on Swedish BC emissions in 2005, the Alternative BC emission calculation is a purely hypothetical calculation. The purpose of this calculation is only to show which potential there could have been for low BC emissions in Sweden in 2005 if alternative BC emission control technologies would have been implemented. The reason for developing a calculation for the year 2005 instead of developing a GAINS model BC

scenario for 2020 is that there is no official Swedish BC emission projection for 2020 available as of yet.

To introduce Alternative BC emission calculations for Sweden in 2005 is causing methodological challenges related to the abatement costs calculated with the GAINS model. The model methodology does not represent costs for instantaneous shifts in the use of emission control technologies. It does instead represent annual costs of technologies, and does not include costs for scrapping of old technologies. This implies that the comparison between the Swedish BC emission inventory 2005 and the Alternative BC emission calculation is a comparison between different air quality policies starting as early as the 1990.

A short explanation is given for the three main scenarios in GAINS in the following subchapters.

5.4.1.1 Scenario GAINS baseline

The main baseline scenario developed for Sweden by IIASA as support for the negotiations of the revision of the Gothenburg protocol is named GOTH_PRIMESBL2009_baseline_rev1 scenario in the GAINS model.

The scenario is based on European scale modeling of activities for the European countries. For the energy and industry sectors, the PRIMES model is used. For the agricultural sectors, the CAPRI model and for the transport sector the TREMOVE model are used. The results from these models are seldom directly comparable with Swedish inventories and projections, although efforts are made by IIASA to get comparable data. The scenario is described in CIAM Report 1/2011 (Amann et al. 2011)

5.4.1.2 Scenario Swedish BC emissions 2005

A scenario, Swedish BC emissions 2005, is a GAINS calculation based on BC emission factors used for the analysis in this report, and data from the Swedish emission inventory as reported to CLRTAP. This scenario provides BC emissions for Sweden, calculated using GAINS, which are in correspondence with the emission inventory in this report. The calculation is adapted from nationally reported data to IIASA (as in contrast to the model calculations in the scenario above). In the GAINS model, the original data is found in the GOTH_NAT_2009_baseline_rev1 scenario.

The use of BC control technologies in Sweden 2005 is identical to the estimates made by IIASA in the latest national scenario reported to IIASA (submitted in October 2009).

5.4.1.3 Scenario Alternative BC emission calculation

A GAINS calculation based on the scenario above (Swedish BC emissions 2005), but with alternative use of a selected number of emission control technologies. The emission control technologies selected are the ones with the highest possible emission removal potential for the selected sectors. The scenario only uses emission control technologies which are available in the GAINS model database on.

The most important assumption is that increased efforts in BC emission control would have started as early as 1990 in some sectors.

5.5 Uncertainties in emission estimates

There are large uncertainties in BC/OC emission estimates depending on the source (e.g. Kupiainen & Klimont, 2007; Johansson & Hansson, 2007) and these uncertainties lead to a range of possible emissions.

The uncertainties have to be kept in mind developing policy recommendations based on models relying on the emission inventories. There is a strong need to decrease these large uncertainties in the estimated EC/OC emission as the policy implications can be strongly affected. The main uncertainties to consider lie in the main sources of BC/OC which are residential wood burning and vehicle exhaust emissions.

For residential wood burning emissions for PM, BC and OC (and also other substances) 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. There are several factors that contribute to the uncertainties in emission estimates:

- Different standards are used in different countries to measure the emissions from wood burning. In Norway, for example, emission factors for PM are much higher than in Sweden due to the fact that they include the condensed OC (i.e. measure on cold smoke), whereas in Sweden PM emission measurements are made on hot smoke, excluding the condensable OC (Nielsen et al., 2010).
- Wood burning habits is very important for the emissions. The Biobränsle Hälsa Miljö project showed that differences between emissions from different appliances were more dependent on the house owner than on the type of appliance (Hedman and Löfgren, 2002)
- Including or excluding the up-start phase is very important for the total emission.
- Fuel wood consumption is also a large uncertainty especially since many households that use a combination of different heating systems and the actual mix of wood, oil and electricity may vary drastically.

When BC/OC emissions are estimated based on fractions of PM for different sources, they are constrained by the amount of PM emitted which could limit uncertainty (van der Gon et al., 2007; Visshedijk et al., 2009). However, the result will be very different if PM include or exclude the condensable OC as noted above.

Different methods have been used to estimate the uncertainties in PM emissions; source receptor modelling and inverse modelling makes use of ambient air measurements and chemical analysis of filter samples to infer emissions (Denby et al., 2009). Johansson et al. (2004) utilized source receptor modeling to infer BC/OC emissions in Lycksele and Växjö. Such source apportionment studies provide source contributions at one receptor site only. To relate these to emissions, local dispersion models are required. A comparison of local dispersion models with receptor models made for Lycksele (Sweden) and Oslo (Norway) by

Denby et al. (2009), indicates that the local dispersion models tend to overestimate the contribution of $PM_{2.5}$ from wood burning by a factor 1.5 to 2. Even though both the receptor and inverse modeling point to an overestimation of the wood burning emissions of $PM_{2.5}$ it is not possible to assign this solely to errors in the emissions inventory as dispersion model error can be significant (Johansson, 2009). Levoglucosan has been used as a tracer to identify wood burning contributions in receptor modeling, but may not be used as a quantitative tracer (Hedberg et al., 2006). Based on measurements and modeling of BC, Krecl et al. (2010) found that the local dispersion model overestimated the observations by 3- to 5-fold at 6 sites in a small residential area in Lycksele. Large residual concentrations were associated with weak winds and relatively high BC concentrations. The uncertainty in dispersion modeling may be of a similar order to the uncertainty in the wood burning emission inventory, so no firm conclusion concerning the quality of the emission inventories for Lycksele and Oslo could be made (Denby et al., 2009). Uncertainties in emissions of PM from road traffic emissions are smaller than for wood burning. Much more is known both about total vehicle kilometers, fuel consumptions and specific vehicle emission factors. But there is still not so many studies on BC and very few on OC emissions in traffic environments. In Stockholm studies of EC and OC emissions have been done in a road tunnel (Kristensson et al., 2004) and recently the spatial and temporal variability of BC has been related to road traffic emissions at several sites in Stockholm (Krecl et al., 2011).

Modeling PM on a larger scales than the local scale discussed above, is further complicated for EC and OC where their life cycle in the atmosphere is less well known. EC is quite hydrophobic when emitted from e.g. diesel engines, while quite hydroscopic when emitted in wood combustion, making it less or more susceptible to wet deposition. Wet deposition is the major deposition path having a very strong influence on the atmospheric concentrations.

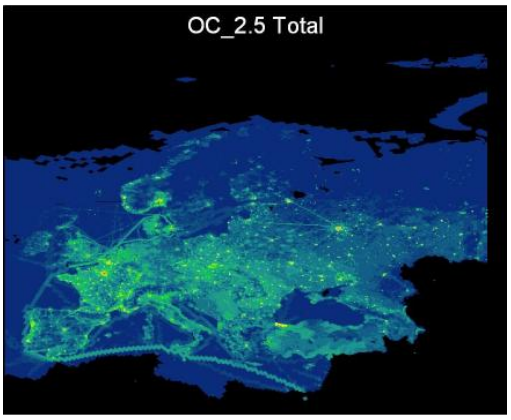

Figure 4. $PM_{2.5}$ Organic carbon annual emissions based on the carbonaceous emission inventory derived within EUCAARI.

First results of modeling done in the EUCAARI project with the PM-CAMx model revealed that the use of the EUCAARI EC and OC inventory to model carbonaceous aerosols during the EUCAARI campaign month May 2008 gave good results but that underestimations were observed for the EUCAARI winter campaign (February 2009) (Kulmala et al, 2011). Especially the OC aerosols appeared to be underestimated in Northern Europe. This may have various causes such as influence of near-by sources at observation sites, strong episodic character but may also be related to an underestimation of especially residential wood combustion emissions. The same conclusion was drawn by Simpson et al. (2007) when modeling carbonaceous aerosols over Europe. A first preliminary revisiting of the emission data gave further clues. In Figure 4 the emission of OC aerosol from residential

combustion is shown. OC from residential combustion originates for almost 90% from residential wood combustion.

There is a significant difference between Norway and Sweden as can be seen by the clear recognition of the country borders. This relates back to the different attribution of wood use to combustion technologies in both countries and the implied emission factors (based on national in-use $PM_{2.5}$ emission factors) which differ substantially.

Understanding OC emissions and resulting ambient concentrations will remain a challenge for the next years to come. Primary organic-particulate emissions consist of a wide variety of compounds and most of these are semi-volatile; thus, they partially evaporate with atmospheric dilution, creating substantial amounts of low-volatility gas-phase material.

5.5.1 Uncertainty in the input information used for determining the Swedish emissions of $PM_{2,5}$, BC and OC

The uncertainty in the national emission inventory of $PM_{2.5}$ depends on the uncertainty in activity data and in emission factors. The activity data in the Swedish national inventory are collected and compiled by Statistics Sweden, 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 lower for fuels traded on the market than for e.g. parts of 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. In international Guidelines for inventory methodology (e.g. IPCC Good Practice Guidance) activity data under those conditions can be assumed to have a low uncertainty level, in the order of 2-5%. In the residential sector, especially the use of biomass is quite uncertain since a part of this amount is not traded on the market. As was described in chapter 4.3.1 the data on biomass use in households and other more diverse sectors is collected by surveys and processed by Statistics Sweden. At present the overall uncertainty for biomass consumption is for inventory purposes estimated to ±10% including all types of biomass fuels.

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.

The estimated uncertainties for the emission factors for $PM_{2.5}$ for mobile sources vary in the inventory from +/- 15 to 40% depending on type of mobile source. The lower emission factor uncertainty is generally assigned to road transport while the emission factors for off-road machinery and navigation/shipping are assumed to be in the higher end.

For residential and other small scale combustion the uncertainty for the emission factors for $PM_{2.5}$ are in the national inventory estimated to be between ±10 and 65%, depending on source. The emission factors for PM from small scale combustion of biomass are considerably lower in Sweden than most other national emission factors and those given in EMEP/EEA Guidebook as default. The Swedish factors are based on a compilation of Nordic measurements of PM as presented in table 1 (Paulrud et al 2006). It is not clear if this is a real

difference or if the Swedish national emission factors may be underestimated. As the estimated emissions of PM is the basis for calculation of BC and OC emissions, a large uncertainty and possible underestimation of PM emissions of course also influences the estimated emissions of BC and OC. The uncertainties in the BC and OC fractions of PM given by IIASA, and used in the calculations of Swedish BC/OC emissions are not known but uncertainties are presumably significant.

The emission factors of particulate matter from small scale biomass combustion depend on several conditions mentioned in chapter 5.1. These include the quality of the fuel such as the moisture content and heating value, the combustion equipment and the condition of the equipment in which the fuel is combusted (boiler, stove, fireplace etc), the handling of the combustion process, eg. high load/lower load, reduced oxygen during combustion etc. For example, the existence of an accumulator tank in conjunction with the combustion appliance will influence the manner in which the combustion is handled.

Several of these conditions are not possible to cover in annual statistical surveys or similar investigations. In order to get a better understanding of the real conditions and thus to be able to reduce the uncertainties in emission estimations of particulate matter, studies have been made where the equipment, the fuel and the handling at firing have been documented at the time of emission measurement (Paulrud et al 2006b). Different kinds of postal surveys have also been used to try to obtain better knowledge to be able to extrapolate conditions regarding type and quality of installed equipment, consumption and handling of fuels etc. to the national level (Paulrud et al 2006b). Even though efforts have been made to collect and compile information to be able to reflect the real emissions as closely as possible, there are still, and will always be uncertainties surrounding firing habits and human behavior. It is thus not only the uncertainty in the actual activity data that influences the calculated emissions but also the human factor.

There is however a source of information that at present may not be used to its full potential and that is the chimney sweepers protocols and information from mandatory control visits. Even though not all the above mentioned conditions can be caught by the protocols from control visits, a better compilation of the information could potentially improve the understanding of national conditions.

5.6 Comparison of emission inventories

There are several emission inventories available. Table 3 gives a list of some emission inventories for PM on global and European scales. However not all address EC/OC.

In the EUCAARI inventory for Europe, diesel use in transport and fuel wood by households is responsible for 70% of the emission of submicron EC and 56% of the emission of OC in $PM_{2.5}$ (Figure 5). In this inventory for 2005, the submicron EC emission amounts to 0.36 and 0.16 Mton C/yr for Europe and the FSU (Former Soviet Union; Armenia, Azerbaijan, Belarus, Georgia, Moldova, Russia, Ukraine, Estonia, Latvia, and Lithuania), respectively.

Previous estimates of submicron EC emissions for Europe for 1995, 1996 and 1995 are respectively 0.47 (FSU 0.26) (Schaap et al. 2004), 0.47 (FSU 0.36) (Bond et al., 2004) and 0.52 Mton C/yr (Kupiainen and Klimont, 2007). To compare with the EUCAARI of 2005, one need to consider the trend in $PM_{2.5}$ emission per sector from 1995 to 2005 using the RAINS/GAINS data (Klimont et al. 2002) and this results in 0.51 Mton C/yr (excl. the FSU) for 1995, which is in close agreement with Schaap et al. (2004), Bond et al. (2004) and Kupiainen and Klimont (2007). This suggests that the difference in EC emissions between 1995 and 2005 is mostly due to a trend in $PM_{2.5}$ emission, although some shifts in source contributions has occurred as well and the EUCAARI estimate includes e.g., agricultural waste burning which is missing from the other inventories. The most marked decreases in $PM_{2.5}$ emissions going from 1995 to 2005 are in residential combustion, due to reduced coal use and from road transport, due to the market penetration of cleaner vehicles. The decrease in EC emissions going from 1995 to 2005 can therefore also be mainly attributed to these two source sectors.

Table 3. Emission inventories of PM, BC/EC/OC.

