Discussion paper – BC methodologies for Energy Industries (1A1)

The GB chapter for energy industries comprises methodological guidance for electricity and heat producing plants (> 50 MW), petroleum refining and manufacture of solid fuels. All three subsectors contain both tier 1 and tier 2 emission factors (EFs).

As discussed in the paper reviewing consistency more consideration should be given to the allocation of different fuels to the overall fuel groups for which there is default EFs available. Some fuels that are categorised as liquid fuels (e.g. LPG) will have more emission characteristics in common with natural gas than e.g. with other liquid fuels such as gas oil, petroleum coke, orimulsion etc.

The majority of available references report values of EC. However, in several reports and articles refer to the values as BC (e.g. Kupiainen & Klimont, 2004). In this discussion paper EC and BC will be used synonymously, please refer to the separate discussion paper on different carbonaceous fractions for more discussion on this topic.

Public electricity and heat production

The chapter contains tier 1 and tier 2 EFs as presented in the table below.

	Tier	Fuel	Technology
Table 3-3	1	Hard coal	
Table 3-4	1	Brown coal	
Table 3-5	1	Natural gas	
Table 3-6	1	Derived gases	
Table 3-7	1	Heavy fuel oil	
Table 3-8	1	Other liquid fuels	
Table 3-9	1	Biomass	
Table 3-11	2	Hard coal	DBB
Table 3-12	2	Brown coal/lignite	DBB+WBB
Table 3-13	2	Residual oil	DBB
Table 3-14	2	Natural gas	DBB
Table 3-15	2	Biomass	DBB
Table 3-16	2	Hard coal	WBB
Table 3-17	2	Hard coal	FBB
Table 3-18	2	Brown coal/lignite	FBB
Table 3-19	2	Biomass	FBB
Table 3-20	2	Gaseous	Gas turbines
Table 3-21	2	Gas oil	Gas turbines
Table 3-22	2	Gas oil	Engines
Table 3-23	2	Gaseous	Engines

Several sources are available for BC (EC) shares of PM for boilers combusting different types of fuel. For other types of combustion installations the data are scarcer. However, some data have been found in the literature and are described below under the individual references.

Hildemann et al. (1991) presents EC shares of PM_2 for gas oil and for natural gas used in home appliances. For a boiler using gas oil the EC share is reported as 28.9 % and the OC share is reported as 4.80 %. The values are based on five experiments. The paper also reports EC and OC shares for natural gas albeit for home appliances. Due to the scarcity of data for natural gas, these data are included in this discussion. Hildemann et al. reports EC and OC shares of 6.7 and 84.9 % respectively. The values are based on three experiments.

Wollf et al. (1981) refer to studies for natural gas, fuel oil and gas oil. For natural gas Wollf et al. deduces a share of EC of 51 %. However, even in the reference it is noted that this share is an order of magnitude higher than other data from the period. Specifically mentioned is Muhlbaier & Williams (1981). Due to this fact and the far lower shares provided in other references, this data set has been excluded from the further discussion. For fuel oil Wollf et al. refer to total shares of total carbon (TC) in fine particles from fuel oil fired boilers (Taback et al., 1979) and share of EC of TC (Watson, 1979). TC is reported as between 31 and 41 %, while the EC share of TC is reported as 32 %. This corresponds to an EC share of particles of between 9.9 and 13.1 % corresponding to an average of 11.5 %. Furthermore, Wollf et al. refers to an EC share of 16 % of total particles for gas oil fired boilers. Watson (1979) is a Ph.D. thesis, the share of 16 % cannot be reproduced based on Watson (1979).

Fisher et al. (1979) reported a total carbon content of particles of between 0.15 % and 0.27 % for coal combustion. For fine particles ($PM_{2.2}$) the share was 0.27 %. Furthermore, it is stated that the carbonaceous material is dominated by EC.

Henry & Knapp (1980) reports data on total carbon for residual oil fired boilers and coal fired boilers. The particle size for which the speciation is made is not explicitly mentioned. It is assumed that the fractions are of TSP. The table below sows the values reported.

Measurement data for total carbon in % of fly ash reported by Henry & Knapp (1980)

Residual oil	12.4	69	21.5	1.5	14.5
Coal	1.7	7	0.5	0.1	0.1

The average values are 23.8 % and 1.88 % for residual oil and coal respectively. It can be seen test two is an outlier for both residual oil and coal. If this is removed the average shares will be 12.5 % and 0.6 % for residual oil and coal respectively. These data are better in line with the other available data.

Griest & Tomkins (1984) reports data for a coal fired power plant. For fine particles ($PM_{2.3}$) the EC share is reported as 0.81 % while the OC fraction is reported as 0.31 %.

Chow et al. (2004) reports measurements from coal fired power plant units in Texas. There are measurement data available for six units with different types of abatement. All six units are dry bottom boilers combusting pulverised coal. For EC the shares of $PM_{2.5}$ are 2.7238 %, 2.3686 %, 0.6386 %, 1.5787 %, 0.1321 % and 0.0961 %. There is no discernible pattern of the EC share regardless of whether the unit is fitted with dry or wet desulphurization and whether ESP or fabric filters are used for particle abatement. The OC shares are reported as 62.8205 %, 55.6750 %, 22.8083 %, 4.1699 %, 10.3044 %, 0.9274 % and 27.1762 %. As can be seen there is no obvious link between the EC and OC shares for the six units.

