Discussion paper – BC methodologies for Small Combustion (1A4)

This discussion paper covers a review of the available data for BC emissions from small combustion. Furthermore, separate discussion papers are dedicated to a review of the current emission factors (EFs) and to discuss different methods for allocating fuel consumption data to different technologies as well as bottom-up methods for estimating fuel consumption for small combustion installations.

Residential plants

Currently the GB contains four tier 1 EF tables and a larger number of tier 2 EF tables as presented in the table below. Currently, there is no match between the technological descriptions in section 2.2 and the EFs provided in section 3 of the chapter. This necessitates a reevaluation of the descriptions of techniques and the EFs provided in the chapter.

List of EF tables for residential plants in the GB chapter on small combustion.

	Tier	Fuel	Sector	Technology
Table 3-3	1	Coal	Residential	
Table 3-4	1	Natural gas	Residential	
Table 3-5	1	Other liquid fuels	Residential	
Table 3-6	1	Biomass	Residential	
Table 3-12	2	Solid fuels	Residential	Fireplaces
Table 3-13	2	Gaseous fuels	Residential	Fireplaces
Table 3-14	2	Wood	Residential	Fireplaces
Table 3-15	2	Solid fuels	Residential	Stoves
Table 3-16	2	Solid fuels	Residential	Boilers < 50 kW
Table 3-17	2	Wood	Residential	Stoves
Table 3-18	2	Wood	Residential	Boilers < 50 kW
Table 3-19	2	Natural gas	Residential	Stoves
Table 3-20	2	Natural gas	Residential	Boilers < 50 kW
Table 3-21	2	Liquid fuels	Residential	Stoves
Table 3-22	2	Liquid fuels	Residential	Boilers < 50 kW
Table 3-23	2	Coal	Residential	Advanced stoves
Table 3-24	2	Wood	Residential	Advanced fireplaces
Table 3-25	2	Wood	Residential	Advanced stoves
Table 3-26	2	Wood	Residential	Pellet stoves

Biomass combustion

Emission factors are currently included in one tier 1 emission factor table and 6 tier 2 emission factor tables. As mentioned above the technology description in chapter 2.2 does not match the tier 2 emission factor tables. Suggested new technology names and the link to the technology description in chapter 2.2 are shown below. Emisssion factors for advanced fireplaces will be deleted and replaced by an emission factor table for energy efficient stoves.

List of EF tables for residential plants in the GB chapter on small combustion.

	Tier	Fuel	Sector	Technology	New technology name	Chapter 2.2 technology name
Table 3-6	1	Biomass	Residential		-	-
Table 3-14	2	Wood	Residential	Fireplaces	Open fireplaces	Open and partly closed fireplace
Table 3-17	2	Wood	Residential	Stoves	Conventional stoves	Closed fireplace, conventional traditional stoves, domestic cooking
Table 3-18	2	Wood	Residential	Boilers < 50 kW	Conventional boilers < 50 kW	Conventional biomass boilers
Table 3-24	2	Wood	Residential	Advanced fireplaces	Energy efficient stoves	Energy efficient conventional stoves
Table 3-25	2	Wood	Residential	Advanced stoves	Advanced/ecolabelled stoves and boilers	Advanced combustion stoves, masonry heat accumulating stoves, catalytic combustor stoves, advanced combustion boilers (and the chimney type stove)
Table 3-26	2	Wood	Residential	Pellet stoves	Pellet stoves and boilers	Modern pellet stoves, automatic wood boilers (pellets / chips)

BC and OC fractions of PM depends of both technology, wood type and PM emission level. For open fireplaces the OC fraction is high whereas a more complete combustion in advanced stoves results in a lower OC fraction. In general, the EC fraction is higher for softwood than for hardwood.

It has not been possible to distinguish between elemental carbon and black carbon. Most references state data for elemental carbon.

In most recent European literature PM and BC measurement data are based on dilution sampling and BC fractions related to $PM_{2.5}$.

Residential wood combustion (tier 1)

The current emission factor for $PM_{2.5}$ is 695 g/GJ (475-1190). This PM emission level is somewhat below the level for conventional stoves. An update of the PM emission factor is not estimated yet, but it is expected that the tier 1 emission factors will follow the emission factors for conventional stoves. The BC fraction for stoves (10 %) will be applied.

Fireplaces

The current emission factor level for $PM_{2.5}$ from fireplaces is 850 (510-1190) g/GJ. The level stated by Nussbaumer et al. (2010) is 50 - > 1000 g/GJ. However, Alves et al. (2011) states an interval in agreement with the current interval and the PM emission factor interval will not be revised.

The BC fraction 7 % of $PM_{2.5}$ that is an average of the listed references will be applied. The average OC fraction is 43 %.

List of BC references for open fireplaces.