Name	Period	Area Resolution	Description Link	PM	BC/EC/OC
EDGAR	2000	Global 1^o x 1^o	The Emissions Database for Global Atmospheric Research (EDGAR) provides past and present day anthropogenic emissions. Joint project of the European Commission JRC Joint Research Centre and the Netherlands Environmental Assessment Agency (PBL). http://edgar.jrc.ec.europa.eu/index.php		Not yet. Still ongoing (no results so far)
EUCAARI	2005	Europe $1/8^o$ x $1/16^o$	Based previous PM emission inventories (e g GAINS), using EC and OC fractions. Ca 200 source categories and 3 size fractions. (Visschedijk et al., 2009; van der Gon et al., 2007)	PM <1 µm 1-2.5 µm 2.5-10 µm	EC, OC
EMEP	1980-2020	Europe 50 km x 50 km	EU-27 emissions under the LRTAP Convention, Parties	PM2.5	Not yet
GAINS	1990-2030	Global 1^o x 1^o	The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS). Model framework for the analysis of co-benefits reduction strategies from air pollution and greenhouse gas sources. http://gains.iiasa.ac.at/gains/EUR	TSP, PM10, PM2.5 and PM1	BC, OC
Junker & Liousse (2008)	1860-2000	Global 1^o x 1^o	Junker and Liousse, 2008	-	BC, OC
Bond	1850-2000	Global 1^o x 1^o	Bond et al. (2004)		BC. OC
REAS	1980-2020	Regional?? 1^o x 1^o	http://www.jamstec.go.jp/frcgc/research/p3/reas_c.html		BC, OC
EPA NEI	1999, 2002, 2005	USA 4 km x 4 km	http://www.epa.gov/ttn/chief/eiinformation.html	PM	
EPA	1970-2006	National	http://www.epa.gov/ttn/chief/trends	PM	

For OC emissions EUCAARI estimated 0.60 Mton C/yr for Europe 2005 (excluding the FSU). Previous European (excluding FSU) estimates for OC < 2.5 µm are 0.57 mton C/yr in 1996 (Bond et al., 2004) and 0.71 Mton C/yr in 1995 (Kupiainen and Klimont, 2007). Scaling

the EUCAARI 2005 estimate back to 1995 based on the RAIN/GAINS PM2.5 trend, results in an OC emission of 0.87 Mton C/yr in 1995 which is substantially higher than the 0.57 – 0.71 Mton C/yr from Bond et al. (2004) and Kupiainen and Klimont (2007). This difference may be attributed to an additional contribution from agricultural waste burning (0.05 Mtons) and a higher OC emission estimate from residential combustion e.g., 0.52 Mtons (scaled back to 1995) compared 0.42 Mtons in Kupiainen and Klimont (2007).

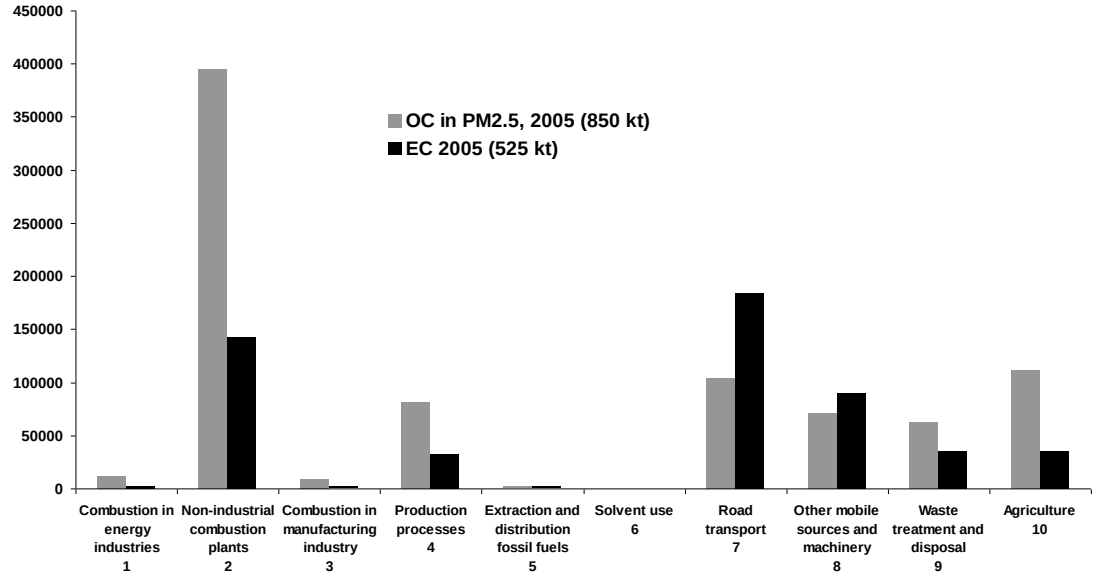

Figure 5. UNECE European emissions of EC and OC in the $PM_{2.5}$ fraction expressed as ton/y based on the EUCAARI emission inventory for different sources in 2005 (van der Gon et al., 2007).

5.7 Summary of BC/OC emissions estimates

Extensive work based on national statistics and reviewed emission factors from the scientific literature is needed to establish useful emission inventories. Besides getting as correct emission inventories as possible, the inventories should be useful for making projection of future emissions and be reliable in the policy negotiations.

Obviously the uncertainties are in some cases large, especially for widespread small scale combustion sources where no official registrations are available. For Sweden the estimates of the emissions from wood combustion are much larger than emissions from fossil fuel combustion. Evaluation of the emissions with local scale meteorological dispersion models reveals large errors in the emission estimates, a factor of 2-3. However the models were found to give similarly large errors giving in total error of a factor 5-6. Regional model evaluations over Europe reveal similarly large deviations for national emission estimates.

It is obvious that it is necessary to review the emission estimates including experimental evaluations of activity and emission factors, especially for the small scale residential emissions. This work has to be done in a European context to get a harmonized inventory

giving at least as correct emissions as possible relatively seen between the European countries and source types.

6 Estimated emissions of EC and OC.

6.1 Existing emission inventories

An important part, and major challenge, in assessing climate and air quality policies is to describe the emissions – for each sector, temporally and geographically in an accurate and consistent way. A summary of existing emission inventories that include PM and/or EC, BC and OC is provided in chapter 5.6 above, see table 3. Some of the emission databases are being updated and/or complemented with more information on e g sectoral emissions (e g the Emission Database for Global Atmospheric Research EDGARv4.1 hosted at JRC http://edgar.jrc.ec.europa.eu).

A number of studies provide information on future emission levels for the short-lived species both globally (for example Streets et al., 2004, Cofala et al., 2007, Rao et al. 2005, Dentener et al., 2005; Dentener et al., 2006) and for specific world regions and countries. Van Vuuren et al., (2008) present future scenarios covering short-lived radiatively important substances including BC.

Based on estimates of emissions of particulate matter (PM) and by using information on the respective fractions of BC and OC of the estimated PM emitted from various sources, emissions of BC and OC can be calculated. IIASA has published on the GAINS website tables with information on the fractions of BC and OC, respectively that are used in their estimates. The data used by IIASA is derived from various sources in the international literature and can be seen as a compilation and harmonization of existing information, see chapter 5.6 above. It is however important to bear in mind that IIASAs objective is to use data that can be generally applicable for all countries for calculating national emissions for overall comparison between countries. For individual sources in individual countries the IIASA general data may not fully reflect the conditions.

6.1.1 Estimated emissions of BC in Sweden

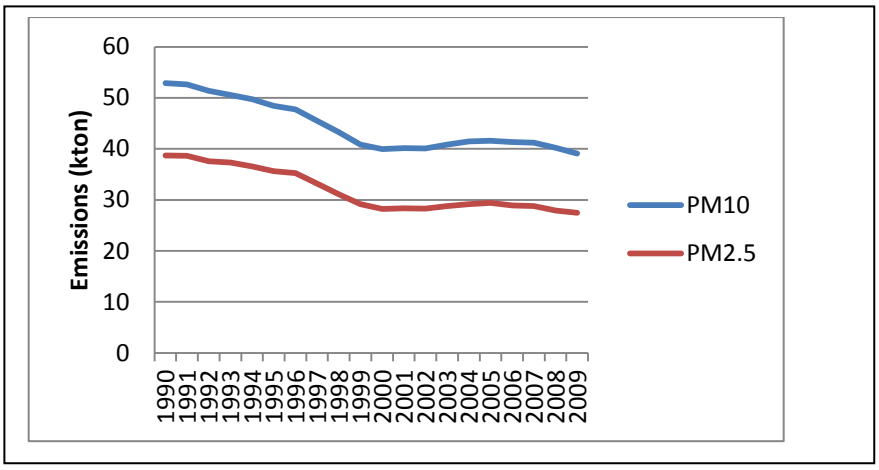

Figure 6. Swedish national total emissions of PM_{10} and $PM_{2.5}$, 1990-2009.

Emissions of BC and OC in Sweden have been estimated based on the national emissions of $PM_{2.5}$ from the official national emission inventory reported to CLRTAP (Swedish EPA, 2011). The level of emitted $PM_{2.5}$ and the development of emissions over time on the national level are presented in figure 6.

National total emissions of $PM_{2.5}$ in 2009 were estimated to 27 kton, a decrease from 39 kton $PM_{2.5}$ in 1990 (figure 6). In 2005 the emissions of $PM_{2.5}$ were estimated to 29 kton.

Figure 7 presents the development of national emissions of $PM_{2.5}$ within the four main sectors of electricity and heat production, road traffic, industrial processes and other sources.

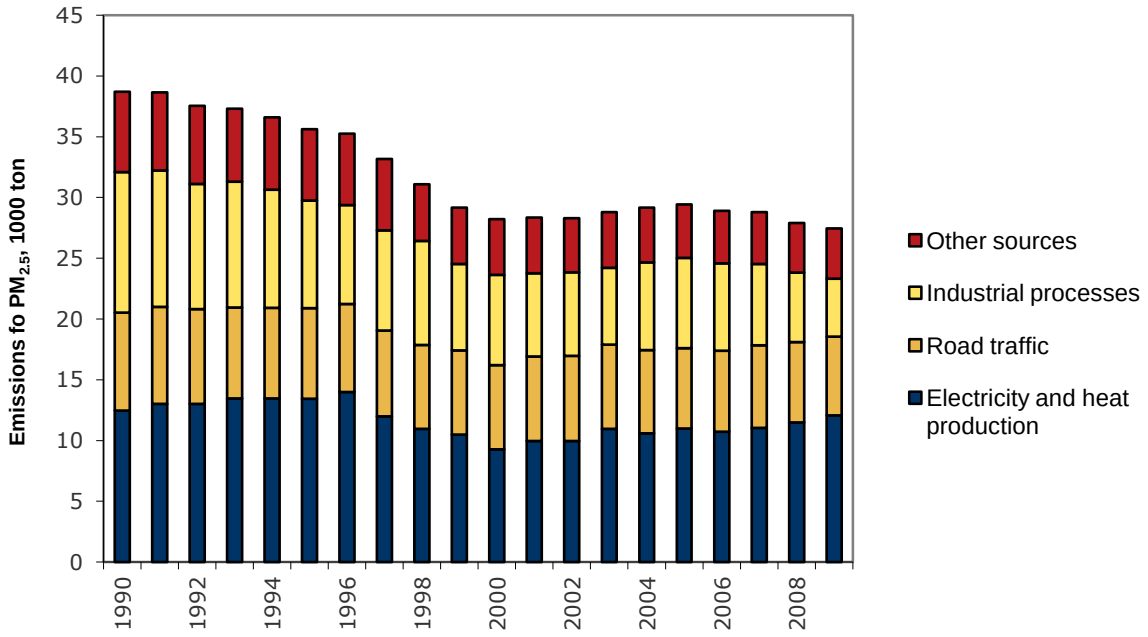

Figure 7. The contribution to emissions of $PM_{2.5}$ from different sectors.

The key sources contributing to 95% of the emissions of $PM_{2.5}$ in 2005 and in 1990 are presented in figure 8 below. Key sources are in the inventory guideleines defined as the sources, ranked from largest to smallest, which sum up and contribute to 95% of the total national emissions of a specific substance. The figures show that in 2005 there were five sources contributing more than 1000 tonnes of $PM_{2.5}$: residential small-scale combustion, the pulp- and paper industry, road abrasion from road transport, public electricity and heat production, and iron and steel production. In 1990 there were 11 sources with higher emissions of $PM_{2.5}$ than 1000 tonnes. For all of the larger sources the emissions of $PM_{2.5}$ are lower or substantially lower in 2005 than in 1990, except for the non-combustion road traffic sources of road abrasion and tyre and brake wear, and for combustion of fuels in public

electricity and heat production. The increases in emission related to road traffic is due to an increased activity while for the public electricity and heat production an increase in total activity in general (from approximately 100 to 200 PJ) and in an 8-fold increase in the use of biomass (from 13 to 100 PJ) is the cause for increased emission of $PM_{2.5}$. Note that in this analysis all fuels in a specific sector are included in the figures.