Engelbrecht et al. (2002) reports EC/BC and OC shares for a coal fired power plant in South Africa. For $PM_{2.5}$ the share of EC is reported as 0.395 %, while the OC share is reported as 8.669 %.

Olmez et al. (1988) present measurement data for two fuel oil fired boilers and one coal fired boiler (There is also data for a waste incineration plant, this is included in the discussion paper for waste incineration). The data are based on 12 particle samples for each plant, however, not all samples are analysed. For EC between 3 and 4 samples are analysed for the plants included in this discussion. For the coal fired plant an EC share of 0.89 % ± 0.12 %-point is reported. The coal plant in question was equipped with an electrostatic precipitator (ESP) that was not functioning properly during the sampling. However, according to the authors this did not impact the composition of the particles when comparing with other studies. The two fuel oil fired boilers that was sampled were equipped with a cyclone and ESP respectively. For the two plants are reported EC shares of fine particles of 0.22 % ± 0.17 %-point and 7.7 % ± 1.5 %-point.

Win Lee et al. (2011) reports measurements of $PM_{2.5}$ emissions from coal fired plants. The measurements cover two types of subbituminous coal, lignite and one blend of lignite and subbituminous coal. In all cases the EC shares are reported as 0.0.

Dayton & Bursey (2001) reports speciated emissions data from a wood fired industrial boiler. The EC/BC and OC shares are reported as percentage of $PM_{2.5}$. The measurements are carried out both with and without a denuder. Without the denuder the EC share is reported as 3.0 ± 0.4 and the OC share is reported as 84.6 ± 11.0. With a denuder the EC share is reported as 13.8 ± 3.1 while the OC share is reported as 32.6 ±8.0. It is seen that the denuder significantly affects the shares of EC and OC. The EC share for the measurement with a denuder (13.8 %) is more than four times higher than the share without a denuder (3 %). For OC the opposite trend is observed with a denuder the OC share (32.6 %) is less than half the share without a denuder (84.6 %). The higher OC value observed without a denuder likely represents adsorbed semi volatile organic compounds. The results obtained without a denuder will be used in the comparison with other data.

Bond et al. (2006) reports measurements from a heat boiler in Leipzig mainly using natural gas. However, during peak loads the boiler switches to use residual fuel oil. The boiler is not equipped with any particle abatement. For oil combustion Bond et al. reports an EC share of $PM_{2.5}$ of 38 % and an OC share of 8 %. These values are similar to those reported by Hildemann et al. (1991). Measurements carried out when the boiler was combusting natural gas were below the detection limit and therefore no EC share is available for natural gas.

Watson et al. (2001) measured $PM_{2.5}$ profiles for two coal fired power stations in Colorado. The two power stations consisted of 2 and 3 units respectively. For the first power station (Hayden) both units are equipped with ESP and ammonia is injected to the flue gas prior to the ESP. For the second power station (Graig) units 1 and 2 are equipped with ESP and wet scrubbers, while unit 3 is dry scrubber followed by a baghouse for particle abatement. Units 1 and 2 are identical and measurements were only carried out on unit 2. Similar coal types were used at all units. The table below shows the measurement results for EC and OC for the units with measurements.

Shares in % of $PM_{2.5}$	EC	OC
Composite of four Craig unit 2 samples	8.08 ± 4.31	2.24 ± 2.68

Composite of three Craig unit 3 samples	1.17 ± 1.20	2.63 ± 2.11
One sample from Hayden unit 1	4.3 ± 0.8216	34.09 ± 3.58
Composite of two Hayden unit 2 samples	0.3944 ± 0.22062	0.4946 ± 0.19725
Composite of Hayden 1+2	1.70 ± 2.25	11.69 ± 19.40
Composite of Hayden 1+2 and Craig 2+3	4.09 ± 4.41	5.20 ± 10.24

The table shows values for the individual units and also as composite results for one on the power stations (Hayden) and the composite result for all of the measurements carried out. Despite the similar combustion conditions for the different units the composition of $PM_{2.5}$ varies significantly.

Wierzbicka et al. (2005) presents particle characterization for district heating plants using different types of biomass. The types of biomass used are forest residues, sawdust and wood pellets. The three units investigated were all of grate boilers. One was a 1.5 MW boiler fired with sawdust, the second unit was a 1.5 MW boiler fired with pellets and the third unit was a 1 MW boiler fired with forest residues. All boilers were equipped with a multiple cyclones as particle abatement. While these boilers are small compared to the boilers usually considered for this chapter (1A1a), they are included here due to the scarce availability of data for BC/EC for biomass fired plants outside of the residential sector. The results of EC and OC are shown in the table below.