Reference	Country	Plant	PM [g/GJ]	EC or BC	OC
Alves et al. 2011	Portugal	Brick open fireplace, wood logs	$PM_{2.5}$: 550-1122	4.7 % (2.2-7.5 %)	43.2-53 %

Alves et al. 2011	Portugal	Brick open fireplace, briquettes	$PM_{2.5}$: 850	5.4 %	47.7 %
Goncalves et al. 2011	Portugal	Brick open fireplace	$PM_{2.5}$: 47-1611	1.1[1]-17 %	20-48 %
Fernandes et al. 2011	Portugal	Brick open fireplace, wood logs	$PM_{2.5}$: 700 (374-1026)	2-12 %	-
Fernandes et al. 2011	Portugal	Brick open fireplace, briquettes	$PM_{2.5}$: 692	2,98 %	45 %
Fine et al. 2002	USA	Open fireplace, hardwood	$PM_{2.5}$: 183-378	1.2-6.4 %	74.2-84.9 %
Fine et al. 2002	USA	Open fireplace, softwood	$PM_{2.5}$: 89-206	14.2-17.9 %	~100 %
Bølling et al., 2009	-	Open fireplace	$PM_{2.5}$: 160-910		
Kupiainen & Klimont 2004 (IIASA)	-	Open fireplace	-	10 %	50 %

Conventional stoves

The current emission factor level and interval for $PM_{2.5}$ from conventional stoves is 810 (486-1130) g/GJ. The level stated by Nussbaumer et al. (2010) for woodstoves (including advanced woodstoves) is 20- 1000 g/GJ. However, advanced woodstoves is included elsewhere and the PM emission factor interval will not be revised.

The BC fraction 10 % of $PM_{2.5}$ that is an average of the listed references will be applied. Some of the BC fractions are however based on TSP. The average OC fraction is 45 %[2].

List of BC references for conventional stoves.

Reference	Country	Plant	PM [g/GJ]	EC or BC	OC
Alves et al. 2011	Portugal	Cast iron woodstove, split logs	$PM_{2.5}$: 557 (344-906)	1.9 - 7.7 %	45.6 - 53.6 %
Alves et al. 2011	Portugal	Cast iron woodstove, briquettes	233	3,9 %	47.1 %
Goncalves et al. 2011	Portugal	Cast iron woodstove, wood logs and briquetts	$PM_{2.5}$: 92 - 1433	0.82 - 9.3 %	30- 50 %
Fernandes et al. 2011	Portugal	Cast iron woodstove, wood logs	$PM_{2.5}$: 447 (278-617)	3-12 %	-
Fernandes et al. 2011	Portugal	Cast iron woodstove, briquettes	$PM_{2.5}$: 396	3.62 %	40.27 %
Bølling et al. 2009	-	Conventional wood stoves	50-2100	-[3]	-
US EPA (SPECIATE), 2002 (IIASA)		Stoves, woodlogs, hardwood	-	14 % of TSP	42 % of TSP
US EPA (SPECIATE), 2002 (IIASA)		Stoves, woodlogs, softwood	-	20 % of TSP	39 % of TSP
Rau, 1989 (IIASA)		Stoves, woodlogs, hardwood	-	5-16 % of TSP	14-57 % of TSP
Rau, 1989 (IIASA)		Stoves, woodlogs, softwood	-	5-38 % of TSP	20-51 % of TSP

Conventinal boilers < 50 kW

The current emission factor level and interval for $PM_{2.5}$ from conventional boilers is 475 (450-1130) g/GJ. The level stated by Nussbaumer et al. (2010) for log wood boilers (with/without heat storage tank) is 20- >1000 g/GJ. However, advanced or ecolabelled boilers are included elsewhere and the PM emission factors will not be changed.

[1] Briquettes
[2] Not including Fine et al. (2002)
[3] EC data only related to TC

BC emission factors have been reported by Kupiainen & Klimont (2007). Based on the default $PM_{2.5}$ emission factor 475 g/GJ the BC fraction 16 % have been estimated.

List of BC references for conventional boilers.

Reference	Country	Plant	PM [g/GJ]	EC or BC	OC
Bølling et al. 2009	-	Conventional wood boilers and masonry heaters	$PM_{2.5}$: 50-2000	10 %-35 % of TC	
Kupiainen & Klimont 2007	-	Boilers < 50 kWth	-	75 mg/MJ[1)]	
Johansson et al. 2004		Old-type boilers	TSP: 87-2200 g/GJ	-	

1) Corresponding to 16 % of the default emission factor 475 g/GJ

Energy efficient stoves

The plant category is new. The same BC fraction as for conventional boilers will be applied.

Advanced/ecolabelled stoves and boilers

The current emission factor level and interval for $PM_{2.5}$ from conventional stoves is 220 (72-230) g/GJ. The $PM_{2.5}$ emission factor level 220 g/GJ refers to the Nordic Swan label. The achievable PM emission level stated by Nussbaumer et al. (2010) for log wood boilers/stoves is 10-25 g/GJ. The emission factor interval will be changed to 10-230 g/GJ.

The limit values for the German Blue Angel label corresponds to ~ 13 g/GJ *at nominal heat output*. The Austrian environmental label for hand fed stoves requires less than 30 g/GJ, also at nominal heat output.

The category includes the chimney type stove.

The BC fraction 28 % of $PM_{2.5}$ that is an average of the listed references will be applied. The average OC fraction is 31 %.