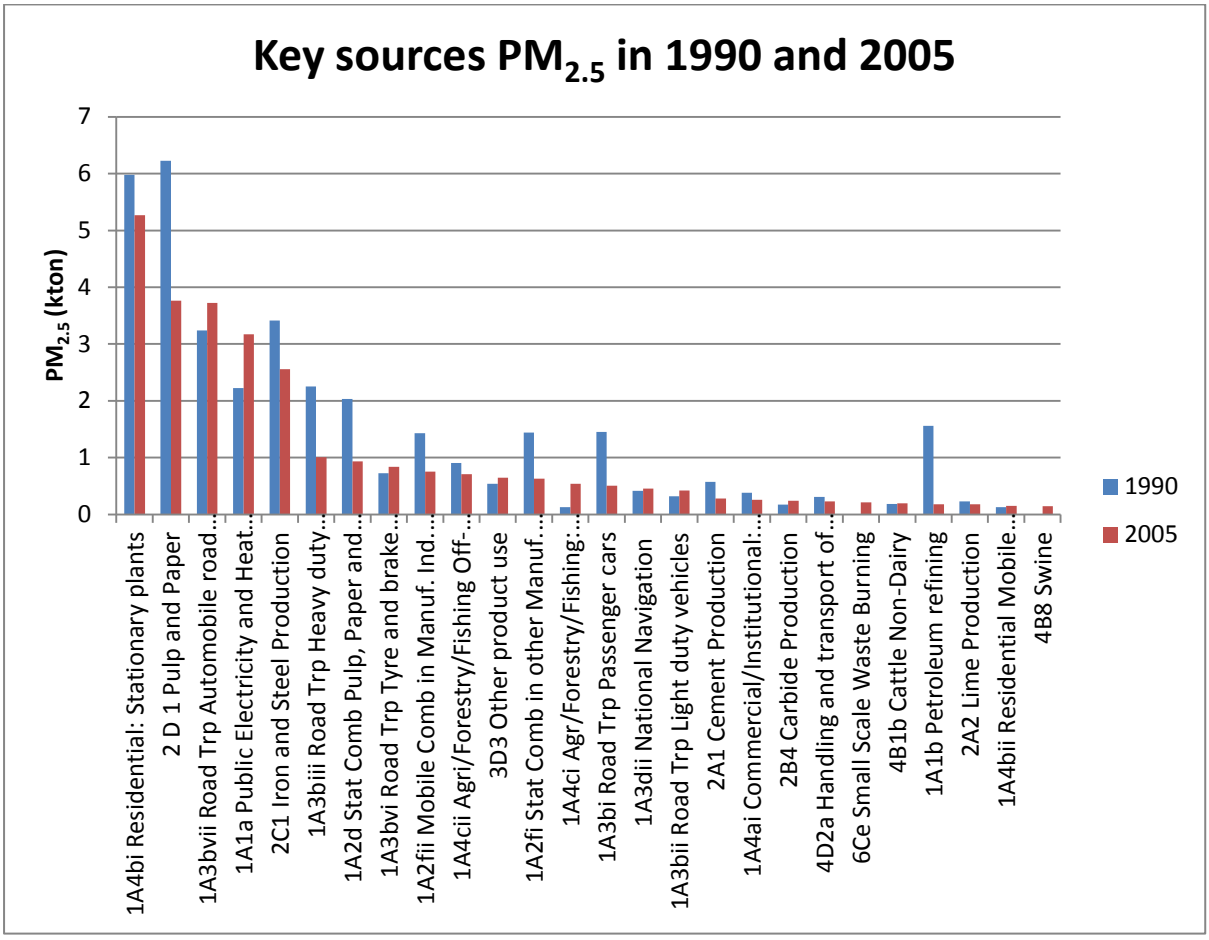

Figure 8. Key sources of $PM_{2.5}$ in 1990 and 2005. Sources ranked from higher to lower for 2005

Estimated total emissions in Sweden of BC and OC in 2005 based on the Swedish reported inventory of $PM_{2.5}$ were 5.1 kton of BC and 6.7 kton of OC. The emissions of $PM_{2.5}$ were 29 kton in 2005. The most important sources of BC, the key sources, according to the estimates are presented in figure 9 and table 4 below. For OC, the key sources are presented in fig 10 and table 5 below. In order to estimate the emissions of BC and OC, tables on fractions of these in emitted PM from IIASA were used, implying that the basis for the calculations are PM and fraction of BC and OC even though the analysis often is thermo-optical it is noted BC. Estimates are made on a source and fuel basis.

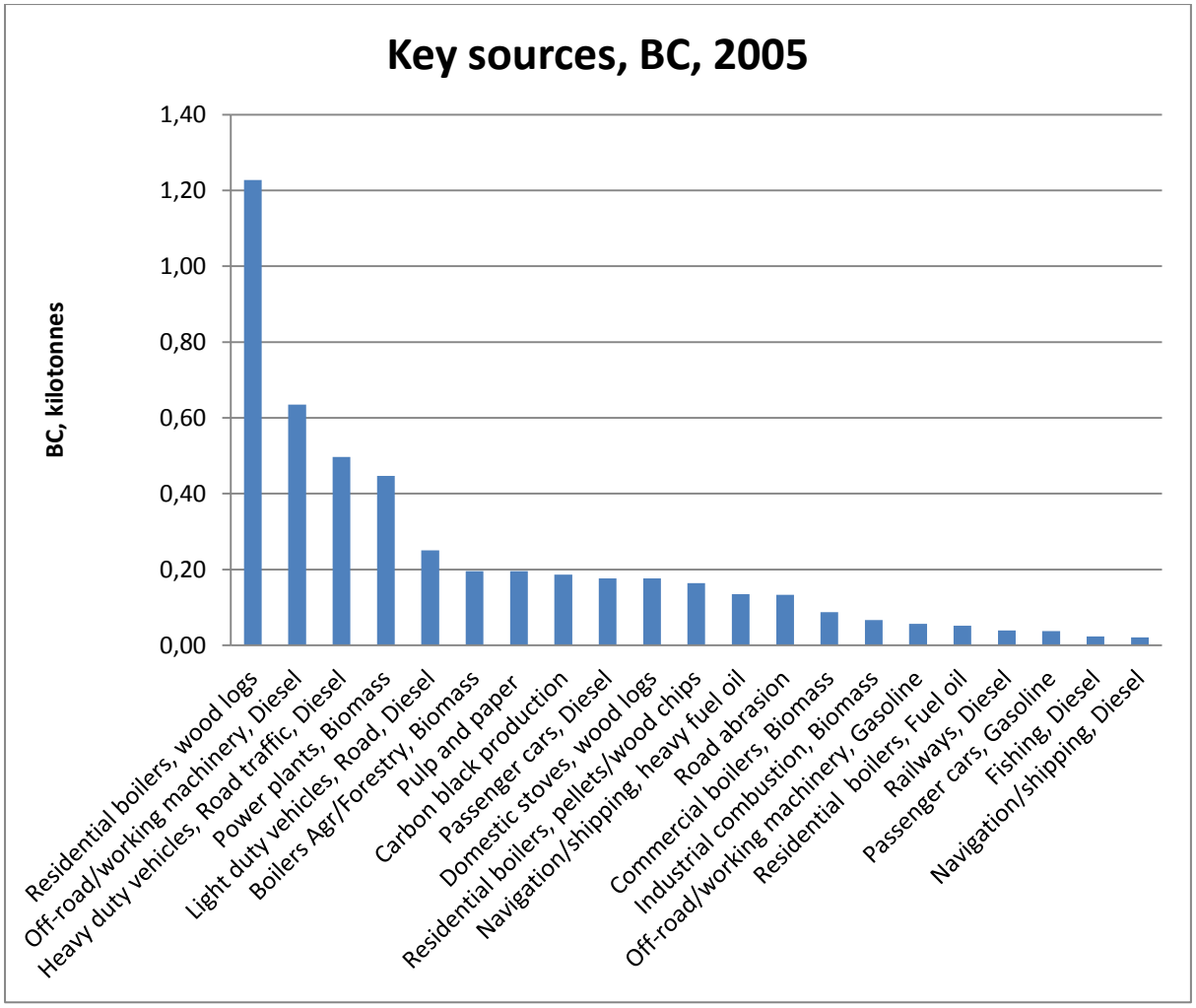

Figure 9. The BC key sources in Sweden, 2005.

Table 4. The BC key sources in Sweden, 2005	**BC (kton)**		**BC (kton)**
Total	**5.1**	***Non-road mobile sources***	***0.91***
Residential sector/small-scale combustion	***1.90***	Off-road/working machinery, Diesel	0.64
Residential boilers, biomass	1.39*	Navigation/shipping, heavy fuel oil	0.13
Boilers Agr/Forestry, Biomass	0.20	Off-road/working machinery, Gasoline	0.06
Domestic stoves, wood logs	0.18	Railways, Diesel	0.04
Commercial boilers, Biomass	0.09	Fishing, Diesel	0.02
Residential boilers, Fuel oil	0.05	Navigation/shipping, Diesel	0.02
Power plants and industry	***0.91***	***Road transport***	***1.09***
Power plants, Biomass	0.45	Heavy duty vehicles, Road traffic Diesel	0.50
Pulp and paper	0.20	Light duty vehicles, Road, Diesel	0.25
Carbon black production	0.19	Passenger cars, Diesel	0.18
Industrial combustion, Biomass	0.07	Road abrasion	0.13
		Passenger cars, Gasoline	0.04

* wood logs contribute 1.23 kton and pellets/wood chips 0.16 kton BC

The most important sources for black carbon, BC, include biomass combustion in different types of appliances, of which combustion of wood logs in residential boilers is the single largest source. Other important sources include those where diesel oil is combusted in mobile sources. The largest BC-sources for diesel are off-road vehicles, working machinery and heavy duty vehicles in road traffic. The pulp and paper industry turns up as an important source for BC-emissions. This estimate is however a bit uncertain. From the IIASA data regarding fractions of BC there are different potentially relevant sets of data to choose from which give different results regarding estimated emissions of BC. In the table below (table 5), the fractions of $PM_{2.5}$, BC and OC respectively, in TSP (total suspended particles) from the IIASA data set are given. There are no specific data regarding the pulp and paper industry from IIASA, instead the data most relevant are industrial combustion (IN_BO=industrial boilers and IN_OC=industrial other combustion) and two different fuels, OS1=biomass fuels and OS2=other biomass and waste fuels. Fractions of BC in $PM_{2.5}$ calculated from the IIASA data gives BC-fractions from between 3% up to 20% of $PM_{2.5}$, and similarly OC fractions from 0 to 20% (table 5).

Table 5. Fractions of $PM_{2.5}$, BC and OC of TSP in industrial combustion emissions according to IIASA, and calculated fractions of BC and OC in $PM_{2.5}$.

Activity	**Sector**	**$PM_{2.5}$**	**PM_BC**	**PM_OC**	**Calculated BC of PM2.5***	**Calculated OC of PM2.5***
Biomass fuels (OS1)	IN_BO	77.0%	4.0%	6.0%	5%	8%
Biomass fuels (OS1)	IN_OC	5.0%	1.0%	1.0%	20%	20%
Other biomass and waste fuels (OS2)	IN_BO	60.0%	10.0%	10.0%	17%	17%
Other biomass and waste fuels (OS2)	IN_OC	26.0%	0.9%	0.0%	3%	0%

*Calculated in this report

In the national inventory, 75% of the emitted particles from pulp and paper production are assumed to be $PM_{2.5}$. The most similar situation regarding $PM_{2.5}$ in the IIASA data corresponds to the case of IN_BO and OS1 (77% $PM_{2.5}$ in TSP), which would give 5% BC of emitted $PM_{2.5}$ (calculated as 4% BC of 77% $PM_{2.5}$ in TSP). This fraction, 5% BC in $PM_{2.5}$, was used in the calculations presented in this report. Obviously the calculated BC-emissions from pulp and paper could be higher or somewhat lower if other choices from the IIASA data set were made.

Depending on the assumptions on to which extent different parts of the pulp and paper processes contribute to the PM emissions, this will have an impact on the choice of BC-fractions and the estimated BC-emissions. Further study is needed both to define more in detail the underlying data and processes included in the national inventory of $PM_{2.5}$ and of the basis for the quite different assumptions regarding fractions of the PM species from IIASA.

The most important sources for OC, organic carbon, are similar to those for BC (Figure 10 and Table 6) but the non-exhaust emissions from road traffic (road abrasion and tyre and brake wear) turn up as a relatively more important source than for BC.

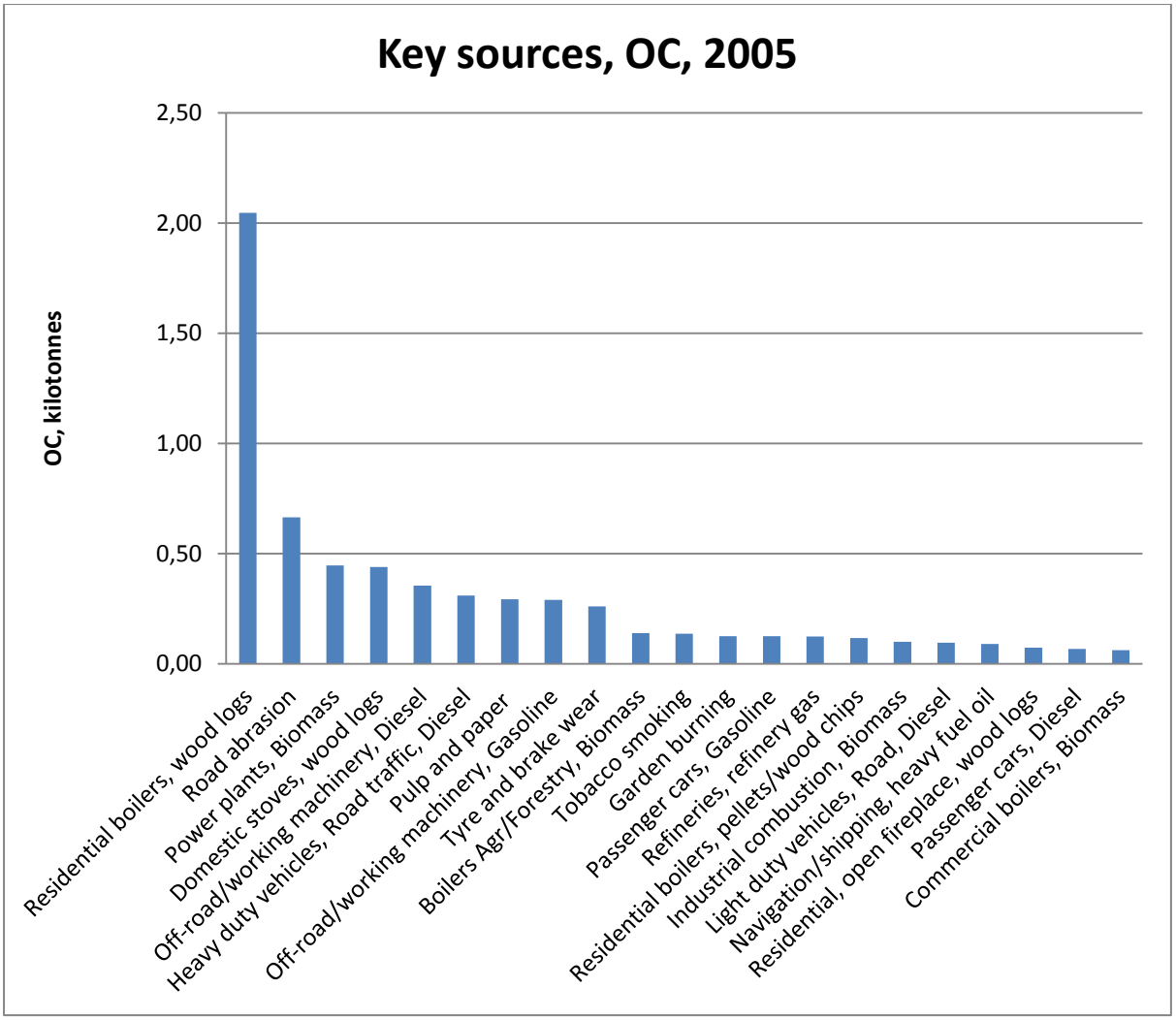

Figure 10. The OC key sources in Sweden, 2005.