Biofuel	Load	OC % of PM_1	EC % of PM_1
Sawdust	Low	5	8
	Medium	8	2
	Medium	8	0
	High	19	1
	High	12	0
Pellets	Low	2	25
	Low	6	37
	Medium	14	18
	Medium	9	56
Forest residues	High	8	0
	High	6	0
	High	1	0

As seen from the table the measurement data for EC varies both with fuel and operating load. Wierzbicka et al. explains the lack of EC data for the unit combusting forest residues with the fact that this larger unit has better control of combustion parameters resulting in more stable and complete combustion. It must be noted that the measurements are carried out in hot flue gas to avoid condensation of semi-volatile compounds. This can have a significant influence of the total particle emission measured but also on the share of carbon in particular OC.

Mugica et al. (2008) reported measurement data on the elemental composition of $PM_{2.5}$ emissions from LP gas combustion and waste incineration. The data on the waste incineration are presented in the discussion paper on waste incineration and not further discussed here. The boiler is a small industrial boiler and is not equipped with any kind of particle abatement. The EC share of $PM_{2.5}$ is reported as 5.353 ± 0.35 and the OC share as 71.32 ± 5.04.

Pinto et al. (1998) reported zero per cent of BC and 7.5 % of OC in $PM_{2.5}$ from the Ledvice power plant near Teplice in the Czech Republic.

Mazzera et al. (2001) reported data for a power plant in Antarctica consisting of diesel engines as well as for diesel heat boilers. For the diesel engines the EC share of PM_{10} is reported as 39.4138 %, while the OC share is reported as 10.4443 %. For the two different heating boilers, the EC shares are reported as 4.4916 % and 7.3929 % respectively. The corresponding OC shares are 54.3207 % and 72.0403 %.

England et al. (2007) provides data on EC/BC and OC shares of $PM_{2.5}$ for natural gas and oil fired plants. For gas fired boilers the EC share is reported as 13 % and the OC share as 61 %. However this includes both natural gas fired, refinery gas fired and dual-fuel fired boilers. For gas fired process heaters EC and OC shares are reported as 6.3 % and 62 % respectively. For gas fired internal combustion combined cycle/cogeneration plants EC and OC shares are reported as 2.5 % and 68 % respectively. For fuel oil fired boilers the EC and OC shares are reported as 7.1 % and 6.9 % respectively. For a diesel powered stationary engine EC and OC shares are reported as 78 % and 22 % respectively. When a particle filter is included the shares of EC and OC are reported as 83 % and 16 % respectively. The underlying data, a thorough description of the methodology and further references to the reports documenting the measurements are available in England (2004).

Querol et al. (1995) found almost no carbonaceous material in fine particles in the fly ash from a coal fired power station. This seems to be similar to the data reported by Pinto et al. (1998).

The SPECIATE database (US EPA, 2011) contains many data sets on analysis of PM from different sources. In this chapter it was attempted to extract all relevant data for the major fuel groups. The data acquired from the SPECIATE database are presented in the tables below.

EC and OC data for gas combustion extracted from the SPECIATE database as per cent of $PM_{2.5}$.

NUMBER	PM PROFILE NAME	CONTROLS	SPECIES PROPERTIES	SPECIATE VERSION	SHARE	NOTES
3195	Gas Combustion	Uncontrolled	EC	4.0	2.9764	
5669	Gas-Fired Boilers	Uncontrolled	EC	4.3	13	Composite data for one natural gas fired boiler. one refinery gas fired boiler and one natural gas fired steam generator
5670	Gas-Fired Process Heaters	Selective catalytic reduction	EC	4.3	6.3	Composite data for three gas fired process heaters
5671	Gas-Fired Combined Cycle and Cogeneration Plants	Lean premix combustion for CO; water injection for NOx	EC	4.3	2.5	Two units fired with natural gas and one fired with refinery gas
3195	Gas Combustion	Uncontrolled	OC	4.0	8.671	
5669	Gas-Fired Boilers	Uncontrolled	OC	4.3	61	Composite data for one natural gas fired boiler. one refinery gas fired boiler and one natural gas fired steam generator

5670	Gas-Fired Process Heaters	Selective catalytic reduction	OC	4.3	62	Composite data for three gas fired process heaters
5671	Gas-Fired Combined Cycle and Cogeneration Plants	Lean premix combustion for CO; water injection for NOx	OC	4.3	68	Two units fired with natural gas and one fired with refinery gas

It can be seen that the share of EC varies between 2.5 % and 13 %, while the OC shares vary from 8.6 % to 68 %. The value of 8.6 % seems to be an outlier compared to the other datasets. The values marked with red in the table are from England et al. (2007).

EC and OC data for oil combustion extracted from the SPECIATE database as per cent of $PM_{2.5}$.