List of BC references for advanced / ecolabelled stoves and boilers.

Reference	Country	Plant	PM [g/GJ]	EC or BC	OC
Goncalves et al. 2010	Portugal	Chimney type (tiled stove)	PM_{10}: 62-161	11.3-37.1 %	19.7-42.8 %
Fernandes et al. 2011	Portugal	Chimney type (tiled stove)	PM_{10}: 101 (50-152)	11-37 %	
Schmidl et al. 2011	Austria	Chimney type (tiled stove) 6.5 kW	PM_{10}: 54-78	24.2-38.7 %	26.8-38.8 %
Schmidl et al. 2011	Austria	Advanced tiled stove 6kW	PM_{10}: 58-66	29.8-37.6 %	22.2-35.6 %

Pellet stoves and boilers

The current emission factor level for $PM_{2.5}$ from pellet stoves is 65-240 g/GJ. This level is above the level stated by Nussbaumer et al. (2010) and the $PM_{2.5}$ emission factors will be revised to 10-50 g/GJ.

The BC fraction 15 % of PM_{10} referring to Schmidl et al. (2011) will be applied. The average OC fraction is 13 %.

List of BC references for pellet stoves and boilers.

Reference	Country	Plant	PM	EC or BC	OC
Schmidl et al. 2011	Austria	Automatically fed pellet stove, 6 kW	PM_{10}: 2-7 g/GJ	13.7-15.87 %	4.7-5.3 %, 22 % in the start-up phase
Schmidl et al. 2011	Austria	Automatically fed boiler 40 kW moving grate	PM_{10}: 6-26 g/GJ	0.2-45.2 %	2-38.2 %

Bølling et al. 2009	?	Pellet stoves and boilers	$PM_{2.5}$: 10-50 g/GJ	6 %	-
Verma et al., 2011	Belgium	Five different pellet boilers (15-35 kW)	1-11 g/GJ[4]	0-38.8 %	-
Sippula et al., 2007	Finland	Pellet boiler	PM_1: 58 g/GJ	1.5 %	6.6 %

Overview of BC emission factors for residential wood combustion

The list below gives an overview of the BC fractions for residential wood combustion and the resulting BC emission factor if the default emission factor for $PM_{2.5}$ is applied. The resulting BC emission factors are compared to the emission factor intervals from Kupiainen & Klimont (2007).

List of EF tables for residential plants in the GB chapter on small combustion.

	Tier	Fuel	Sector	New technology name	$PM_{2.5}$	BC fraction	BC [g/GJ]	Kupiainen & Klimont 2007
Table 3-6	1	Biomass	Residential	-	810[5]	10%	81	0.83-105
Table 3-14	2	Wood	Residential	Open fireplaces	850	7%	60	75-100
Table 3-17	2	Wood	Residential	Conventional stoves	810	10%	81	75-105
Table 3-18	2	Wood	Residential	Conventional boilers < 50 kW	475	16 %	76[6]	75
Table 3-24	2	Wood	Residential	Energy efficient stoves	?	16 %	-	56-79
Table 3-25	2	Wood	Residential	Advanced/ecolabelled stoves and boilers	220	28%	62	56-79
Table 3-26	2	Wood	Residential	Pellet stoves and boilers	45	15%	7	0.83

An overview of BC and OC fractions is shown below. In general, the BC fraction increases with improved combustion technology. However, the fraction for pellet stoves and boilers is lower than for advanced / ecolabelled stoves and boilers. The OC fraction decreased with improved combustion technology.

List of BC and OC fractions for residential wood combustion.

	Tier	Fuel	Sector	New technology name	$PM_{2.5}$	BC fraction	OC fraction
Table 3-6	1	Biomass	Residential	-	810	10%	-
Table 3-14	2	Wood	Residential	Open fireplaces	850	7%	43%
Table 3-17	2	Wood	Residential	Conventional stoves	810	10%	45%
Table 3-18	2	Wood	Residential	Conventional boilers < 50 kW	475	16 %	-
Table 3-24	2	Wood	Residential	Energy efficient stoves	?[7]	16 %	-
Table 3-25	2	Wood	Residential	Advanced/ecolabelled stoves and boilers	220	28%	31%
Table 3-26	2	Wood	Residential	Pellet stoves and boilers	45	15%	13%

Solid fuel combustion

There are five EF tables in the current GB for solid fuels in residential plants. One of the EF tables is for tier 1, while the remaining four tables is tier 2 EF tables for fireplaces, stoves, small boilers and advanced stoves.

	Tier	Fuel	Sector	Technology

[4] Not diluted
[5] Not estimated yet. Assumed that the emission factor for conventional stoves will be applied.
[6] Refers to Kupiainen & Klimont (2007)
[7] Not estimated yet

Table 3-3	1	Coal	Residential	
Table 3-12	2	Solid fuels	Residential	Fireplaces
Table 3-15	2	Solid fuels	Residential	Stoves
Table 3-16	2	Solid fuels	Residential	Boilers < 50 kW
Table 3-23	2	Coal	Residential	Advanced stoves

Some data are available for BC emission shares from small scale coal combustion. However, it has not been possible to find specific data for all technologies. Most data are available for stoves, with no data being available for advanced stoves and small boilers (< 50 kW).