Table 6. The OC key sources in Sweden, 2005	**OC (kton)**		**OC (kton)**
Total	**6.7**		
Residential sector/small-scale combustion	***2.88***	***Non-road mobile sources***	***0.74***
Residential boilers, biomass	2.16	Off-road/working machinery, Diesel	0.36
Domestic stoves, wood logs	0.44	Off-road/working machinery, Gasoline	0.29
Boilers Agr/Forestry, Biomass	0.14	Navigation/shipping, heavy fuel oil	0.09
Residential, open fireplace, wood logs	0.07	***Road transport***	***1.53***
Commercial boilers, Biomass	0.06	Road abrasion	0.67
Power plants and industry	***0.96***	Heavy duty vehicles, Road traffic, Diesel	0.31
Power plants, Biomass	0.45	Tyre and brake wear	0.26
Pulp and paper	0.29	Passenger cars, Gasoline	0.13
Refineries, refinery gas	0.12	Light duty vehicles, Road, Diesel	0.10
Industrial combustion, Biomass	0.10	Passenger cars, Diesel	0.07
Other sources	***0.26***		
Tobacco smoking	0.14		
Garden burning	0.13		

6.1.1.1 THE GAINS PERSPECTIVE

IIASA has in their GAINS model characterised the BC fraction of PM emissions from different emission sources. Kupiainen & Klimont (2007) summarized an inventory on BC emission factors. These estimates where introduced into the GAINS model. For Sweden in 2005, the emission factors for the largest sources of BC emissions in the GAINS baseline scenario are presented in table 7 below. These emission factors are based on the latest (March 2011) revision of the GAINS model emission factors. The methodology used to implement these BC emission factors for Sweden into the GAINS model is still under development. Because of this we have only used IIASA data on BC emission factors in the Swedish BC Emission Inventory 2005 and Alternative BC Emission calculations, rather than using GAINS model results for these calculations. The results from the IIASA:s GAINS baseline scenario presented in this report are however based on the GAINS model results.

Table 7: The GAINS-Baseline scenario BC emission factors for the largest sources in Sweden 2005

Sector, Activity, Technology	Emission factor (Ton BC/ Peta Joule (PJ))
Residential-Commercial: Single house boilers (<50 kW) - manual-Fuelwood direct-Biomass single house boiler improved-	95.2
Other transport: mobile sources in construction and industry-Medium distillates (diesel, light fuel oil)-No control	49.3
Other transport: agriculture and forestry-Medium distillates (diesel, light fuel oil)-No control	43.7
Light duty vehicles: light commercial trucks with 4-stroke engines-Medium distillates (diesel, light fuel oil)-No control	60
Power heat plants: Exist. other-Biomass fuels-Cyclone - power plants	2.14
Light duty vehicles: light commercial trucks with 4-stroke engines-Medium distillates (diesel, light fuel oil)-EURO 3 on light duty diesel road vehicles	21
Heavy duty vehicles - trucks -Medium distillates (diesel, light fuel oil)-EURO I on heavy duty diesel road vehicles	19.5
Light duty vehicles: light commercial trucks with 4-stroke engines-Medium distillates (diesel, light fuel oil)-EURO 2 on light duty diesel road vehicles	26.9
Heavy duty vehicles - trucks -Medium distillates (diesel, light fuel oil)-EURO III on heavy duty road vehicles	9.45
Residential-Commercial: Single house boilers (<50 kW) - manual-Fuelwood direct-Biomass single house boiler new	78.1
Residential-Commercial: Single house boilers (<50 kW) - automatic-Fuelwood direct-No control	14
Residential-Commercial: Heating stoves-Fuelwood direct-Biomass stove improved	64.6
Heavy duty vehicles - trucks -Medium distillates (diesel, light fuel oil)-EURO II on heavy duty diesel road vehicles	9.88
Other transport: inland waterways -Medium distillates (diesel, light fuel oil)-No control	43.2
Light duty vehicles: light commercial trucks with 4-stroke engines-Medium	23.5

distillates (diesel, light fuel oil)-EURO 1 on light duty diesel road vehicles	
Other transport: mobile sources in construction and industry-Medium distillates (diesel, light fuel oil)-Stage 1 control on construction and agriculture mobile sources	27.9
Light duty vehicles: cars and small buses with 4-stroke engines -Medium distillates (diesel, light fuel oil)-EURO 2 on light duty diesel road vehicles-	17.4
Light duty vehicles: cars and small buses with 4-stroke engines -Medium distillates (diesel, light fuel oil)-EURO 1 on light duty diesel road vehicles-	21.8
Light duty vehicles: cars and small buses with 4-stroke engines -Non exhaust PM emissions - road abrasion-No control-	1.54

These BC emission factors are the basis for the GAINS model BC emissions calculated for Sweden in 2005 in the GAINS-baseline scenario. In the GAINS-baseline scenario, emissions from single household boilers constitutes the largest source of BC emissions for Sweden in 2005, followed by emissions from nonroad mobile machinery in the construction and agricultural sectors.

Table 8 below presents the largest sources of BC emissions for Sweden 2005 in the GAINS-Baseline scenario.

Table 8: The GAINS-Baseline BC emission sources for Sweden 2005	**BC (kton)**		**BC (kton)**
Total	**7.13**	***Non-road mobile sources***	**1.76**
Residential sector/small-scale combustion	**2.07**	Off-road/working machinery, Diesel	1.38
Residential boilers, biomass	1.65	Navigation/shipping, heavy fuel oil	0.08
Domestic stoves, wood logs	0.30	Off-road/working machinery, Gasoline	0.08
Residential boilers, Fuel oil	0.03	Railways, Diesel	0.01
Other residential (bbq etc)	0.09	Aviation	0.00
		Navigation/shipping/fishing, Diesel	0.21
Power plants and industry	**0.56**		
Fuel conversion	0.00	***Road transport***	**2.73**
Power plants, incl CHP	0.42	Heavy duty vehicles, Road traffic Diesel	0.83
Other industrial boilers & combustion	0.08	Light duty vehicles, Road, Diesel	1.17
Industrial processes	0.06	Passenger cars, Diesel	0.41
		Road abrasion, brake & tyre wear	0.26
		Passenger cars, Gasoline	0.02
		Other road transport	0.04

The total BC emissions in Sweden 2005 would in total be 7.13 kton according to the GAINS-Baseline model scenario. When comparing to the Swedish emission inventory, the GAINS-Baseline calculates total Swedish BC emissions to be 2 kton larger than the Swedish emission inventory, see table 10.

Table 10. Comparison of diffent BC emission inventories for Sweden

Annual BC emissions (kton/y)	Swedish national (2005)	GAINS-Baseline (2005)	Bond (1995)
Total	**5.1**	**7.13**	**12.5**
Residential sector/small-scale combustion	**1.90**	**2.07**	**3.0**
Power plants and industry	**0.91**	**0.56**	**1.7**
Non-road mobile sources	**0.91**	**1.76**	**2.9**
Road transport	**1.09**	**2.73**	**4.6**

Quite interesting is the major differencies found in estimates of the road and non-road mobile sources, as well as the power plant and industrial sources. The differencies between the two estimates are about a factor of 2 to 3. These sources are usually considered to be rather well known and thus the estimate to be rather precise, while the uncertainty in the residential sector is considered to be much larger. The GAINS-Baseline calculates emissions from diesel engines in road transport to be some 1.5 kton larger than estimated in the Swedish emission inventory 2005. There are two main sources for this difference. First, the difference is partly explained by differences in the activity data between Swedish and IIASA estimates. Secondly, there is a difference in which emission removal technologies, vehicle vintages that is considered to be implemented for the sector of consideration. When combined, these two sources for differences can cause large discrepancies. Further the sub-sectors are in some cases not identical to the ones identified in the Swedish BC emission inventory. This is due to differences in the representation of sectors. More efforts would be needed for a full review of the differences presented above.

6.2 Summary and suggestion for developing the Swedish emission inventory for BC/OC

The total Swedish national BC emissions as given by the national BC emission inventory and the GAINS-Baseline-scenario agree fairly well, i.e within about 30-40%. However the different major source type could vary as much as a factor 2-3, even for road transport, that usually is considered as well known. This will definitely affect the development of a robust abatement strategy and thus calls for a strongly increased effort in understanding and assessing the causes for differences between the national inventory and the GAINS-Baseline-scenario and based on this, to improve and harmonise the inventory and the GAINS model baseline scenario.

7 Abatement measures, effects and costs

In order to explore how BC emissions could have been lower in Sweden in 2005 we have compared the largest BC emission sources identified in the Swedish BC emission inventory with the GAINS model database on the most efficient (with respect to emission reduction)

end-of-pipe emission control technologies for the sources. Since this study was performed for the year 2005, this comparison cannot show expected future reductions in emissions according to current legislation. This is of special importance for emissions from mobile sources, where the introduction of continuously strengthened emission limit values (Euro standards) will reduce emissions substantially by the year 2020. This is applicable for light duty and heavy duty vehicles, as well as for heavy non-road mobile machinery (excl. shipping). These emission sources are therefore presented separately in this report. The comparison then served as basis for the Alternative BC emission calculations performed by using the GAINS model. The GAINS model database was then used to explore which of the options that was most cost efficient, but also to explore impacts on other air pollutants and greenhouse gases. This later aspect is important since many of the most common control technologies used today will have both positive and negative impacts on emissions of other pollutants than PM. This impact needs to be quantified in order to provide useful guidance on which emission abatement strategy that should be advocated from a cost effectiveness perspective, but also from a climate and air quality perspective. As mentioned earlier, the calculations of the Alternative BC emissions is a hypothetical scenario for 2005.

7.1 Important sources of BC in Sweden

When comparing the largest BC emission sources in Sweden 2005 with the GAINS model database on emission control technologies of relevance for PM, the following 7 sectors were identified as most important. These sectors were chosen for in-depth studies on 'Alternative BC emissions' in 2005.

Table 11: Sectors chosen for in-depth analysis

NFR-sector	Fuel	Sector
Stationary		
1.AA.1.A	Biomass	Combustion in power production
1.AA.2._	Biomass	Combustion in industry
1.AA.4.B/Stationary	Fuelwood	Combustion in households
Mobile		
1.AA.2/3 off road all	*Diesel*	*Heavy non-road mobile machinery*
1.AA.3.B	*Diesel*	*Heavy duty trucks and buses*
1.AA.3.B	*Diesel*	*Light duty passenger vehicles*
1.AA.3.B	*Gasoline*	*Light duty passenger vehicles*

In table 11 we have specified the fuel use in the sectors. The previous emission inventory presented in this report has sometimes aggregated the sectors, which might lead to difficulties in the comparison with earlier numbers presented in this report. Based on the emission inventory, the following BC emissions originated from these chosen sectors (table 12).

Table 12: Major BC emission sources in Sweden, Swedish BC emission inventory 2005

Fuel	Sector	Emissions
Stationary		
Biomass	Combustion in power production	0.45
Biomass	Combustion in industry	0.07
Fuelwood	Combustion in households	1.38
Mobile		
Diesel	*Heavy non-road mobile machinery (excl. shipping)*	*0.63*
Diesel	*Heavy duty trucks and buses*	*0.50*
Diesel	*Light duty passenger vehicles*	*0.18*
Gasoline	*Light duty passenger vehicles*	*0.04*

All in all, the use of fuelwood, diesel and gasoline in these sectors caused 3.24 kton of the total Swedish 5.1 kton BC emissions in 2005.

7.2 Estimates on emission abatement by using the GAINS model

The GAINS model emission calculation routine has been harmonized with the Swedish emission inventory with respect to emissions of PM2.5 and BC for the most important BC emission sources in Sweden 2005. The GAINS model database on abatement technologies has then been used to explore which abatement options that could be considered for reducing the emissions of BC. In this step the most efficient technologies available in the database were chosen for analysis, without considering the cost of the measures. This implies that the calculations performed represent a hypothetical maximum technical feasible reduction for the selected BC emission sources.

Based on the largest BC emission sources in Sweden, three hypothetical options for emission removal in 2005 were explored in the Alternative BC emission 2005 calculations. These options included a complete shift to pellets usage in combination with electrostatic precipitator in single household boilers (instead of wood logs or wood chips); an upgrade of PM emission control technologies in the Swedish industry and power plants to Dutch standards; a 10% rejuvenation of the vehicle fleet for non-road mobile machinery (excl. shipping), heavy duty trucks and buses, as well as light duty passenger vehicles. The last option serves only as illustration, since new emission standards (EURO) have been implemented since 2005. All the results presented below illustrate the difference between the emissions and abatement costs associated with the Swedish BC emission inventory 2005 and the Alternative BC emission 2005 calculation.

The table 13 only presents the most high-efficient end-of-pipe options to reduce emissions from the largest sources, but still shows that there could have been room for significant improvement in 2005, if Swedish air quality policies would have been different from the 1990:ies and onwards. It should however be mentioned again that for some sectors, much of the improvement is projected to take place according to current air quality policies (mainly the mobile sectors) as shown below. For other sectors such as industry, power plants and

households, it is anticipated that there will be room for improvement in emission standards up until at least 2020.

Table 13: BC emissions in selected sectors 2005, comparison between the Swedish BC emission inventory and the Alternative BC emission calculation

Kiloton emissions of BC in 2005				
NFR-sector	Fuel	Sector	Swedish Emission inventory	Alternative BC emission calculation
Stationary				
1.AA.1.A	Biomass	Combustion in power production	0.45	0.01
1.AA.2._	Biomass	Combustion in industry	0.07	0.03
1.AA.4.B/Stationary	Fuelwood	Combustion in households	1.38	0.12
Mobile				
1.AA.2/3 off road all	*Diesel*	*Heavy non-road mobile machinery*	*0.63*	*0.57*
1.AA.3.B	*Diesel*	*Heavy duty trucks and buses*	*0.50*	*0.44*
1.AA.3.B	*Diesel*	*Light duty passenger vehicles*	*0.18*	*0.13*
1.AA.3.B	*Gasoline*	*Light duty passenger vehicles*	*0.04*	*0.03*
TOTAL			3.24	1.33

Table 14 shows the implementation years for the engine euro standards for heavy and light duty vehicles.

Table 14: Year of introduction for Euro emission standards (mobile engines)

	Euro 1/I*	Euro 2/II	Euro 3/III	Euro 4/IV	Euro 5/V	Euro 6/VI
Light duty vehicles	1992	1996	2000	2005	2009	2014
Heavy duty vehicles	1992	1995	1999	2005	2008	End 2012

(www.ec.europa.eu, as of 2011-07-10)
*The roman number applies to heavy duty vehicles.