NUMBER	PM PROFILE NAME	CONTROLS	SPECIES PROPERTIES	SPECIATE VERSION	SHARE	NOTES
3253	Oil Combustion	Uncontrolled	EC	4.0	3.01	Oil field crude oil boiler emission.
3293	Oil Combustion	Uncontrolled	EC	4.0	0	Oil field crude oil boiler emission.
4736	Distillate Oil Combustion	Low NOx burners. no PM controls	EC	4.0	10	Industrial-scale distillate oil-fired boiler
4737	Residual Oil Combustion	5-field Electrostatic Precipitator	EC	4.0	1	Steam generator burning residual fuel oil
5672	Oil-Fired Boilers	Not Available	EC	4.3	7.1	
11507	Oil-Fired Power Plant	Uncontrolled	EC	3.2	12.8	Twenty five samples from four boilers collected over a 6-dayperiod.
11508	Oil-Fired Power Plant	Uncontrolled	EC	3.2	7.7	
11509	Oil-Fired Power Plant	Uncontrolled	EC	3.2	0.22	
12710	Boiler - #2 Fuel Oil Fired	Not Applicable	EC	3.2	28.9	
13501	Residual Oil Combustion	Uncontrolled	EC	3.2	2.42	
13504	Oil-Fired Boiler	Uncontrolled	EC	3.2	8.69	
13505	Residual Oil-Fired Boiler / Petroleum Refinery	Uncontrolled	EC	3.2	13.56	Represents the composite of 4 sampling runs. fuel oil and fuel gas used during the tests
3253	Oil Combustion	Uncontrolled	OC	4.0	1.99	Oil field crude oil boiler emission.
3293	Oil Combustion	Uncontrolled	OC	4.0	0.09	Oil field crude oil boiler emission.
4736	Distillate Oil Combustion	Low Nox burners. no PM controls	OC	4.0	25	Industrial-scale distillate oil-fired boiler
4737	Residual Oil Combustion	5-field Electrostatic Precipitator	OC	4.0	1	Steam generator burning residual fuel oil
5672	Oil-Fired Boilers	Not Available	OC	4.3	7.9	
11507	Oil-Fired Power Plant	Uncontrolled	OC	3.2	5	Twenty five samples from four boilers collected over a 6-dayperiod.
11508	Oil-Fired Power Plant	Uncontrolled	OC	3.2	3.2	
11509	Oil-Fired Power Plant	Uncontrolled	OC	3.2	1	

NUMBER	PM PROFILE NAME	CONTROLS	SPECIES PROPERTIES	SPECIATE VERSION	SHARE	NOTES
12710	Boiler - #2 Fuel Oil Fired	Not Applicable	OC	3.2	4.8	
13501	Residual Oil Combustion	Uncontrolled	OC	3.2	7.8	
13504	Oil-Fired Boiler	Uncontrolled	OC	3.2	8.96	
13505	Residual Oil-Fired Boiler / Petroleum Refinery	Uncontrolled	OC	3.2	2.279	Represents the composite of 4 sampling runs. fuel oil and fuel gas used during the tests

It is suspected that the EC data marked with red are in fact data from Hildemann et al. (1991) and Olmez et al. (1988). The EC factors (excluding the above mentioned) are between 1 % and 13.6 % of $PM_{2.5}$.

EC and OC data for biomass combustion extracted from the SPECIATE database as per cent of $PM_{2.5}$.

NUMBER	PM PROFILE NAME	CONTROLS	SPECIES PROPERTIES	SPECIATE VERSION	SHARE	NOTES
4704	Wood-fired Industrial Boiler - NWWAS	Multistage ESP	EC	4.0	13.8	EC/OC samples were collected following a denuder. Fine particulate emissions from a wood-fired industrial boiler. Composite of two samples.
4705	Wood-fired Industrial Boiler	Multistage ESP	EC	4.0	3	Same as above except denuder
11801	Wood-Fired Boiler	Multicyclone	EC	3.2	2.15[1]	
12704	Wood-Fired Boiler	Wet Scrubber	EC	3.2	4.6	
4704	Wood-fired Industrial Boiler - NWWAS	Multistage ESP	OC	4.0	32.6	EC/OC samples were collected following a denuder. Fine particulate emissions from a wood-fired industrial boiler. Composite of two samples.
4705	Wood-fired Industrial Boiler	Multistage ESP	OC	4.0	84.6	Same as above except denuder
11801	Wood-Fired Boiler	Multicyclone	OC	3.2	5.55[2]	
12704	Wood-Fired Boiler	Wet Scrubber	OC	3.2	5.6	

[1]Share reported as 0 in the database. For PM_{10} and PM_{30} the share is reported as 2.15. This is assumed to also be valid for $PM_{2.5}$.
[2]Share reported as 0 in the database. For PM_{10} and PM_{30} the share is reported as 5.55. This is assumed to also be valid for $PM_{2.5}$.

There is a very limited number of datasets available for wood combustion when excluding residential plants. The share of EC in $PM_{2.5}$ varies between 2.15 % and 13.8 % with a simple average of 5.9 %. The OC share varies between 5.55 % and 84.6 %, with a simple average of 32.1 %. The values marked with red in the table are from Dayton & Bursey (2001).

For coal the majority of data in the SPECIATE database the references are Watson et al. (2001) and Chow et al. (2004). The remaining data available in SPECIATE are listed in the table below.

EC and OC data for coal combustion extracted from the SPECIATE database as per cent of $PM_{2.5}$. (Excluding data included in other listed references)

NUMBER	PM PROFILE NAME	CONTROLS	SPECIES PROPERTIES	SPECIATE VERSION	SHARE	NOTES
3191	Coal Combustion	Baghouse	EC	4.0	6.676	
3192	Coal Combustion	Mechanical Collectors; Electrostatic Precipitator; Wet Scrubber	EC	4.0	1.877	
3194	Coal Combustion	Wet Scrubber	EC	4.0	1.235	
3191	Coal Combustion	Baghouse	OC	4.0	4.416	
3192	Coal Combustion	Mechanical Collectors; Electrostatic Precipitator; Wet Scrubber	OC	4.0	1.91	
3194	Coal Combustion	Wet Scrubber	OC	4.0	2.888	

The discussed emission factors are presented in the tables below.