Engelbrecht et al. (2002) reports source profiles for residential coal combustion in South Africa. Engelbrecht et al. (2002) presents data for stoves and braziers (assumed comparable to fireplaces) for bituminous coal and for low smoke fuels. The data reported are shown in the table below.

	Stove	Fireplace	Stove	Stove
% of $PM_{2.5}$	Bituminous coal	Bituminous coal	Low-smoke coal	Low-smoke coal
EC	9.5167	9.839	18.9857	6.8002
OC	70.8	78.268	56.3225	73.6005

Very similar results are obtained for stoves and fireplaces combusting bituminous coal. The EC shares of $PM_{2.5}$ for the low-smoke coal are differing slightly more, but are still comparable to the data for bituminous coal.

Pinto et al. (1998) reports EC and OC shares of $PM_{2.5}$ from residential combustion of lignite in hand-fired stoves. The analysis was done for particles collected during the smouldering phase as well as during the active phase. The data are included in the table below.

% of $PM_{2.5}$	Residential coal combustion, smouldering	Residential coal combustion, active
EC	6.2	10
OC	68	62

Watson et al. (2001) presents data for a composite of two stoves and two fireplaces. The reported EC share of $PM_{2.5}$ is 26.08 % and the OC share is reported as 69.49 %. The four datasets are not included in the original reference but is included in the SPECIATE database. The four single datasets are shown in the table below.

% of $PM_{2.5}$	EC	OC
Stove burning coal from Trapper Mine.	6.7953	65.4335
Stove burning coal from Trapper Mine.	33.2055	45.4365
Fireplace and stove burning coal from Seneca Mine.	21.2664	75.9568
Fireplace and stove burning coal from Seneca Mine.	43.0381	91.1323

Bond et al. (2004) reports EC fractions of 0.5 to 0.6 for residential coal combustion in stoves based on unpublished data. It has not been possible to find any later publication where these measurement data have been described in more detail.

Zhang et al. (2012) reports EC and OC shares of $PM_{2.5}$ based on five measurements in China. The EC share is reported as 6.4 % ± 2.3 %-point. The OC share is reported as 48.7 % ± 19.1 %-point.

In the table below is a summary of the available data concerning EC.

Technology	Engelbrecht et al., 2002	Engelbrecht et al., 2002	Pinto et al., 1998	Watson et al., 2001	Bond et al., 2004	Zhang et al., 2012
	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$	% of $PM_{2.5}$		% of $PM_{2.5}$
Fireplaces	9.839					
Stoves	9.5167	18.9857; 6.8002	2; 6.2	26.08	50	6.4

The data reported by Watson et al. (2001) and Bond et al. (2004) seem like outliers compared to the remaining datasets. One of the measurements by Watson et al. (2004) (6.8 %) was close to the other data sources but the remaining three data points differed significantly. The data for low-smoke fuels from Engelbrecht et al. (2002), the data by Pinto et al. (1998) and the data from Zhang et al. (2012) is thought to be the best data set for stoves. The value for low-smoke fuel (AFC) reported by Engelbrect et al. (2002) of 6.8 % is in close agreement with the percentage of 6.4 reported by Zhang et al. (2012). Pinto et al. (1998) reports a share of 6.2 % for the smoldering phase and only 2 % for the active phase. Considering these datasets and noting that the other available data are higher, it is recommended that data from Zhang et al., (2012) are used as BC share for coal stoves. For fireplaces the share reported by Engelbrecht et al. (2002) is the only source and is therefore included. No information has been found in the literature neither for advanced coal stoves nor for small coal boilers. Since there is no information available to suggest that the composition of particles for these technologies are different than for coal stoves, it is recommended to use Zhang et al. (1998) as the reference for the BC EF.

	Tier	Fuel	Sector	Technology	BC share of $PM_{2.5}$	Reference
Table 3-3	1	Coal	Residential		6.4	Zhang et al., 2012
Table 3-12	2	Solid fuels	Residential	Fireplaces	9.839	Engelbrecht et al., 2002
Table 3-15	2	Solid fuels	Residential	Stoves	6.4	Zhang et al., 2012
Table 3-16	2	Solid fuels	Residential	Boilers < 50 kW	6.4	Zhang et al., 2012
Table 3-23	2	Coal	Residential	Advanced stoves	6.4	Zhang et al., 2012

Other fuel combustion

The current guidebook includes seven tables for residential combustion of gaseous and liquid fuels. Two of the tables cover Tier 1 for natural gas and liquid fuels, respectively. The three tier 2 tables for gaseous fuels cover fireplaces, stoves and boiler, while the two tables for liquid fuels cover stoves and boilers. **It is proposed to change the technology for table 3-13 from fireplaces to cooking appliances**, as the use of gaseous fuels in fireplaces to be of limited relevance.