7.3 Estimates on emission abatement cost efficiency by using the GAINS model

The GAINS model use internationally reviewed cost estimates for a number of different emission control options. The cost estimates take into account fixed and variable investments,

lifetime of technology, fixed and variable costs for operation & management, solvent use, fuel penalties as well as costs for waste disposal when applicable (Amann et al. 2004). The costs are annualized in order to enable comparison between technologies with short or long life spans. In this study we have chosen the best available technology for each BC emission source studied (i.e. largest potential for emission removal or maximum technical feasible reduction), regardless of cost. The measures can be very costly but are used to show the maximum technical potential for emission removal from these sectors. This analysis should be completed with a more full-scale analysis in a follow-up to this study.

In order to design cost effective air quality and climate change policies it is important to take into account the abatement costs for the specified emission control options.

Table 15: Emission control costs for the selected options in the studied sectors

Kiloton emissions of BC		Swedish BC emission inventory	Alternative BC emission calculation	Costs on top of the Swedish BC emission inventory	Costs on top of the Swedish BC emission inventory
Stationary					
Fuel	Sector	Emissions	emissions	M€ / year	k€ / ton
Biomass	Combustion in power production	0.45	0.01	6.3	14
Biomass	Combustion in industry	0.07	0.03	2.2	61
Fuelwood	Combustion in households	1.38	0.12	49.2	39
Mobile					
Diesel	*Heavy non-road mobile machinery*	*0.63*	*0.57*	*5.7*	*92*
Diesel	*Heavy duty trucks and buses*	*0.50*	*0.44*	*17.1*	*282*
Diesel	*Light duty passenger vehicles*	*0.18*	*0.13*	*0.7*	*16*
Gasoline	*Light duty passenger vehicles*	*0.04*	*0.03*	*24.5*	*4 368*

This initial cost efficiency analysis of the technologies chosen indicates that PM emission control in power plants using fuel wood should be most cost efficient, followed by emission reductions from light duty vehicles using diesel. The rather high cost for reducing particle emissions from house hold firewood combustion is due to the rather expensive technology chosen, pellet stoves with particle filter (ESP), so it could be considered as a maximum cost alternative. Also, the pellet stoves with particle filters are in this calculation almost implemented on 100% of all stoves burning fuel wood, which is a purely technical limit. It should not be considered as possible to fully implement this option. It is also important to remember the environmental and health impact of the emission reduction, which is likely to vary between sectors. The emission control options in the transport sector will reduce

emissions of NO_X as well as PM. Also, future emission reductions from transport are already in the current legislation.

In order to put the cost estimates in perspective, the total Swedish abatement costs for reducing emissions of SO_2, NO_X, PM, VOC, and NH_3 amounts to 1 232 M€ / year in 2005 in the studied scenario.

The cost estimates in GAINS are based on documentation developed by IIASA as well as EGTEI and JRC and are thoroughly reviewed. The technologies considered to be of high international importance are included in the database, but some country specific measures can be missing. The Swedish EPA (2009) analyzed options to reduce future BC emissions from households. In that analysis, other options than in the current version of the GAINS model were considered. Overall, the options considered implied abatement costs ranging between 6–80 k€/ton $PM_{2.5}$. These options included scrapping, fuel shifts (from wood to pellets) and energy efficiency improvements of household stoves (accumulation tanks).

There are also other examples of national concern, such as national options to reduce emissions from shipping sources and larger Non-Road Mobile Machinery (NRMM). Examples for 2020 are fuel shifts and shore side electricity for the shipping sector and scrapping for the NRMM. These are cost-effective options that are not considered in the current version of the GAINS model (Fridell & Åström 2009). There are certainly more examples than the ones listed here, but these serve as examples to show that the analysis made with the GAINS model needs to be completed with national specific considerations in order to make a full analysis of cost effective options.

7.4 BC abatement, co-benefits and trade-off effects

7.4.1 Results related to synergies and trade-offs by using the GAINS model

Emission control options focused on reducing emissions of PM or BC will have varying effects on other pollutants, dependent on sector and technology of choice.

As can be seen in the table 16, the selected PM emission abatement options from larger stationary sources are mainly having an effect on one pollutant. While for the option studied for households, there will be an impact on other pollutants as well. The same is valid for the mobile sector. The impacts on fuel efficiency in transport and on electricity demand in stationary combustion are also indicated. Negative numbers indicate an increase in either emissions or electricity used.

The results for all emissions except for BC have been calculated by using the emission factors in the GAINS model. These emission factors are not always in correspondence to the Swedish emission inventory which has been explained earlier. This implies some uncertainty in these estimates. Also, an increased use of newer Euro standards is estimated to imply a fuel penalty, which will increase the emissions of CO_2. Correspondingly, advanced PM control options from stationary PM sources imply an increased electricity need in these sectors.

Table 16: Impact on BC and other pollutants from the selected control options in Alternative BC emission calculation, 2005

	kton reduction of emissions compared to Swedish BC emission inventory 2005								Electricity
Control option in Sector	**BC**	**NOx**	**NH_3**	**N_2O**	**CH_4**	**VOC**	**OC**	**CO_2**	**Electricity reduction [GWh]**
Stationary									
Upgraded technology (Ut) in older power plants using fuelwood	0.44			0.00	0.00	0.00	0.16	0.00	-0.59
Ut in industrial boilers	0.04			0.00	0.00	0.00	0.02	0.00	-1.17
A 100 % shift to pellets with electrostatic precipitator in household boilers	1.26			0.00	10.4	8.96	1.83	0.00	-2.91
Mobile									
***Increased use (Iu)** of new heavy non-road mobile machinery*	*0.06*	*2.69*		*0.00*	*0.00*	*0.30*	*0.07*	*-2.72*	*0.00*
Iu of new heavy trucks & buses	*0.06*	*1.69*		*0.00*	*0.00*	*0.33*	*0.07*	*-5.44*	*0.00*
Iu of new passenger vehicles	*0.05*	*10.8*	*-0.02*	*-0.05*	*0.91*	*13.4*	*0.07*	*0.00*	*0.00*
Iu of new passenger vehicles (reduced evaporation)						*7.16*			

7.4.2 The climate effect of BC/OC/$PM_{2.5}$

The effects of atmospheric aerosols on climate are emphasized in the 4th assessment by IPCC (2007). The aerosols affect the present climate through a set of different processes. It both cool and heat the climate, direct cooling by scattering sun light back to space and indirectly by affecting the albedo and increasing the life time of clouds. Certain aerosols heat the climate, e.g. soot, by absorbing the sun light thus heating the surrounding atmosphere and through decreasing the life time of the clouds. However it is many different atmospheric processes involving particles that have a potential effect on climate. These processes and their influence on climate are in most cases not well known.

This lacking knowledge gives not only a fairly large uncertainty in determining present climate influence of the aerosols but also the future climate effect of increasing greenhouse gases, e.g. CO_2. The reason for this is that as the present uncertain influence of aerosols makes it difficult to estimate the influence of the present greenhouse gases. This information

is crucial in determining how much increasing CO_2, e.g. at a doubling of the natural CO_2 concentrations, 550 ppm, will heat the future climate. The expected increase in global temperature at a doubling of the CO_2 concentration will according to the IPCC most likely be in the range of +1.5 – +4.5°C. The IPCC report further stated that it was ‘‘very unlikely’’ (less than 5% probability) that the climate sensitivity is less than 1.5 °C, but was unable to recommend a corresponding very unlikely upper bound to the estimate, stating rather that on the basis of present understanding values greater than 4.5 °C could not be excluded.

Using the concept radiative forcing gives a better basis for comparisons of different actions as their influence on the global climate can be directly compared. This has been used to show the importance of abatement of BC, ozone and methane and it is illustrated in the figures 11-13. CO_2 is the major greenhouse gas and will also in the future dominate the climate influence. We have used the projected concentrations and resulting radiative forcing given in IIASA’s Representative Concentration Pathways (4.5 W/m^2) for CO_2. In RCP 4.5 CO_2 emissions are estimated to increase with about 15% up till 2040 and then decrease to about half of today’s emission 2100.

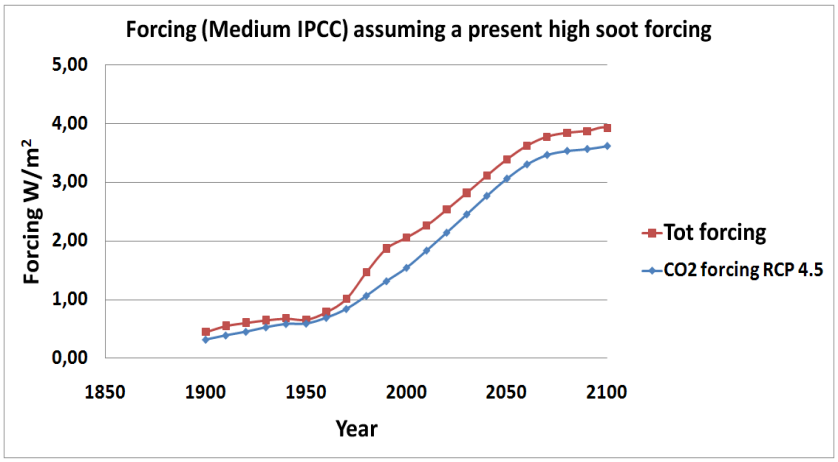

Figure 11. Historical and forcasted global total and CO_2 forcing according to RCP 4.5

In figure 11 the other climate forcing components including BC, ozone and methane are kept constant and according to the IPCC estimated mean forcing except for soot where a somewhat higher forcing, 0.8 W/m^2, has been assumed. The total forcing is as shown dominated by the CO_2 forcing. In the 70ties the total forcing bump seems according to the IIASA RCP 4.5 to depend mainly on temporal increase in forcing from methane and halocarbon gases and to some extend BC. Changes in BC emissions will also affect the emissions of scattering aerosols and cloud affecting aerosols. A 10% reduction of warming BC is totally compensated by 3% reduction in cooling particle forcing using our assumed forcing values even though a high BC forcing is assumed. This is corroborated in the UNEP-assessment (see 7.4.6). However as shown in figure 12 a 20% reduction / decade of anthropogenic tropospheric ozone forcing gives a substantial cooling of the climate. Reducing anthropogenic methane similarly enhances the cooling showing that it might be possible to compensate future warming by CO_2. However considerable CO_2-abatement measures have to be taken.

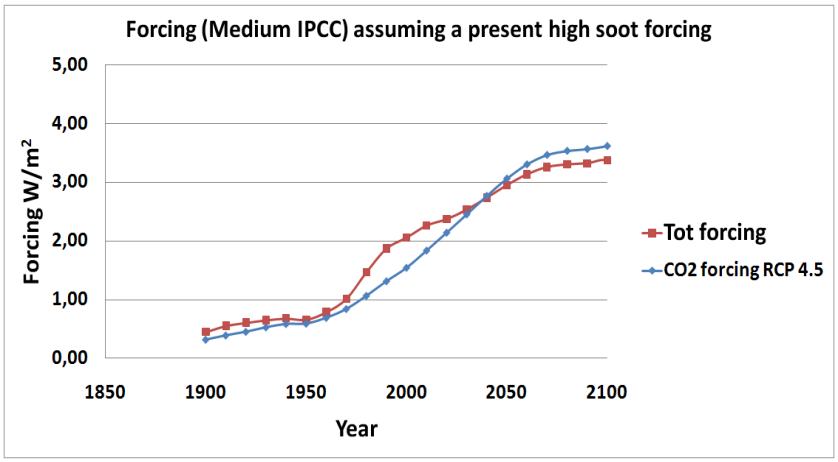

Figure 12. Historical and forcasted global total and CO_2 forcing according to RCP 4.5 assuming forcing due to ozone decrease 20% per decade.

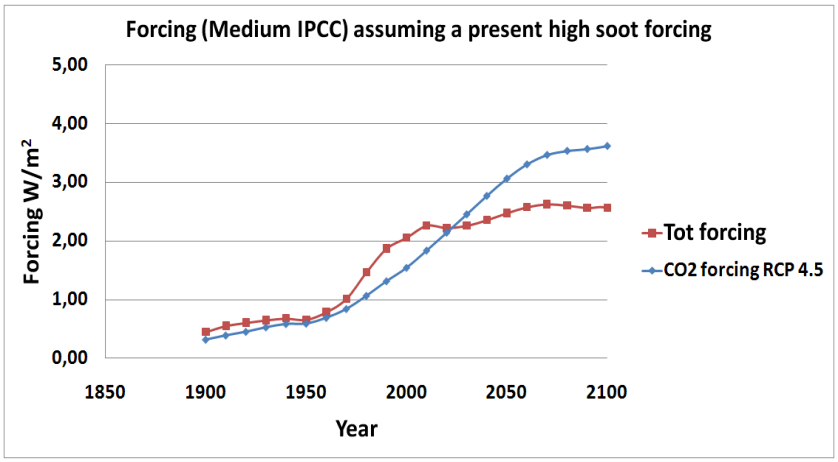

Figure 13. Historical and forcasted global total and CO_2 forcing according to RCP 4.5 assuming forcing due to ozone and methane decrease 20% per decade.

It is clear that emission abatements should include all the climate forcing components in a well balanced way. Short lived air pollutants can be abated giving a better air quality and simultaneously reducing the climate warming.

7.4.3 Co beneficial abatement measures

The UNEP Integrated Assessment of Black Carbon and Tropospheric Ozone was performed by setting up a set of mixture of available measures, see table 17, considered to be possible to implement. The measures focus on BC and methane emission, but co-emitted compounds as OC and ozone precursors are considered in the analysis.

Table 17. Measures that improve climate change mitigation and air quality and have a large emission reduction potential

Measure[1]	**Sector**
CH4 measures	
Extended pre-mine degasification and recovery and oxidation of CH4 from ventilation air from coal mines	Extraction and transport of fossil fuel
Extended recovery and utilization, rather than venting, of associated gas and improved control of unintended fugitive emissions from the production of oil and natural gas	
Reduced gas leakage from long-distance transmission pipelines	
Separation and treatment of biodegradable municipal waste through recycling, composting and anaerobic digestion as well as landfill gas collection with combustion/utilization	Waste management
Upgrading primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control	
Control of CH4 emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs	Agriculture
Intermittent aeration of continuously flooded rice paddies	
BC measures (affecting BC and other co-emitted compounds)	
Diesel particle filters for road and off-road vehicles	Transport
Elimination of high-emitting vehicles in road and off-road transport	
Replacing coal by coal briquettes in cooking and heating stoves	Residential
Pellet stoves and boilers, using fuel made from recycled wood waste or sawdust, to replace current wood-burning technologies in the residential sector in industrialized countries	
Introduction of clean-burning biomass stoves for cooking and heating in developing countries[2, 3]	
Substitution of clean-burning cookstoves using modern fuels for traditional biomass cookstoves in developing countries[2, 3]	
Replacing traditional brick kilns with vertical shaft kilns and Hoffman kilns	Industry
Replacing traditional coke ovens with modern recovery ovens, including the Industry improvement of end-of-pipe abatement measures in developing countries	
Ban of open field burning of agricultural waste[2]	Agriculture

[1] There are measures other than those identified in the table that could be implemented. For example, electric cars would have a similar impact to diesel particulate filters but these have not yet been widely introduced; forest fire controls could also be important but are not included due to the difficulty in establishing the proportion of fires that are anthropogenic.
[2] Motivated in part by its effect on health and regional climate, including areas of ice and snow.
[3] For cookstoves, given their importance for BC emissions, two alternative measures are included.