EC (BC) shares found in literature, part 1.

Fuel	Hildemann et al., 1991	Muhlbaier & Williams, 1982	Wolff et al., 1981	Henry & Knapp, 1980	Olmez et al., 1988	Win Lee et al., 2011	Bond et al., 2006	Speciate	Watson et al., 2001	Wierzbicka et al., 2005
	% of PM_2		% of TSP	% of TSP	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of PM_1
Hard coal				0.6	0.89	0		6.676; 1.8766; 1.2354	8.08; 1.17; 4.30; 0.3944	
Brown coal						0				
Natural gas	6.7	4					ND	2.9764		
LPG										
Heavy fuel oil			11.5	12.5	0.22; 7.7			2.42; 8.69; 12.8; 7.1; 1; 3.01		
Gas oil	28.9						38	10		
Biomass								2.15; 4.6		
Wood pellets										25; 37; 18; 56
Forest residues										0; 0; 0
Sawdust										8; 2; 0; 1; 0
Gas fired process heaters										
Gas fired internal combustion CC										
Diesel engine										

EC (BC) shares found in literature, part 2.

Fuel	Mugica et al., 2008	Pinto et al., 1998	England et al., 2007	Querol et al., 1995	Fisher et al., 1979	Griest & Tomkins, 1984	Engelbrecht et al., 2002	Dayton & Bursey, 2001	Mazzera et al., 2001	Chow et al., 2004
	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$		% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of PM_{10}	% of $PM_{2.5}$
Hard coal				0	0.27	0.81	0.395			2.7238; 2.3686; 0.6386; 1.5787; 0.1321; 0.0961;
Brown coal		0								
Natural gas			2.8; 3.8							
LPG	5.353									
Heavy fuel oil			7.1							
Gas oil									4.4916; 7.3929	
Biomass								3		
Wood pellets										
Forest residues										
Sawdust										
Gas fired process heaters			6.3							
Gas fired internal combustion CC			2.5							
Diesel engine			78						39.4138	

It is not possible to find a correlation between different kinds of combustion technologies for e.g. coal and the reported EC shares. Most data have been for dry bottom boilers. It has not been possible to obtain data from coal combustion using fluidised bed technology. Therefore, it has been assumed that the BC share of $PM_{2.5}$ is identical to the chosen share for pulverised coal combustion in dry bottom boilers.

It is most likely that different abatement measures will impact the chemical composition of the particulate emissions. E.g. the efficiency of the inertia based methods (cyclones, fabric filters) differs as a function of particle size (Kupiainen & Klimont, 2004). Therefore, particles with a specific composition may be found in increased concentrations in the controlled emissions if they are primarily found in a specific size class for which the abatement efficiency is low.

Recommendations

The recommendations below focus on the individual main fuel groups separately.

Solid fuels

The available data for coal fired power plants are shown in the table below.

Fuel	Henry & Knapp 1980	Olmez et al., 1988	Win Lee et al., 2011	Speciate	Watson et al., 2001
	% of TSP	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$
Hard coal	1.88	0.89	0	6.676 1.8766 1.2354	8.08 1.17 4.30 0.3944
Fuel	Querol et al., 1995	Fisher et al., 1979	Griest & Tomkins, 1984	Engelbrecht et al., 2002	Chow et al., 2004
		% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$
Hard coal	0	0.27	0.81	0.395	2.7238 2.3686 0.6386 1.5787 0.1321 0.0961

In general coal combustion is the activity where most data are available compared to the other fuel types. Some references reports an EC of 0 (zero). This is the case for Win Lee et al. (2011), Pinto et al. (1998) and Querol et al. (1995). For the remaining references the EC share varies between 0.096 % of $PM_{2.5}$ to 8.08 % of $PM_{2.5}$. Some of the data sources report EC shares for units with different types of abatement (e.g. Chow et al., 2004). However, based on these data it is not possible to find a correlation between EC shares and different types of abatement.

Similarly, for all reference where the combustion technology is specified, the used technology has been dry bottom boilers. It has not been possible to find any specific data for wet bottom boilers and fluidised bed. Therefore, the same BC share of $PM_{2.5}$ as for dry bottom boilers will be used.

Pinto et al. (1998) reports an EC share of 0 for a brown coal fired power plant in the Czech Republic. A value of 0 is also reported by Win Lee et al. (2011). The very low share for brown coal is supported by data from Veranth et al. (2000). Veranth et al. (2000) reports a share of total carbon in fine particles as ≈ 0.02 %.

Therefore, it is recommended at the moment to place BC as Not Applicable in the EF tables for brown coal both for tier 1 and tier 2.

To derive a BC EF for hard coal the zero values reported by Win Lee et al. (2011) and Querol et al. (1995) are not considered. For the remaining data the average value is 2.2 % of $PM_{2.5}$. The data from Henry & Knapp (1980) has been recalculated to $PM_{2.5}$ using the current particle size distribution in the GB (TSP = 30 g/GJ, $PM_{2.5}$ = 9 g/GJ).