A literature study has been carried out and a short description of the most important references is given in the following;

Hildemann et al, 1991: Presents EFs for natural gas combustion in home appliances based on measurements of emissions from a residential natural gas fired space heater and a water heater;

EC = 6.7 % of $PM_{2.5}$
OC = 84.9 % of $PM_{2.5}$

Muhlbaier, 1981: Present EFs for residential gas fired appliances, based on measurements for three furnaces and one hot water heater;

EC = 4 % of $PM_{2.5}$
OC = 8 % of $PM_{2.5}$

Reff et al, 2009: In order to make an inventory of $PM_{2.5}$ trace elements in the United States, Reff et al has set up a list of 84 source categories based on CSSs from NEI and profiles from SPECIATE. SPECIATE profile #92156 gives Reff et al as reference, and according to the notes in SPECIATE the EFs are based on the EFs given in Hildemann et al. Reff et al (supp. Info.) has scaled OC down as the sum of species > 100 % of $PM_{2.5}$ in the original reference because Hildemann et al did not correct for artifacts. The following EFs are presented in the article for residential natural gas combustion;

EC = 6.7 % of $PM_{2.5}$
OC = 84.9 % of $PM_{2.5}$

Bond et al, 2004: together with a global BC inventory EFs for BC and OC applicable for small combustion appliances are presented;

	Kerosene, residential	LPG*, residential	Natural gas, All	Heavy fuel oil, All
Ratio to	PM_1	PM_1	PM_1	PM_1
BC, %	13	13	6	8
OC, %	10	10	50	3

*Bond et al assumes the same EFs as for kerosene

A summary of EC and OC emission factors from the reviewed literature is given in the table below.

Reference	**Hildemann et al., 1991**	**Muhlbaier, 1981**	**Battye and Boyer**	**Reff et al., 2009**	**Bond et al, 2004**	**Bond et al, 2004**	**SPECIATE 4.3**
Source	residential	residential	residential	Residential	Residential	Residential	Residential
Technology		Furnaces and water heater					oil boiler
Fuel	natural gas	Natural gas	natural gas	natural gas	LPG	Kerosene	distillate oil
Ratio to	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	**PM_1*****	**PM_1*****	$PM_{2.5}$
BC, %	6.7	4	6.7	6.7	**13**	**13**	3.898
OC, %	84.9*	8		49.0**	**10**	**10**	1.765
Note			high estimate = 15				EFs not found in the reference (Hays et al, 2008)

*Also refered in Chow et al., 2011
**Down-scaled values from Hildemann et al
*** Bond et al, 2004 reference mention that PM_1 make up 100 % of TSP

Hildemann et al, 1991, Reff et al. 2009 and Muhlbaier, 1981 are assumed to be the best sources for BC and OC EFs for residential appliances. The remaining references seem to use the EFs by Hildemann et al. An

average of the EFs from Hildemann et al and Muhlbaier are **proposed for residential natural gas combustion** (for OC an average of Muhlbaier and Reff et al are proposed as the EF_{OC} in Reff et al are a scaled value based on Hildemann et al.).

The most appropriate reference to emission factors for LPG and kerosene combustion in residential stoves are Bond et al, 2004. For liquid fuel combustion in residential boilers only one emission factor has been observed, and the EF has not been found in the original reference (Hays et al, 2008) but only in SPECIATE 4.3. Still, this EF is proposed for application in the guidebook.

The following table resumes the proposed EFs for the guidebook:

	Tier	Fuel	Sector	Technology	BC	OC	Reference
Table 3-4	1	Natural gas	Residential		5.35	28.5	Hildemann et al, 1991; Muhlbaier, 1981
Table 3-5	1	Other liquid fuels	Residential		3.898	1.765	SPECIATE 4.3
Table 3-13	2	Gaseous fuels	Residential	Fireplaces	5.35	28.5	Hildemann et al, 1991; Muhlbaier, 1981
Table 3-19	2	Natural gas	Residential	Stoves	5.35	28.5	Hildemann et al, 1991; Muhlbaier, 1981
Table 3-20	2	Natural gas	Residential	Boilers < 50 kW	5.35	28.5	Hildemann et al, 1991; Muhlbaier, 1981
Table 3-21	2	Liquid fuels	Residential	Stoves	13	10	Bond et al, 2004
Table 3-22	2	Liquid fuels	Residential	Boilers < 50 kW	3.898	1.765	SPECIATE 4.3

Other small combustion plants

Other small combustion plants refer to plants typically in the commercial/institutional sector but the EFs are generally applicable to plants smaller than 50 MW. The chapter contains tier 1 EFs for the main fuel groups and tier 2 EFs for different technologies for coal, wood, natural gas and oil. The list of current EF tables is presented in the table below.

List of EF tables for non-residential combustion in the GB chapter on small combustion.