The impact on the global climate and air quality was investigated by using 2 different well established global climate models, the ECHAM and GISS models. Besides the measures mentioned above CO_2 abatement was assumed such a maximum concentration of 450 ppm of CO_2 will be reached. This scenario is close to RCP 2.6, which assumes the CO2 emissions to stagnate 2020 and then decrease to reach 0 at 2080. The investigation then was performed to evaluate the impact of the BC and Methane abatement measures.

The results showed in the figure 14 show that the BC and methane measures will give half a degree lower global temperature. The temperature decrease as an effect of the BC and methane abatement measures is superimposed on the general temperature trend dependant on the ambient CO_2 concentrations. The abatement of SLCF will only give a temporary release in global warming if the CO_2 emissions are allowed to increase.

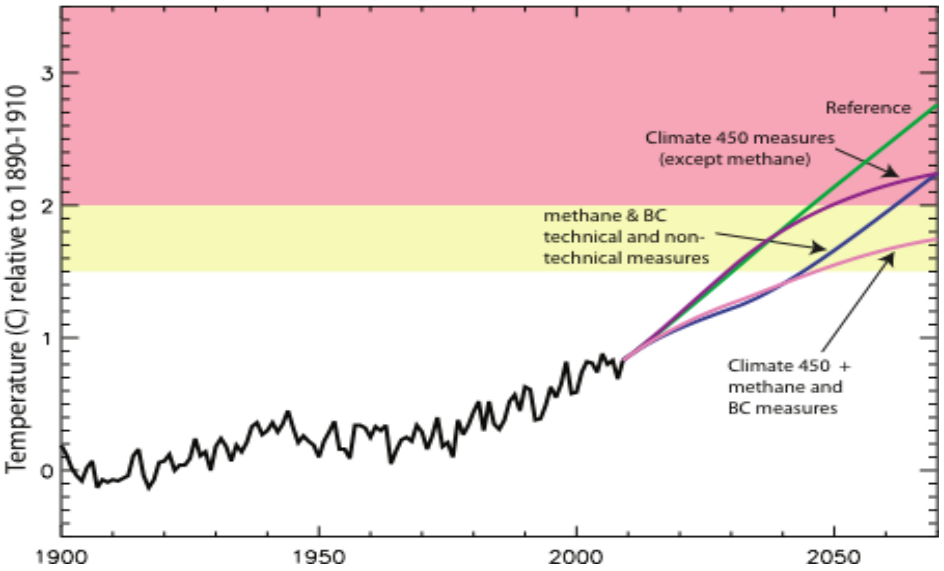

Figure 14 . Observed temperatures through 2009 and projected temperatures thereafter 2 under various scenarios, all relative to the 1890-1910 mean. Shaded backgrounds show zones beyond 1.5 and 2ºC (UNEP report, 2011)

The CO_2 abatement and its effect on the climate are crucial for the temperature trend but the BC and methane abatement measures give a significant effect adding to the lowering of the global temperature. As the response is fast to changes in the emissions of SLCF components an increasing temperature due to high CO_2 emissions are slow.

Besides the climate effect the influence on food supply and human health was investigated. Figure 15 from the UNEP-report clearly shows the gain less losses both of less mortality and loss of crop as a result of decreasing emissions of SCLF. It is obvious that climate mitigation measures can have considerable positive health and ecosystem effects.

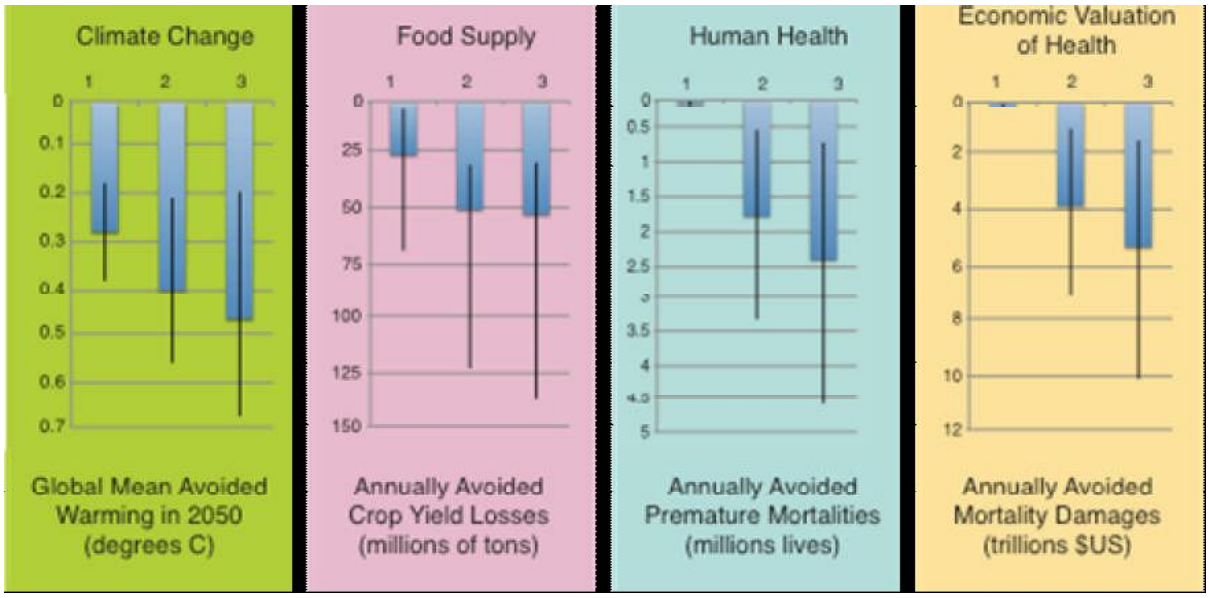

Figure 15. Global impacts of the additional emissions controls on methane and products of incomplete combustion (including BC, OC and CO). 1/ Methane measures, 2/ 1+BC technical measures, 3/ 2+ Non-technical measures (UNEP-report, 2011).

Crop yield losses are summed values for wheat, rice, soybean and maize. Uncertainties include: climate change – range from uncertainty in radiative forcing and climate sensitivity, food supply – range from impacts calculated using ozone changes from different models and uncertainty in exposure-response relationship, human health – uncertainty in concentration-response relationships and using results from different models, economics – range using uniform valuation of premature mortalities and income-adjusted valuation and results from different models. The results for BC technical measures include 5 of the 7 measures, so are conservative.

7.4.3.1 Results from the GAINS model for Sweden

Before the recognition of BC as a greenhouse gas, the policies aimed at reducing emissions of particulate matter were focused on reducing health effects. In order to achieve cost effective solutions to do so, policies needs to take into account the varying costs of different measures.

When focusing only on emission reductions of PM2.5, the cost efficiency of the presented measures looks as follows (see table 17):

Table 18: PM2.5 cost efficiency of the studied emission control options

NFR-sector	Fuel	Sector	k€ / ton	Rank
Stationary				
1.AA.1.A	Biomass	Combustion in power production	3	1
1.AA.2._	Biomass	Combustion in industry	3	2
1.AA.4.B/Stationary	Fuelwood	Combustion in households	13	4

Mobile				
1.AA.2/3 off road all	*Diesel*	*Heavy non-road mobile machinery*	*41*	*5*
1.AA.3.B	*Diesel*	*Heavy duty trucks and buses*	*140*	*6*
1.AA.3.B	*Diesel*	*Light duty passenger vehicles*	*10*	*3*
1.AA.3.B	*Gasoline*	*Light duty passenger vehicles*	*725*	*7*

However, when shifting focus to BC, one has to take into account that different combustion processes produces different shares of BC, which has been explained above. When looking only at reducing BC, the cost efficiency of the measures differs slightly.

Table 19: BC cost efficiency of the studied control options

NFR-sector	Fuel	Sector	k€ / ton	Rank
Stationary				
1.AA.1.A	Biomass	Combustion in power production	14	1
1.AA.2._	Biomass	Combustion in industry	61	4
1.AA.4.B/Stationary	Fuelwood	Combustion in households	39	3
Mobile				
1.AA.2/3 off road all	Diesel	Heavy non-road mobile machinery	92	5
1.AA.3.B	Diesel	Heavy duty trucks and buses	282	6
1.AA.3.B	Diesel	Light duty passenger vehicles	16	2
1.AA.3.B	Gasoline	Light duty passenger vehicles	4 368	7

All the costs expressed in table 18 above are fully allocated to the pollutant in consideration, which is why unit costs for BC are higher than for PM2.5. When comparing the two tables, 17 and 18 below it can be seen that from a BC perspective, the relative cost efficiency of the options changes between the sectors.

As shown above it is necessary to make a considerable reduction the BC/OC emissions to reach a significant climate effect. On the other hand considering the fast climate response to SLCF emission changes and the slow response to CO2 emission changes the reduction of SLCF can be made over several decades, e.g. there is time for a radical conversion to new techniques.

7.4.4 The effect on health, ecosystems and climate by reducing of BC emissions in Sweden.

A reduction of the Swedish BC emissions will give less health effects close to the sources. But it is difficult to determine how much. According to Forsberg et al., 2005, the number of premature deaths in Sweden are about 5300 per year calculated on measured PM levels and using the exposure-response function WHO of 0.43 % per µg/m3 PM10. Generally seen

about a third of the premature death, about 1700 per year, due to air pollution in Sweden are due to local pollution while the rest is from long distance transported. Taking Stockholm as an example the main fraction of PM10 exposure for the ordinary inhabitant originates from road dust while only about 10% is exhaust particles (Forsberg et al., 2011). A very coarse assumption would be that at the most 10% of the mortality caused by local air pollution is caused by the locally emitted BC-particles, i.e. about 170 premature deaths a year. The same very coarse calculation for the BC-particles in the long distance transported air pollution will give about the same number, thus totally about 3-400 premature deaths per year are caused by BC-particles assuming that the relative risk factors given by WHO is correct.

However epidemiological studies using NO_X as a proxy for vehicle exhaust indicated very much higher relative risk, a factor of 50, for mortality for vehicle exhaust, then possibly the BC-particles (Nafstad et al., 2004, Forsberg et al., 2011). Lacking detailed knowledge on how ultrafine BC particles affect human health and extensive epidemiological studies on specifically the effects of BC-particles on health it is very difficult to state what effect a reduction of local BC-particle emission will have on mortality. It is most probable though BC-particles cause much more than 170 premature deaths per year.

The BC abatement measures assumed in the UNEP study (see above 6.4.3) are including abatement of ozone precursors as well as methane giving lower ozone concentrations. This will as well have a beneficial effect on both health and ecosystem, giving less damage on crops and forest. However as the life time of ozone is about a month in the atmosphere the Swedish ozone concentrations are totally dependent on foreign sources.

BC particles in the $PM_{2.5}$ fraction have an atmospheric life time of about 4 days giving them a mean transport distance of about 2000 km before deposition. A significant fraction of the emitted BC particles will reach the Arctic as the main wind direction is NE.

Table 20. Emissions of black carbon for 1994, for different sectors in the Arctic countries (kton/year)(Bond et al, 2004)

Sector\ Countries kton/year	North America	Russia	Nordic	Swed frac tion of Nordic emissions
Ag Burn	15,3	8,86	0	0
Industry	17,3	12	3,27	0,52
Open Burn	101	80,6	0,28	0,50
Power Gen.	2,99	1,26	0,05	0,20
Residential Biofuel	35,9	27,8	5,63	0,54
Residential Coal	20,2	12,3	0,09	0,00
Residential Other	3,73	0,56	0,29	0,41
Road Transport	228	30	13,3	0,35
Off-road transport	116	27	11,9	0,24
Total	**542**	**200**	**34,8**	**0,36**

In the middle of the 1990-ies, the Nordic countires BC emission were about 5% of the total emissions from the Arctic countries (table 9). The major fraction from all the Arctic Countries (AC) emerge from road transport, open burning, off-road transport and residential biofuel mentioned in order of the size of the emissions. While for the Nordic countries the emissions are dominated by road transport, off-road transport, residential biofuel and industry, mentioned in size of emissions. Open burning seems to be a considerably smaller source in the Nordic countries, while industry seems equally larger relatively seen. Considering the population the Swedish fraction of the Nordic emissions to expected for most source types but for road trafic to beeing low.

Due to the general meteorology the transport of air pollutant to the Arctic from the Nordic countries is more efficient thus making the influence of Nordic emission larger than its actual fraction of the emissions. The European emissions have a much stronger impact on pollution levels at the Arctic surface while.the contribution from European source regions decreases with altitude as the contribution from South Asian source regions increases with altitude Stohl (2006). It is clear that European emissions have a large impact on aerosol sulfate and BC at the Arctic surface, Asian emissions become more important with increasing altitude, and North America dominates the abundance of O_3 at all altitudes within the Arctic (AMAP/Quinn et al., 2008).

The Arctic features of a long dark winter with and extensive snow cover lasting for the most if not the whole year changes the influence on the climate of different atmospheric processes. During the winter the polluted clouds are more effective than the clean to block long wave radiation going into space and thus warming the lower atmosphere. BC soils the surface snow giving it a lower albedo and possibly causing earlier melting and showing an darker surface with considerably lower albedo. The seasonal transport pattern cause different kind of pollution emerge into the Arctic at different times of the year, e.g. Arctic haze from fast transport of particulate pollution from Europe into the Arctic during the spring. The pollution cause thus both warming and cooling, and it change with season as e.g. in direct effect of particles through affecting the clouds are warming during the winter while cooling during the rest of the year. In total it seems that the BC, Ozone and Methane well balance the cooling of the particles, however it must be remembered that all the processes involved are not known, not well know or the magnitude of the effect is not well determined and thus there is large uncertainties in the calculations (AMAP/Quinn et al., 2008).