A different approach could be to consider the lowest and highest shares, i.e. 0.096 % and 8.08 % and then take the geometric mean. This would result in a share of 0.9 % of $PM_{2.5}$.

The average is based on 18 data, where several reflect multiple measurements on the same unit. Therefore it is considered that the sample size is sufficient to justify using the average value. A BC share of 2.2 % of $PM_{2.5}$ is therefore proposed in the table below.

	Tier	Fuel	Technology	BC % of $PM_{2.5}$	Reference
Table 3-3	1	Hard coal		2.2	See text
Table 3-4	1	Brown coal		NA	Pinto et al., 1998 & Win Lee et al., 2011
Table 3-11	2	Hard coal	DBB	2.2	See text
Table 3-12	2	Brown coal/lignite	DBB+WBB	NA	Pinto et al., 1998 & Win Lee et al., 2011
Table 3-16	2	Hard coal	WBB	2.2	See text
Table 3-17	2	Hard coal	FBB	2.2	See text
Table 3-18	2	Brown coal/lignite	FBB	NA	Pinto et al., 1998 & Win Lee et al., 2011

Liquid fuels

The available data for oil are shown in the table below.

Fuel	Hildemann et al., 1991	Wolff et al., 1981	Henry & Knapp 1980	Olmez et al., 1988	Bond et al., 2006	Speciate	England et al., 2007	Mazzera et al., 2001	Hernandez et al., 2004
	% of PM_2	% of TSP	% of TSP	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of PM_{10}	% of $PM_{2.5}$
Heavy fuel oil		11.5	12.5	0.22; 7.7		2.42; 8.69; 12.8; 7.1; 1; 3.01	7.1		
Gas oil	28.9				38	10		4.4916;7.3929	
Diesel engine								39.4138	78

For fuel oil, there are some datasets available. The majority of the datasets expresses EC shares of $PM_{2.5}$. The datasets from Wolff et al. (1981) and Henry & Knapp (1980) are expressed as shares of TSP. Using the average particle size distribution in the GB $PM_{2.5}$ = 0.49 * TSP (Tier 1: TSP = 25, $PM_{2.5}$ = 13 and tier 2: TSP = 20, $PM_{2.5}$ = 9), the factors from Wolff et al. (1981) and Henry & Knapp (1980) can be recalculated to 23.5 % and 25.5 % respectively. These percentages are far higher than all other data available. It is considered that these two represents outliers, and they are therefore excluded from consideration. The average of the remaining datasets is 5.6 % EC of $PM_{2.5}$. It is recommended that this factor is used as the BC share for the tier 1 EF table for heavy fuel oil and for the tier 2 EF table for residual oil combustion in dry bottom boilers.

For the tier 1 EF table on "Other liquid fuels" gas oil will be used as a representative fuel. In that respect it is important that proper guidance is provided in the GB to avoid users incorrectly using EFs that are developed for gas oil as EFs for e.g. LPG. The issue of fuel allocation is discussed further in the discussion paper regarding review of consistency for chapter 1A1 of the GB. There are few datasets available for gas oil and the values are varying significantly. The dataset from the SPECIATE dataset is not quality rated and based on unpublished data. The data by Mazzera et al. (2001) are based on data from heating boilers on Antarctica. It is believed that these are not representative for this sector. Therefore, the recommendation is to only consider the data by Hildemann et al. (1991) and Bond et al. (2006) in the derivation of the BC share for gas oil boilers. Hildemann et al. (1991) reports an EC share of PM_2 of 28.9 %, while Bond et al. (2006) reports an EC share of $PM_{2.5}$ of 38 %. The average of these is 33.5 %, which is recommended as the BC share of $PM_{2.5}$ to be used in the GB for tier 1 "Other liquid fuels".

It has not been possible to find data particularly for gas oil used in gas turbines, therefore, it is recommended that the same factor is applied for this combustion technology as the factor derived for gas oil and used in the tier 1 EF table, i.e. a BC share of 33.5 % of $PM_{2.5}$.

Hernandez et al. (2004) and Mazzera et al. (2001) reports EC shares for gas oil fired engines. Hernandez et al. (2004) reports an EC share of $PM_{2.5}$ of 78 % increasing to 83 % when a particle filter was installed. Mazzera et al. (2001) reports an EC share of 39.4138 % of PM_{10}. With the current particle size distribution in the GB (PM_{10} = 22.4 g/GJ and $PM_{2.5}$ = 21.7 g/GJ), this equates to 40.69 % of $PM_{2.5}$. When looking at mobile diesel engines the EC share of TSP is usually between 50 % and 80 %. This would seem to indicate that the value reported by Hernandez et al. (2004) is more appropriate. Therefore, it is recommended that 78 % will be implemented as BC share of $PM_{2.5}$ for gas oil fired engines in the GB.