	Tier	Fuel	Sector	Technology
Table 3-7	1	Coal	Non-residential	
Table 3-8	1	Gaseous fuels	Non-residential	
Table 3-9	1	Liquid fuels	Non-residential	
Table 3-10	1	Biomass	Non-residential	
Table 3-27	2	Coal	Non-residential	Boilers 50 kW to 1 MW
Table 3-28	2	Coal	Non-residential	Boilers 1-50 MW
Table 3-29	2	Coal	Non-residential	Manual boilers < 1 MW
Table 3-30	2	Coal	Non-residential	Automatic boilers < 1MW
Table 3-31	2	Wood	Non-residential	Manual boilers < 1 MW
Table 3-32	2	Wood	Non-residential	Automatic boilers < 1MW
Table 3-33	2	Natural gas	Non-residential	Boiler 50 kW to 1 MW
Table 3-34	2	Natural gas	Non-residential	Boiler 50 kW to 1 MW
Table 3-35	2	Natural gas	Non-residential	Gas turbines
Table 3-36	2	Gas oil	Non-residential	Gas turbines
Table 3-37	2	Gaseous fuels	Non-residential	Gas engines

Table 3-38	2	Gas oil	Non-residential	Gas engines

Biomass combustion

Three emission factor tables are relevant for biomass combustion in non-residential plants.

The $PM_{2.5}$ emission factor for non-residential combustion of biomass is 149 g/GJ (50-240 g/GJ). The BC fraction for advanced/ecolabelled boilers will be applied.

The $PM_{2.5}$ emission factor for non-residential manual boilers combusting wood is 76 g/GJ (65-240 g/GJ). For automatic boilers the emission factor is 66 g/GJ (50-240 g/GJ). For both plant categories the BC fraction for pellet stoves and boilers will be applied.

	Tier	Fuel	Sector	Technology	$PM_{2.5}$ [g/GJ]	BC fraction	BC [g/GJ]	Kupiainen & Klimont (2007)
Table 3-10	1	Biomass	Non-residential		149	28 %	42	-
Table 3-31	2	Wood	Non-residential	Manual boilers < 1 MW	76	15 %	11	35
Table 3-32	2	Wood	Non-residential	Automatic boilers < 1MW	66	15 %	10	-

Solid fuel combustion

There are five EF tables in the current GB for solid fuels in small-scale non-residential plants. One of the EF tables is for tier 1, while the remaining four tables is tier 2 EF tables for boilers.

	Tier	Fuel	Sector	Technology
Table 3-7	1	Coal	Non-residential	
Table 3-27	2	Coal	Non-residential	Boilers 50 kW to 1 MW
Table 3-28	2	Coal	Non-residential	Boilers 1-50 MW
Table 3-29	2	Coal	Non-residential	Manual boilers < 1 MW
Table 3-30	2	Coal	Non-residential	Automatic boilers < 1MW

It is not clear from the current GB, what is the distinction between EF table 3-27 and either table 3-29 or 3-30. Table 3-27 should presumably be the same as either 3-29 or 3-30.

It has not been possible to find in the literature detailed EC (or BC) measurements on this level of detail regarding the combustion technology. Therefore, the proposal is to use the same BC share for small boilers (< 1 MW) as the one for domestic boilers, while medium sized boilers are proposed to have the same share as large boilers (see discussion paper on BC for 1A1).

Other fuel combustion

The current guidebook includes eight tables for non-residential combustion of gaseous and liquid fuels. Two of the tables cover Tier 1 for gaseous fuels and liquid fuels, respectively. The tier 2 tables cover natural gas combustion in boilers 50kW-1MW and 1MW-50MW, natural gas and liquid fuel combustion in turbines and in engines.

A literature study has been carried out and a short description of the most important references is given in the following text;

Mugica et al, 2008: Include emission factors for a smaller industrial LP gas steam boiler (1 m^3 capacity);

EC = 5.353 % of $PM_{2.5}$ (± 0.35)
OC = 71.32 % of $PM_{2.5}$ (± 5.04)

England et al, 2007: Present data from eight gas-fired units, here among a dual-fuel institutional boiler and a diesel powered electricity generator. The profile presented by England et al for gas-fired boilers include EFs for BC and OC;

BC = 13 %
OC = 61 %

Bond et al, 2004: together with a global BC inventory EFs for BC and OC applicable for small combustion appliances are presented;

	Kerosene, residential	LPG*, residential	Natural gas, All	Heavy fuel oil, All
Ratio to	PM_1	PM_1	PM_1	PM_1
BC, %	13	13	6	8
OC, %	10	10	50	3

*Bond et al assumes the same EFs as for kerosene

Mazzera et al, 2001: Measurements from McMurdo station, Antarctica, for e.g. diesel-fueled heating appliances for space heating are used as basis for the presented EFs for EC and OC;

	Diesel, non-residential	Diesel, non-residential Recalculated*
Ratio to	PM_{10}	$PM_{2.5}$
BC, %	4.4916; 7.3929	5.85; 9.63
OC, %	54.3207; 72.0403	70.78; 93.87

*recalculated according to the current size distribution for PM in the guidebook (TSP = 27.5 g/GJ, PM_{10} = 21.5 g/GJ, $PM_{2.5}$ = 16.5 g/GJ)

Battye et al, 2002: It is not clear which sources the EFs are based on, but they are included here as they refer to combustion in commercial appliances;

	Petroleum, commercial	Natural gas commercial
Ratio to	$PM_{2.5}$	$PM_{2.5}$
BC, %	7.4	6.7

Cooper et al, 1987: Presents a number of PM species profiles for combustion. The profile for oil boiler, Cubatao, T<15 are assumed applicable for small non-residential appliances;

BC = 8.69 % of $PM_{2.5}$

OC = 8.96 % of $PM_{2.5}$

A summary of EC and OC emission factors from the reviewed literature is given in the tables below.