To decrease concentrations of ozone precursors and black carbon in the lower atmosphere, emissions in northern Eurasia should be reduced. The source regions of short-lived pollutants in the upper Arctic atmosphere include northern Eurasia and also areas in North America and Asia. Therefore, a substantial reduction of ozone and BC in the upper troposphere will require more widespread emission reductions throughout the northern hemisphere. The correspondence between surface temperature response in the Arctic and global and Northern Hemisphere extratropical forcings due to ozone emphasizes the need to reduce ozone on a northern hemisphere and global basis to reduce climate response in the Arctic. Finally,

emissions of ozone precursors and BC within the Arctic should be kept at a minimum as these will have a disproportionately large impact on within-Arctic concentrations (AMAP/Quinn et al., 2008).

Reducing methane emissions will decrease ozone production. Reductions in NOx also will contribute but, at the same time, will decrease OH which is the major sink for methane. Hence, an ozone reduction strategy using NOx controls that benefits climate will also include methane, NMVOCs, and/or carbon monoxide reductions.

7.4.4.1 Results from the GAINS model

As presented above, the GAINS model calculates impacts on a number of air pollutants and greenhouse gases. Since the aim of reducing BC is to reduce global but specifically regional warming, it is useful to calculate the impact of the studied measures as impact on GWP to simplify comparison with other climate forcing agents. Given the large uncertainty on climate impacts of BC, and the varying political focus on long term versus short term solutions, a number of different calculations have been made. The calculations are made for a high impact of SLCF (high), low impact of SLCF (low), a short term focus (GWP20), and a long term focus (GWP100). GWP is a metric that compares the climate impact of 1 kg (or ton) climate forcing gas when the lifetime of the gas is taken into consideration (IPCC 4th assessment). All gases are compared to CO_2, which is why CO_2 is given a GWP of 1 in all GWP estimates. The time frames of the GWP metric used in this report is the 100 year approach or the 20 year approach.

Table 21: GWP for Climate forcers used for calculations of climate impact of the studied control options

	Metric	BC	N2O	CH4	VOC	OC	CO_2
HIGH	GWP100	1500	298	25	3.4	-75	1
HIGH	GWP20	4700	289	72	12	-240	1
LOW	GWP100	210	298	25	3.4	-75	1
LOW	GWP20	690	289	72	12	-240	1
Source		Bond and Sun 2006	IPCC 4th assess	IPCC 4th assess	IPCC 4th assess	BOND et al 2007	IPCC 4th assess

The numbers in table 21 are based on a presentation from IIASA (Amann 2009), and the original sources have been introduced at the bottom of the table. These GWP estimates are used to explore the net climate impact from the control options studied in the Alternative BC emission 2005 calculation. The increased attention to BC and other Short Lived Climate Forcers (SLCF) and the maintained uncertainty in the GWP estimates motivates an in-depth comparison of results. Of main concern in this chapter is the cost efficiency of the studied control options. But since the uncertainty is so large the cost efficiency estimates are likely to be affected.

In most earlier assessments, GWP100 has been the metric of choice when comparing emission reductions of various greenhouse gases. If using this approach together with an assumed high climate impact of BC, the following cost efficiency estimate can be derived.

Table 22: Cost efficiency of the studied control options when HIGH GWP 100 is used as a climate metric

HIGH GWP 100 reduction of SLCF			€ / ton CO2eq	Rank
Stationary				
1.AA.1.A	Biomass	Combustion in power production	10	1
1.AA.2._	Biomass	Combustion in industry	42	4
1.AA.4.B/Stationary	Fuelwood	Combustion in households	24	3
Mobile				
1.AA.2/3 off road all	*Diesel*	*Heavy non-road mobile machinery*	*66*	*5*
1.AA.3.B	*Diesel*	*Heavy duty trucks and buses*	*211*	*6*
1.AA.3.B	*Diesel*	*Light duty passenger vehicles*	*11*	*2*
1.AA.3.B	*Gasoline*	*Light duty passenger vehicles*	*285*	*7*

The results in the table above take into account emission reductions of all the above presented climate forcers from the presented control options. These emission reductions have been converted into the common unit CO_{2eq}. The HIGH climate forcing estimate for BC and OC have been used, which puts large emphasis on the climate impact on BC emission reduction. Interesting from an economic point of view is that some of the measures qualify as relatively cost efficient climate measures. This also applies for the very advanced options in household combustion.

If we were to assume that the relative climate impacts of BC is low, but that the suitable time frame is the one hundred year perspective, the following cost efficiency estimates can be calculated.

Table 23: Cost efficiency of the studied control options when LOW GWP 100 is used as a climate metric

LOW GWP100 reduction of SLCF			€ / ton CO2eq	Rank
Stationary				
1.AA.1.A	Biomass	Combustion in power production	79	1
1.AA.2._	Biomass	Combustion in industry	345	5
1.AA.4.B/Stationary	Fuelwood	Combustion in households	118	3
Mobile				
1.AA.2/3 off road all	*Diesel*	*Heavy non-road mobile machinery*	*970*	*6*

1.AA.3.B	*Diesel*	*Heavy duty trucks and buses*	*5735*	*7*
1.AA.3.B	*Diesel*	*Light duty passenger vehicles*	*114*	*2*
1.AA.3.B	*Gasoline*	*Light duty passenger vehicles*	*311*	*4*

Table 23 above shows that changing the BC climate forcing estimate cause large changes in the estimated cost efficiency of the control options. What is clear is that the options that reduce fuel efficiency are highly impacted by the assumed climate impact of BC emissions.

The climate impact of BC is not only of concern due to the uncertainties in the climate impact as explored above. It is currently a high focus on the urgency of reducing the rate of temperature increase. In other words, it is important to reduce emissions soon. One way to illustrate this is to change the time frame of the GWP metric from a 100 year perspective to a 20 year perspective.

Table 24 below shows the cost efficiency of the studied control options when BC is assumed to have a high climate impact and when the importance of the timing of emission reductions is emphasized.

Table 24: Cost efficiency of the studied control options when HIGH GWP 20 is used as a climate metric

HIGH GWP20 reduction of SLCF			€ / ton CO2eq	Rank
Stationary				
1.AA.1.A	Biomass	Combustion in power production	3	1
1.AA.2._	Biomass	Combustion in industry	13	4
1.AA.4.B/Stationary	Fuelwood	Combustion in households	8	3
Mobile				
1.AA.2/3 off road all	*Diesel*	*Heavy non-road mobile machinery*	*21*	*5*
1.AA.3.B	*Diesel*	*Heavy duty trucks and buses*	*64*	*6*
1.AA.3.B	*Diesel*	*Light duty passenger vehicles*	*3*	*2*
1.AA.3.B	*Gasoline*	*Light duty passenger vehicles*	*78*	*7*

Table 24 can be seen as a table that puts maximum attention to the need to reduce emissions of BC. The cost efficiency of all measures are below 100 € / ton CO2eq, with reduced particle emissions from fuel wood being a very cost efficient climate measures.

To complete the comparison the LOW GWP metric for BC is used together with the short GWP time frame (table 25).

Table 25: Cost efficiency of the studied control options when LOW GWP 20 is used as a climate metric

LOW GWP20 reduction of SLCF			€ / ton CO2eq	Rank
Stationary				
1.AA.1.A	Biomass	Combustion in power production	24	1
1.AA.2._	Biomass	Combustion in industry	104	5
1.AA.4.B/Stationary	Fuelwood	Combustion in households	38	3
Mobile				
1.AA.2/3 off road all	Diesel	Heavy non-road mobile machinery	217	6
1.AA.3.B	Diesel	Heavy duty trucks and buses	744	7
1.AA.3.B	diesel	Light duty passenger vehicles	28	2
1.AA.3.B	Gasoline	Light duty passenger vehicles	83	4

Again, as was the case for the LOW 100 GWP estimate presented above, the impact of the options that affect fuel efficiency can be clearly seen.

If one were to rank the cost efficiency for the different approaches, the following table summarizes the results. The most cost efficient solution is indicated with the number 1 for each approach, as given in the tables 18, 19 and 22 – 25.

Table 26 gives in spite of different assumptions concerning climate impact as well as considering the impact on different timescales a ranking topped by the same abatement measures; reductions in emissions from combustion in power production, reducing emissions from diesel powered light duty passenger vehicles and reductions in emissions from combustion in households. The most cost effective action is abatement of emission from combustion in power production in all scenarios. The other two actions cost not more than a factor 3 more while actions towards emission from heavy duty vehicles costs 7 times or more.

Table 26: Ranking of cost efficiency

So which is the most cost effective option to reduce?			PM2.5	BC	GWP (high 100)	GWP (low 100)	GWP (high 20)	GWP (low 20)
1.AA.1.A	Biomass	Combustion in power production	1	1	1	1	1	1
1.AA.2._	Biomass	Combustion in industry	2	4	4	5	4	5
1.AA.4.B/ Stationary	Fuelwood	Combustion in households	4	3	3	3	3	3

1.AA.2/3 off road all	Diesel	Heavy non-road mobile machinery	5	5	5	6	5	6
1.AA.3.B	Diesel	Heavy duty trucks and buses	6	6	6	7	6	7
1.AA.3.B	Diesel	Light duty passenger vehicles	3	2	2	2	2	2
1.AA.3.B	Gasoline	Light duty passenger vehicles	7	7	7	4	7	4

7.4.4.2 The different cost levels for the different scenarios

The calculations of CO_2 equivalent tons due to a certain measure of soot abatement are directly dependent on the estimate of the climate impact of soot. The estimate of the climate impact of soot is highly uncertain. This means that the absolute cost estimates are quite uncertain, however found relation between the different source types and the different scenarios are realistic. The high and low estimate of the climate impact of SLCF's differ with a factor of about 10 indicates the possible uncertainty in the absolute cost estimate. The different integration time GWP20 and GWP100 gives an indication of the difference due to response time. The full effect of CO_2 abatement is reached first after 100 years while for SLCF abatement takes effect within a year. Roughly 3 times more tons of CO_2 have to be abated to reach the same climate mitigation over 100 years as over 20 years, which is illustrated in the difference in comparing GWP20 and GWP100.

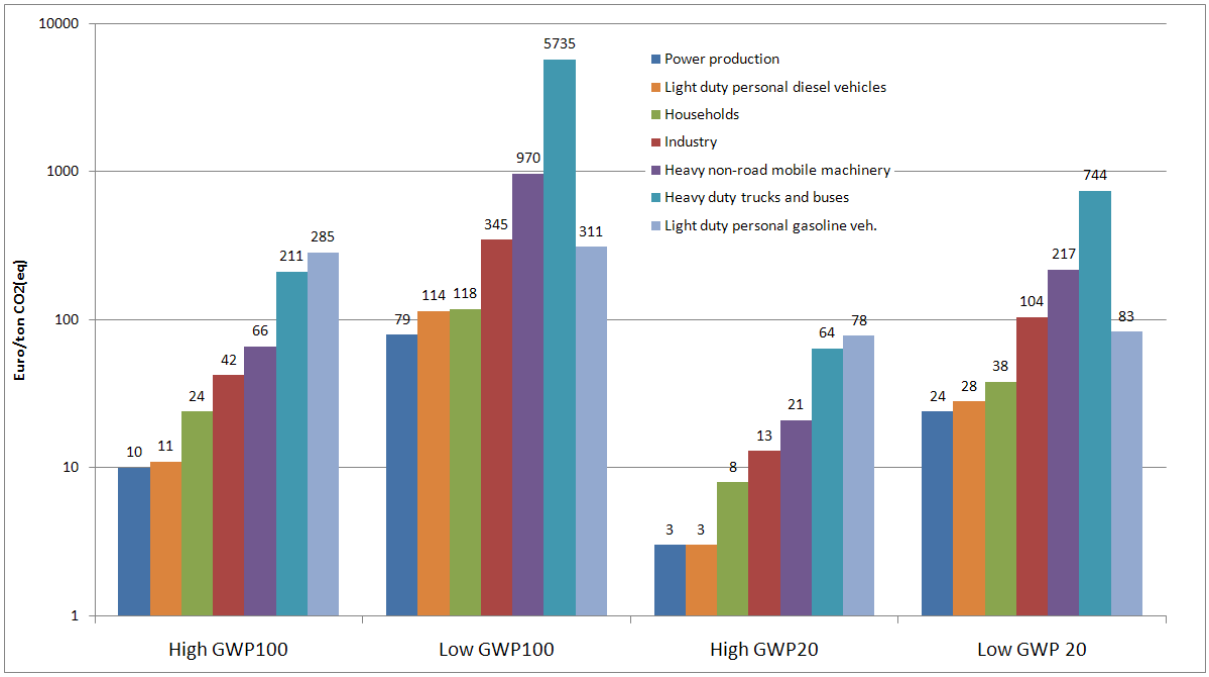

Figure 16. The tables 22 – 25 are summarized in this figure showing the actual cost for different measures assuming different climate sensitivity, High and Low, and time spans for the GWP calculations, 20 and 100 years.

However different approaches lead in our example to slightly different cost effective solutions. What is most evident is that a fairly cost effective PM control option, emission reduction from industrial boilers, turns into a relatively inefficient control option if the climate impact is considered.

These results show the varying climate abatement cost efficiency from only six studied control options. This study needs to be complemented with a full scale analysis, which was not feasible under the time frame of this project.

One result from this is once again that policy makers needs to recognize the interactions taking place and adopt policy solutions that can cover many pollutants, their different impacts on air quality and climate change as well as the impact over time. It is not a simple task, but if a partial approach is taken, Sweden risk investing in emission control strategies that misses out on the opportunity to deal with a number of environmental concerns at once. This in turn would lead to cost-inefficient policies.

7.4.4.3 Discussion of GAINS model results

At the time of writing, given our current understanding of BC but still recognising that more knowledge is needed, some policy recommendations can be made.

The environmental impacts of BC emissions have as all short lived climate forcing, SLCF, compounds an limited life time in the atmosphere, implying that it will have mainly a regional impact and reductions of the emissions will have an almost effect reducing the impact. Thus Sweden and the other Arctic countries SLCF emissions are likely to have a stronger climate impact on the arctic region. This motivates the use of the higher range of the GWP estimate for BC presented above when estimating impacts of BC emission reductions in Sweden. The short response time to emission reductions does in turn motivate the use of GWP20 as a relevant time frame when identifying which emission abatement options that should be considered as cost efficient. GWP in itself is recommended due to the fact that many of the abatement measures of consideration is anticipated to have impacts on emissions of other greenhouse gases. What we have seen so far, there are no BC emission reductions that increase emissions of PM2.5, so there is very little risk for the omission of negative health impacts when using the GWP approach. It remains to be seen if this holds for other short lived climate forcers.