	Tier	Fuel	Technology	BC % of $PM_{2.5}$	Reference
Table 3-7	1	Heavy fuel oil		5.6	See text
Table 3-8	1	Other liquid fuels		33.5	See text
Table 3-13	2	Residual oil	DBB	5.6	See text
Table 3-21	2	Gas oil	Gas turbines	33.5	See text
Table 3-22	2	Gas oil	Engines	78	Hernandez et al., 2004

Gaseous fuels

For natural gas there are few measurement data available. Hildemann et al. (1991) reports an EC share of 6.7 % of PM_2 for domestic appliances. Muhlbaier and Williams (1982) has not been obtained yet, but presumably reports an EC share of 4 %. The SPECIATE database contains one dataset (not otherwise included). This shows an EC share of 2.98 % of $PM_{2.5}$.

England et al. (2007) reports EC shares for natural gas boilers and Combined Cycle cogeneration plants. For the boilers the result is a combination of one refinery gas boiler, one natural gas steam generator and one dual-fuel boiler (natural gas and residual fuel oil). The dual fuel boiler has only been measured when running on fuel oil (Wien et al., 2004a), and therefore this value could be considered too high. The data for the natural gas steam generator are not freely available and have not been sourced. The combined cycle plants consist of two natural gas fired plants and one refinery gas fired plants. The two natural gas fired plants have EC shares of 1.8 % and 2.8 % respectively (England et al., 2004; Wien et al., 2004b).

An overview of the considered BC shares is presented in the table below.

Fuel	Hildemann et al., 1991	Muhlbaier & Williams, 1982	Speciate	England et al., 2004	Wien et al., 2004b
	% of PM_2		% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$
Natural gas	6.7	4	2.9764	1.8	2,8

Since the data from Hildemann et al. (1991) are for home appliances, it is considered that this dataset is excluded. The average of the four remaining datasets is 3.26 % of $PM_{2.5}$. If a copy of Muhlbaier and Williams (1982) cannot be obtained it is recommended to also exclude this dataset. In that case the resulting average share would be 2.89 % of $PM_{2.5}$.

Regarding derived gases, no measurement data have been found for gas works gas, coke oven gas or blast furnace gas. Therefore, the same BC share is proposed for derived gases as for natural gas.

It has not been possible to find specific EC/BC shares for natural gas combustion in gas engines or gas turbines. The tier 2 EF for natural gas combustion in dry bottom boilers, gas turbines and gas engines is assumed to be the same as the tier 1 EF for natural gas.

	Tier	Fuel	Technology	BC % of $PM_{2.5}$	Reference
Table 3-5	1	Natural gas		3.26 (2.89)	See text
Table 3-6	1	Derived gases		3.26 (2.89)	See text
Table 3-14	2	Natural gas	DBB	3.26 (2.89)	See text
Table 3-20	2	Gaseous	Gas turbines	3.26 (2.89)	See text
Table 3-23	2	Gaseous	Engines	3.26 (2.89)	See text

Biomass

Very few datasets are available for large scale combustion of biomass, since the vast majority of measurements have been carried out in small scale stoves and boilers mainly in the residential sector. The table below lists the three sources that have been found. Wierzbicka et al. (2004) is reporting speciated emissions from three boilers using different types of biomass. However, all three boilers are small scale each being around 1-1.5 MW. Similarly, the data for large boilers combusting biomass are too scarce to allow any kind of assessment of difference between combustion technologies.

Fuel	Speciate	Wierzbicka et al., 2005	Dayton & Bursey, 2001
	% of $PM_{2.5}$	% of PM_1	% of $PM_{2.5}$
Biomass	2.15; 4,6		3
Wood pellets		25; 37; 18; 56	
Forest residues		0; 0; 0	
Sawdust		8; 2; 0; 1; 0	

The datasets provided in the SPECIATE database and by Dayton & Bursey (2001) are therefore considered to be the best available data. The average of the three datasets is 3.25 % of $PM_{2.5}$ and this value is proposed implemented as the BC share of $PM_{2.5}$ for all technologies.

	Tier	Fuel	Technology	BC % of $PM_{2.5}$	Reference
Table 3-9	1	Biomass		3.25	See text
Table 3-15	2	Biomass	DBB	3.25	See text
Table 3-19	2	Biomass	FBB	3.25	See text

Petroleum refining

The chapter on petroleum refining contains tier 1 and tier 2 EFs as presented in the table below.

	Tier	Fuel	Technology
Table 4-3	1	Refinery gas	
Table 4-5	2	Residual oil	Process furnaces
Table 4-6	2	Gas oil	Process furnaces
Table 4-7	2	LPG	Process furnaces
Table 4-8	2	Natural gas	Process furnaces
Table 4-9	2	Natural gas	Stationary engines
Table 4-10	2	Gas oil	Stationary engines

In general there are few specific BC/EC shares available for refining operations. Therefore, some of the literature sources for oil and gas, included in the discussion for chapter 1A1a, are also considered in this chapter.

Some data specific to oil refining are available in the SPECIATE database. The data are referenced to Chow et al. (2004) (only for catalytic cracking, see paper on fugitive emissions) and Chang et al. (2004). The data referenced to Chang et al. in the SPECIATE database cannot immediately be identified from the published article. The relevant SPECIATE data are presented in the table below.