Gaseous fuels

Reference	**Battye and Boyer**	**Bond et al, 2004**	**England et al, 2007**
Source	commersial	All	All
Technology			Boiler
Fuel	natural gas	natural gas	Gaseous fuels
Ratio to	$PM_{2.5}$	PM_1*	PM_{10}
BC, %	6.7	6	13
OC, %		50	61
Note	high estimate = 15		

* Bond et al, 2004 reference mention that PM_1 make up 100 % of TSP

Liquid fuels

Reference	**SPECIATE 4.3**	**Battye and Boyer**	**Mugica et al, 2008**	**Cooper et al, 1987**	**Bond et al, 2004**	**Mazzera et al, 2001**
Source	Commercial and institutional	Commercial			All	Non-residenti
Technology	boilers		boiler	boiler		(Air heating)
Fuel	residual oil	petroleum	LPG	Oil	Heavy fuel oil	Diesel
Ratio to	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_1*	$PM_{2.5}$**
BC, %	2.42	7.4	5.353	8.69	8	5.85**
OC, %	7.8		71.32	8.96	3	70.78**
Note	Average of 8 samples from schools, hospitals, apartments, and industrial boilers EFs not found in the reference (Watson, 1979)	high estimate = 13	Smaller industrial boiler	included in SPECIATE (13504*)	From SPECIATE 3.1	

* Bond et al, 2004 reference mention that PM_1 make up 100 % of TSP

** Recalculated shares according to the current size distribution in the guidebook

The guidebook only includes Tier 1 emission factors for liquid fuel combustion in small appliances. None of the seven BC emission factors stand out as more applicable than the others. Therefore it is proposed to

apply the average of the seven EF values to the guidebook. The OC emission factors show more variation than the BC emissions factors and further investigation might be useful to find the most appropriate emission factor. Here the average of the six EFs is given with the corresponding BC EF.

The following EFs are proposed for combustion of liquid and gaseous fuels in small appliances. For combustion in non-residential turbines and engines it is proposed to apply the EFs proposed for turbines and engines in sector 1A1:

	Tier	Fuel	Sector	Technology	BC	OC	Reference
Table 3-8	1	Gaseous fuels	Non-residential		5.35	28.5	Hildemann et al, 1991; Muhlbaier, 1981
Table 3-9	1	Liquid fuels	Non-residential		6	36	See text
Table 3-33	2	Natural gas	Non-residential	Boiler 50 kW to 1 MW	5.35	28.5	Hildemann et al, 1991; Muhlbaier, 1981
Table 3-34	2	Natural gas	Non-residential	Boiler 1 MW to 50 MW	5.35	28.5	Hildemann et al, 1991; Muhlbaier, 1981
Table 3-35	2	Natural gas	Non-residential	Gas turbines			*
Table 3-36	2	Gas oil	Non-residential	Gas turbines			*
Table 3-37	2	Gaseous fuels	Non-residential	Gas engines			*
Table 3-38	2	Gas oil	Non-residential	Gas engines			*

References

Battye, W., Boyer, K. & Pace, T.G., 2002: Methods for improving global inventories of black carbon and organic carbon particulates. Change 2002

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J-H & Klimont, Z., 2004: A Technology-based Global Inventory of Black and Organic Carbon Emissions from Combustion. Journal of Geophysical Research 109, D14203, doi:10.1029/2003JD003697

Chow, J.C., Watson, J.G., Kuhns, H.D., Etyemezian, V., Lowenthal, D.H., Crow, D.J., Kohl, S.D., Engelbrecht, J.P. & Green, M.C., 2004: Source profiles for industrial, mobile, and area sources in the Big Bend Regional Aerosol Visibility and Observational (BRAVO) Study. Chemosphere 54 (2), 185-208.

Cooper, J.A., Redline, D.C., Sherman, J.R., Valdovinos, L.M., Pollard, W.L., Scavone, L.C. & Badgett-West, C., 1987: PM10 Source Composition Library for the South Coast Air Basin, Volume II. Prepared for the South Coast Air Quality Management District, El Monte, CA.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T., 2002: The comparison of source contributions from residential coal and low-smoke fuels, using CMB modeling, in South Africa. Environmental Science and Policy 5 (2), 157–167.

England, G.C., Watson, J.G., Chow, J.C., Zielinska, B., Chang, M.-C.O., Loos, K.R. & Hidy, G.M., 2007: Dilution-based emissions sampling from stationary sources: Part 2. Gas-fired combustors compared with other fuel-fired systems. Journal of the Air & Waste Management Association 57 (1), 79-93.