In table 24 above we presented a ranking of cost effectiveness based on different approaches to air pollutants, and given the arguments presented here, we would recommend a GWP20(high) approach during the development of a national strategy to reduce BC emissions. However, all climate impact approaches point towards the same primary cost effective actions even though the estimated costs vary strongly. Reduction of emissions from household combustion sources will give substantial reduction mainly on particle emissions.

When looking at the costs for BC emission reductions and using the GWP20(high) approach, as is shown in table 24 above, it is interesting that several of the measures ends up with costs lower than €16 / ton CO_2, which is the CO_2 ETS price projected for Sweden by 2020 in the

2010 long term projection from the Swedish Energy Agency (STEM 2011). Although there are strong policy recommendations from the UNEP BC Assessment (2011) NOT to include BC emission abatement as a way to meet obligations under the EU C&E package (including the EU ETS), it is still interesting to see that BC emission reductions might be fairly inexpensive as a 'short term climate' measure for Sweden.

We have not been able to study the impact on ozone formation in detail. The GAINS model does however calculate impacts on mortality from short term exposure to ground level ozone. When performing the analysis it can be seen that the impact on ozone related mortality is lower in the Alternative BC emission 2005 calculation than in the Swedish BC emission inventory 2005 calculation. This indicates that the ozone levels are lower in Sweden (at least in populated areas), as a result of the PM control options applied.

In terms of health benefits of reduced BC emissions, one needs to consider how different sources affect population exposure. Reductions in the emissions from residential wood burning, as well as light and heavy duty vehicles will be more efficient in reducing the general population exposure. These options therefore have greater health benefits than reductions of emissions from non-road mobile machinery, industry and power plants. The GAINS model is not well suited to assess health benefits from emission reduction within a single country due to the coarse resolution of the model. But it may be concluded that considering more carefully the cost efficiency including the health benefits (reduced morbidity and mortality), would further favor actions on household combustion.

The control options aimed at reducing PM emission from stationary combustion is associated with a increase in the use of electricity. The climate impact from increased electricity use has been omitted in this study. The reason for this is that there are different approaches to evaluate climate impact from increased electricity consumption. Whether one should use 'Swedish', 'Nordic', or 'North European' emission factors for 'marginal' or 'average' electricity production on the 'short', 'mid' or 'long' term still remains an issue of concern for experts in many areas. We warmly welcome their conclusion.

7.5 Summary concerning abatement measures, effects and costs

No official BC emission projection for Sweden is available for 2020. Therefore we have compared emissions in the emission inventory for 2005 performed in this report with an hypothetical 'Alternative BC emission 2005 calculation. Abatement measures with a potential of reducing the BC emissions with almost 60% has been investigated concerning their cost effectiveness. The most cost effective measures range up to an hypothetical abatement of about 35% of the present Swedish BC-emission according to the Swedish national emission inventory in 2005. The major remaining source is heavy duty vehicles responsible for about 20% of the present emissions. Following the development of emission standards from mobile sources (i.e. Euro standards) emissions of BC from mobile sources is anticipated to be reduced until 2020. It is however anticipated that there will be room for improvement in the residential and industry sectors.

The total abatement costs of reducing Swedish BC emissions still remains to be analyzed. Sweden have several country specific abatement options not covered in European scale models such as the GAINS model, and a review of national options is needed. Starting points can be REKO, Fridell & Åström (2009) as well as many other studies. The Swedish EPA is currently studying the possibility to develop a database on abatement options. Such a database would be very useful (www.naturvardsverket.se, as of 2011-07-10). It is important to remember that most of the comparisons available have been developed from other data sources, which makes direct comparisons difficult. When comparing the results for options aimed at households with Swedish EPA (2009), we can see that the GAINS model option analysed in this study is not directly comparable with Swedish EPA (2009). From a cost effectiveness perspective, the options are fairly similar. But the GAINS model option does not specifically relate to any Swedish standards. It is interesting to see that even if no single option could be fully implemented, there is a number of policy options available for an abatement cost of some 40 – 60 € / kg PM2.5.

Furthermore, one should keep in mind that some traditional energy & climate measures, such as energy efficiency improvements in buildings will also reduce emissions of BC via the reduced need for heating. But it should also be remembered that other energy & climate measures, such as fuel shifts to fuelwood, can increase emissions of BC.

8 What knowledge is missing? Need for more research.

BC and OC are not well defined entities and research and technical development (RTD) on how to sample and measure BC and OC will be needed. Especially needed is the detailed knowledge of the artifacts of the present methods and how to correct the measurements. Substantial progress has been made lately but more is needed.

It is obvious from the presentations of emission inventories above that further efforts are needed to reduce the uncertainty surrounding the national emission estimates of PM, including BC and OC and consistency between PM and particle composition. A better understanding of the present and future contribution from different individual sources to the emissions of $PM_{2.5}$ and BC/OC is necessary in order to serve as background information and a basis for policy development and recommendations for mitigation efforts. To obtain this better understanding, it would be necessary to:

- Review and improve the emission factors for $PM_{2.5}$ for important Swedish sources by revisiting available material in order to develop more detailed emission factors and if needed make new field measurements.
- Investigate the fractions of BC/OC in emitted PM from important Swedish sources by measurements and assessment of available information through in depth literature review.
- Recalculate the Swedish national emissions of $PM_{2.5}$ and BC/OC by using e.g. updated emission factors and uncertainty information to produce better emission estimates, accompanied by uncertainty intervals of the estimated emissions.

- Projections of future Swedish emissions of BC (and OC) do not exist at present, but are needed as a basis for developing policy recommendations.
- Clarify the causes for differences between the national emission inventory and the GAINS calculations, especially regarding the sector contributions, in order to create a better basis for policy recommendations. This includes comparing and assessing activity data, emission factors and other assumptions underlying the calculations.

In the Task Force on Emission Inventories and Projections, TFEIP, under UNECE CLRTAP, discussions have started regarding BC. At its latest meeting in May 2011, the TFEIP noted the progress of BC emission estimates from a number of countries, and included an item in the TFEIP workplan for 2011-2012 to assess the information that is currently available. The ultimate aim of this work would be to update the EMEP/EEA Emission Inventory Guidebook with information on BC. This updated information will probably be available within a couple of years. It is however necessary to have a good knowledge about the national conditions in order to be able to assess the representativeness for Swedish conditions of the more general coming guidance in the Emission Inventory Guidebook.

The health and climate effects due to BC are not well known. There are some indications that the health effects are considerably larger than earlier anticipated, however, the necessary epidemiological studies is lacking. It is of utmost importance to establish a better basis for the estimating the health effects as it might totally change the set of abatement measures needed to reduce the health and climate effects.

BC affects several climate influencing atmospheric processes, however most of the detailed process description and magnitude is not known. The climate affects of other air pollutants are also not well known. This uncertainty has a profound effect on not only estimating the present effect on the climate, e.g. in the Arctic, but mainly on the possibilities to estimate the future climate. Better estimates of both the health and climate effects of air pollutants are crucial for successful negotiations in reaching effective co-beneficial abatement measures which calls for more and extensive basic research.

Research clearly shows that the air pollutants ozone and particles including BC have considerable health effects calling for large emission reductions and abatement. Further CO_2, ozone and particles including BC significantly affect climate. Mitigation has to be done in a balanced way as some of the climate influencing air pollutants cool the climate. The major source for all these components are combustion. Combustion is often the major base for energy production for heating, electricity and transport. The required reductions are large, more than 50% for all components to reach required mitigation, i.e. emissions of all components from combustion have largely to be omitted. This means that in the longer perspective the use of combustion in any production have to be questioned and replaced by other processes or technique. A sustainable development of transport and energy production calls for a considerable RTD effort in these areas.

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Annex 1

Emissions factors used in the national Swedish emission inventory for $PM_{2.5}$. (http://www.naturvardsverket.se/sv/Start/Statistik/Luftfororeningar/Gransoverskridande-fororeningar/).

Combustion of fuels in mobile sources (kg $PM_{2.5}$/GJ).

Fuel type	**Mobile sources** Sector	Subsector	kg PM2.5/GJ 2005	2009	Source
Aviation Gasoline	Aviation	Domestic (Cruise/LTO)	0.01	0.010	CEPMEIP TNO
		Military	0.010	0.0000	CEPMEIP TNO
Biogas	Road Traffic	All	NE	NE	
Diesel oil	Fisheries	Fisheries	0.023	0.023	SMED 2005
	Military abroad	Bunkers	0.016	0.002	Swedish National Road Administration
	Off Road Vehicles and Working Machinery	Farming	0.043	0.038	Fridell, Jernström & Lindgren 2008
		Forestry	0.033	0.029	Fridell, Jernström & Lindgren 2008
		Households	0.046	0.047	Fridell, Jernström & Lindgren 2008
		Industry	0.034	0.030	Fridell, Jernström & Lindgren 2008
		Other	0.087	0.087	Fridell, Jernström & Lindgren 2008
	Railways	Railways	0.096	0.096	EMEP/CORINAIR, CEPMEIP TNO
	Road Traffic	Heavy duty vehicles	0.014	0.011	Swedish National Road Administration
		Light duty vehicles	0.020	0.014	Swedish National Road Administration
		Mopeds & Motorcycles	NO	NO	
		Passenger cars	0.016	0.006	Swedish National Road Administration
		Military	0.016	0.002	Swedish National Road Administration
Ethanol	Road Traffic	All	NE	NE	
FAME	Road Traffic	Civil	NE	NE	
		Military	NE	NE	
Gas/Diesel oil	Navigation/Shipping	Bunkers	0.016	0.016	SMED 2004
		Domestic	0.016	0.016	SMED 2004
		Military	0.016	0.016	SMED 2004
Gasoline	Navigation/Shipping	Military	0.090	0.090	EMEP/CORINAIR
		Small boats	0.090	0.090	EMEP/CORINAIR
	Off Road Vehicles and Working Machinery	Farming	0.109	0.084	Fridell, Jernström & Lindgren 2008
		Forestry	0.065	0.063	Fridell, Jernström & Lindgren 2008
		Households	0.039	0.035	Fridell, Jernström & Lindgren 2008
		Industry	0.020	0.019	Fridell, Jernström & Lindgren 2008
		Other	0.007	0.007	Fridell, Jernström & Lindgren 2008
	Road Traffic	Heavy duty vehicles	0.060	0.061	Swedish National Road Administration
		Light duty vehicles	0.005	0.004	Swedish National Road Administration

		Mopeds & Motorcycles	0.067	0.065	Swedish National Road Administration
		Passenger cars	0.001	0.001	Swedish National Road Administration
		Military	0.002	0.002	Swedish National Road Administration
Jet Gasoline	Aviation	Military	NO	NO	
Jet Kerosene	Aviation	Bunkers (Cruise/LTO)	0.001	0.001	CEPMEIP TNO
		Domestic (Cruise/LTO)	0.001	0.00116	CEPMEIP TNO
		Military	0.001	0.0000	CEPMEIP TNO
Natural Gas	Road Traffic	All	NE	NE	
Residual Oil	Navigation/Shipping	Bunkers	0.104	0.104	SMED 2004
		Domestic	0.104	0.104	SMED 2004
Note that the figures above are to a large extent Implied Emission Factors.					
Emissions in the Swedish inventory are estimated by models where fuel consumption is only one of all input parameters used.					
NO = Not occurring, NE = Not estimated					

Combustion of fuels in stationary sources (kg $PM_{2.5}$/GJ).

	Stationary sources	kg PM2.5/GJ
Fuel type	Area of consumption	2001-
Gas/diesel oil	Power plants, district heating, industry	0.002
Gas/diesel oil	Other consumption	0.003
Residual fuel oil	Power plants, district heating, industry	0.0083
Residual fuel oil	Other consumption	0.01245
LPG	Power plants, district heating, industry	0.0001
LPG	Other consumption	0.0002
Gas works gas	Power plants, district heating, industry	0.0001
Gas works gas	Other consumption	0.0005
Natural Gas	Power plants, district heating, industry	0.0001
Natural Gas	Other consumption	0.0005
Coke oven gas	All consumption	0.001
Blast furnace gas	All consumption	0.001
Steel converter gas	All consumption	0.001
Coking coal, other bituminous coal	Power plants, district heating	0.0166
Coking coal, other bituminous coal	Industry	0.009
Coking coal, other bituminous coal	Other consumption	0.025
Coke	Power plants, district heating	0.0166
Coke	Industry	0.021
Coke	Other consumption	0.025
Wood	Power plants, district heating	0.0245
Wood	Industry	0.028
Wood	Households	**
Wood	Other consumption	**
Peat	Power plants, district heating, industry	0.0245
Municipal Solid Waste	Power plants, district heating, industry	0.00081
Tall oil	All consumption	0.002
Kerosene	All consumption	0.002
Landfill gas	Power plants, district heating, industry	0.0001
Landfill gas	Other consumption	0.0005
Petroleum coke	Power plants, district heating	0.0166
Petroleum coke	Industry	0.021

Petroleum coke	Other consumption	0.025
Refinery oil	All consumption	0.005
Other biomass	Power plants, district heating	0.0245
Other biomass	Industry	0.028
Other biomass	Other consumption	0.0315
Other petroleum fuels	All consumption	0.035
Other solid fuels	All consumption	0.035
Other not specified fuels	All consumption	0.035
Refinery gases	All consumption	0.005

note: Black liquor (Swedish "avlutar", biomass fuel) is only combusted in industrial processes.
Emissions from black liquor are not estimated from fuel consumption and emission factors, and hence not specified here.

Source: Boström et al., *Emissions of particles, metals, dioxins and PAH in Sweden*. SMED report no 7, 2004

**** Small scale combustion of biomass 1990-**

Sector	Appliance type	Fuel type	kg PM2.5/GJ	Source
Residential	Boilers	Wood logs	0.15	Paulrud et al., 2006
		Wood chips	0.1	Paulrud et al., 2006
		Pellets	0.03	Paulrud et al., 2006
	Stoves	Wood logs	0.1	Paulrud et al., 2006
		Wood chips	0.1	Paulrud et al., 2006
		Pellets	0.03	Paulrud et al., 2006
	Open fire places	Wood logs	0.15	Paulrud et al., 2006
		Wood chips	-	Paulrud et al., 2006
		Pellets	-	Paulrud et al., 2006
Other consumption	All technologies	All biomass	0.15	Paulrud et al., 2006