EC and OC data for refining extracted from the SPECIATE database as per cent of $PM_{2.5}$. (Excluding data included under fugitive emissions)

NUMBER	PM PROFILE NAME	CONTROLS	SPECIES PROPERTIES	SPECIATE VERSION	SHARE	NOTES
4394	Oil Refinery	Not Available	EC	4.0	20.1	Dilution tunnel sampling of a refinery gas-fired process heater at Refinery Site D.
4395	Oil Refinery	Not Available	EC	4.0	14.22	Same as above
4396	Oil Refinery	Not Available	EC	4.0	7.634	Same as above
4397	Oil Refinery	Not Available	EC	4.0	36.33	Same as above
4404	Oil Refinery	Uncontrolled	EC	4.0	29.98	Dilution tunnel sampling of a boiler firing refinery process gas at Site A.
4405	Oil Refinery	Uncontrolled	EC	4.0	15.77	Same as above
4406	Oil Refinery	Uncontrolled	EC	4.0	33.8	Same as above
4412	Oil Refinery	Uncontrolled	EC	4.0	14.22	Dilution tunnel sampling of a process gas-fired refinery process heater at Site B.
4413	Oil Refinery	Uncontrolled	EC	4.0	5.161	Same as above
4414	Oil Refinery	Uncontrolled	EC	4.0	6.551	Same as above

The data above represents the best available data for EC shares from combustion of refinery gas. The average of the values listed is 18.38 %. An alternative approach could be to consider the minimum and maximum values and then take the geometric mean. This would result in an EC share of 13.69 % of $PM_{2.5}$.

Wien et al. (2004c) reports an EC share of 8.6 % of $PM_{2.5}$ from a natural gas fired process heater. This is the only dataset available for natural gas use in process heaters.

Mugica et al. (2008) is the only source identified for an EF for LPG. The paper reports an EC share of $PM_{2.5}$ of 5.353 %.

Hernandez et al. (2004) and **Mazzera et al. (2001)** reports EC shares for gas oil fired engines. Hernandez et al. (2004) reports an EC share of $PM_{2.5}$ of 78 % increasing to 83 % when a particle filter was installed. Mazzera et al. (2001) reports an EC share of 39.4138 % of PM_{10}. With the current particle size distribution in the GB (PM_{10} = 22.4 g/GJ and $PM_{2.5}$ = 21.7 g/GJ), this equates to 40.69 % of $PM_{2.5}$.

Recommendations

For refinery gas the recommendation would be to use the average EC share of the SPECIATE data (18.38 % of $PM_{2.5}$) as the BC EF.

For natural gas in process furnaces the dataset from Wien et al. (2004c) is considered the best data.

For residual oil and gas oil combusted in process furnaces, it has not been possible to find specific data. Therefore, the same shares have been used as derived for heavy fuel oil and other liquid fuels for sector 1A1a. The BC shares of $PM_{2.5}$ are therefore 5.6 % and 33.5 % for residual oil and gas oil respectively. For the discussion on the references and derivation, please see the discussion under sector 1A1a.

For LPG the only dataset available is Mugica et al. (2008), this is therefore proposed as the BC share in the GB.

For natural gas engines, it has not been possible to find specific EC/BC shares. Therefore the recommendation is to use the general share derived for natural gas under sector 1A1a.

For stationary engines using gas oil only two datasets have been found. The two datasets from Hernandez et al. (2004) and Mazzera et al. (2001) differ by a factor of 2. When looking at mobile diesel engines the EC share of TSP is usually between 50 % and 80 %. This would seem to indicate that the value reported by Hernandez et al. (2004) is more appropriate. Therefore, it is recommended that 78 % will be implemented as BC share of $PM_{2.5}$ for gas oil fired engines in the GB.

	Tier	Fuel	Technology	BC % of $PM_{2.5}$	Reference
Table 4-3	1	Refinery gas		18.38	See text
Table 4-5	2	Residual oil	Process furnaces	5.6	See text
Table 4-6	2	Gas oil	Process furnaces	33.5	See text
Table 4-7	2	LPG	Process furnaces	5.353	Mugica et al., 2008
Table 4-8	2	Natural gas	Process furnaces	8.6	Wien et al., 2004c
Table 4-9	2	Natural gas	Stationary engines	3.26 (2.89)	See text
Table 4-10	2	Gas oil	Stationary engines	78	Hernandez et al., 2004

Manufacture of solid fuels and other energy industries

The chapter on manufacture of solid fuels and other energy industries contains tier 1 and tier 2 EFs as presented in the table below.

	Tier	Fuel	Technology
Table 5-2	1	Coal	
Table 5-3	2	Coal	Coke oven with by-product recovery
Table 5-4	2	Coal	Coke oven without by-product recovery

The SPECIATE database only contains EC/BC and OC shares for Coke Cooler. The EC/BC and OC shares are reported as 73.9 % and 3.28 % of $PM_{2.5}$. However, this operation is considered under fugitive emissions.

Bond et al. (2004) assumed that 95 percent of the emissions is carbonaceous, half of which is BC and the other half OM. However, this is considering the whole process of coke production, i.e. both fuel related and fugitive emissions.

No other data have been found that could be used to estimate the BC shares from the fuel related part of coke production. At the moment, it is therefore recommended that BC is listed as Not Estimated in the three EF tables in sector 1A1c.

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