Hildemann, L.M., Markowski, G.R. & Cass, G.R., 1991: Chemical Composition of Emissions from Urban Sources of Fine Organic Aerosol. Environmental Science & Technology 25(4), 744-759.

Mazzera, D.M., Lowenthal, D.H., Chow, J.C. & Watson J.G., 2001: Sources of PM_{10} and sulfate aerosol at McMurdo Station, Antarctica. Chemosphere 45 (2001) 347-356.

Mugica, V., Mugica, F.,Torres, M. & Figueroa J., 2008: $PM_{2.5}$ Emission Elemental Composition from Diverse Combustion Sources in the Metropolitan Area of Mexico City. The Scientific World Journal (2008) 8, 275–286.

Muhlbaier, J.L., 1981: Participate and gaseous emissions from natural gas furnaces and water heaters. Journal of the air pollution control association, 31:12, pp. 1268-1273

Pinto, J.P., Stevens, R.K., Willis, R.D., Kellogg, R., Mamane, Y., Novak, J., Šantroch, J., Beneš, I., Leníček, J. & Bureš, V., 1998: Czech Air Quality Monitoring and Receptor Modeling Study. Environmental Science & Technology 32(7), 843-854.

Reff, A., Bhave, P.V., Simon, H., Pace, T.G., Pouliot, G.A., Mobley, J.D. & Houyoux, M., 2009: Emissions inventory of PM2.5 trace elements across the United States. Environ. Sci. Technol., 43, pp. 5790-5796

US EPA, 2011: SPECIATE Version 4.3

Watson, J.G., Chow, J.C. & Houck, J.E., 2001: $PM_{2.5}$ Chemical Source Profiles for Vehicle Exhaust, Vegetative Burning, Geological Material, and Coal Burning in Northwestern Colorado during 1995. Chemosphere 43, 1141-1151.

Zhang, H., Wang, S., Hao, J., Wan, L., Jiang, J., Zhang, M., Mestl, H.E.S., Alnes, L.W.H., Aunan, K. & Mellouki, A.W., 2012: Chemical and size characterization of particles emitted from the burning of coal and wood in rural households in Guizhou, China. Atmospheric Environment 51 (2012) 94-99

Alves, C., Goncalves, C., Fernandes, A.P., Tarelho, L. & Pio, C. (2011): Fireplace and woodstove fine particle emissions from combustion of western Mediterranean wood types. Atmospheric Research Volume: 101 (2011), pages: 692-700.

Bølling, A.K., Pagels, J., Yttri, K.E., Barregard, L., Sallsten, G., Schwarze, P.E. & Boman, C. (2009). Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties. Particle and Fibre Toxicology 2009, 6:29.

Fernandes, A.P., Alves, C.A., Goncalves, C., Tarelho, L., Pio, C., Schmidl, C. & Bauer, H. (2011): Emission facgtors from residential combustion appliances burning Portuguese biomass fuels. Journal of Environmental Monitoring, 2011, 13, 3196.

Fine, P.M., Cass, G.R. & Simoneit, B.R.T. (2002): Chemical Characterization of Fine Particle Emissions from the Fireplace Combustion of Woods Grown in the Southern United States. Environmental Science & Technology, vol. 36, No. 7, 2002.

Goncalves, C., Alves, C., Evtyugina, M., Mirante, F., Pio, C., Caseiro, A., Schmidl, C., Bauer, H. & Carvalho, F. (2010): Characterisation of PM_{10} emissions from woodstove combustion of common woods grown in Portugal. Atmospheric Environment 44 (2010) 4474-4480.

Goncalves, C., Alves, C., Fernandes, A.P., Monteriro, C. Tarelho, L., Evtyugina, M., Pio, C. (2011): Organic compounds in $PM_{2.5}$ emitted from fireplace and woodstove combustion of typical Portuguese wood species. Atmospheric Environment 45 (2011), pages 4533-4545.

Johansson, L.S., Leckner, B., Gustavsson, L., Cooper, D., Tullin, C. & Potter, A. (2004): Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. Atmospheric Environment 38 (2004) 4183-4195.

Kupiainen K. & Klimont Z. (2002): Primary Emissions of Submicron and Carbonaceous Particles in Europe and the Potential for their Control. IIASA Interim Report IR-04-079.

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

Schmidl, C., Luisser, M., Padouvas, E., Lasselberger, L., Rzaca, M., Cruz, C.R.-S., Handler, M., Peng, G., Bauer, H. & Puxbaum, H. (2011): Particulate and gaseous emissions from manually and automatically fired small scale combustion systems. Atmospheric Environment 45 (2011) 7443-7454.

Sippula, O., Kytönen, K., Tissari, J., Raunemaa, T. & Jokiniemi, J. (2007): Effect of Wood Fuel on the Emissions from a Top-Feed Pellet Stove. Energy and Fuels, 2007, 21, 1151-1160.

Verma, V.K., Bram, S., Vandendael, I., Laha, P., Hubin, A. & Ruyck, J.D. (2011): Residential pellet boilers in Belgium: Standard laboratory and real life performance with respect to European standard and quality labels. Applied Energy 88 (2011) 2628-2634.