Task Force on Techno-Economic Issues

PM abatement measures also effective to reduce Black Carbon

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Acknowledgments to Bertrand Bessagnet for the TFTEI report

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Background

- ✓ A technical work carried out in 2020 in the scope of questions addressed by the Gothenburg Protocol Review Group (GPG) to TFTEI on BC and PAH emissions and better know what measures can be implemented to reduce them.
- ✓ A review of latest scientific papers carried out (around 200 papers).
- ✓ Three target sectors identified: small domestic combustion appliances, road transport and gas flaring
- ✓ This technical work is complementary to the draft “guidance document on prioritizing reductions of particulate matter to also achieve reduction of black carbon”, developed by TFIAM

Outline

- ✓ Small scale residential combustion
- ✓ Road transport
- ✓ Gas flaring
- ✓ Key messages

Small scale residential combustion

✓ BC emissions from residential combustion is by far the largest contributor at the global scale.

✓ In EU27+UK, BC from stationary combustion emissions is 3 times higher than BC from the passenger car emissions in 2018.

✓ These emissions are mostly due to biomass burning and particularly wood burning.

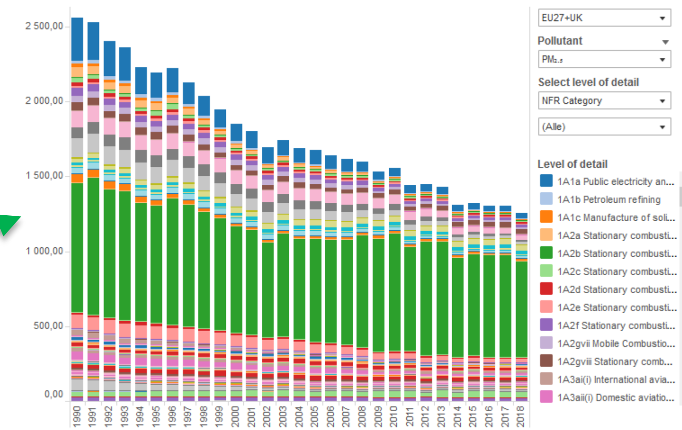
Main target sectors for EU27+UK

✓ 2018, PM2.5

1A4bi Residential: Stationary

5C2 Open burning of waste

1A1a Public electricity and heat production

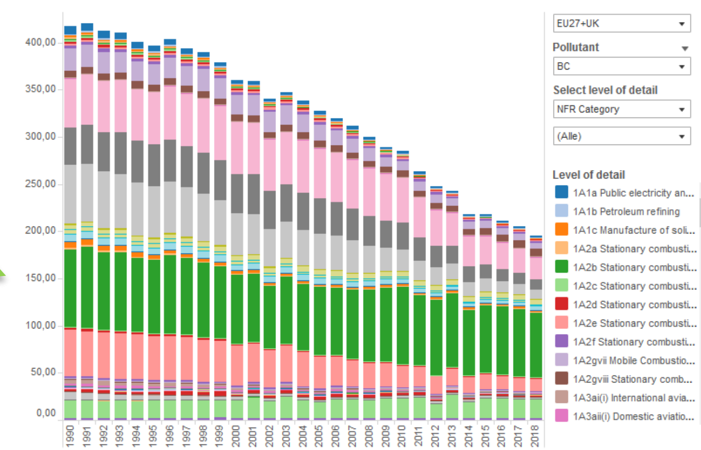


✓ 2018, BC

1A4bi Residential: Stationary

5C2 Open burning of waste

1A4cii Agriculture/Forestry/Fishing: Off-road vehicles and other machinery



https://www.ceip.at/data-viewer

Small scale residential combustion

- ✓ Residential wood burning remains a major source of PM2,5 and BC
- ✓ BC, Condensable Organic Compounds (COC), VOC, CO are products of incomplete combustion
- ✓ Most BC emissions occur during the ignition stage
- ✓ Large range of BC emission factors

- ✓ From the EMEP/EEA guidebook EF:
  - PM2.5 : 740 g/Gj
  - PM10 : 760 g/Gj
  - TSP=800 g/Gj
  - BC as a fraction of PM2.5 (2-20% taken as 10%: 74 g/Gj)
- ✓ BC EF certainly underestimated according to a french study (CARABLACK, Raventos et al., 2018)
- ✓ BC by thermo-optical methods difficult to estimate if OM is high

GAINS Emission factors ranges

Stoves	BC (g/GJ)	BC(%PM)
Traditionnal	32-100	4-22
Improved	30-95	25-55
New	9-30	18-30
Pellet	1.3-4.0	10-17

Klimont et al. (2017)

Small scale residential combustion

The Gothenburg Protocol

1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long range Transboundary Air Pollution, as amended on 4 May 2012 (ECE/EB.AIR/114)

- ✓ *"dust" is supposed to be TSP (ELV expressed under standard conditions)*
- ✓ *Limit values for emissions of particulate matter from stationary sources*
- ✓ *Recommended limit values for dust emissions released from small combustion sources*

Recommended limit values for dust emissions released from new solid fuel combustion installations with a rated thermal input < 500 kWth to be used with product standards

	Dust (mg/m³)
Open/closed fireplaces and stoves using wood	75
Log wood boilers (with heat storage tank)	40
Pellet stoves and boilers	50
Stoves and boilers using other solid fuels than wood	50
Automatic combustion installations	50

Recommended limit values for dust emissions released from boilers and process heaters with a rated thermal input of 100 kWth–1 MWth

		Dust (mg/m³)
Solid fuels 100 kWth–500 kWth	New installations	50
	Existing installations	150
Solid fuels 500 kWth–1 MWth	New installations	50
	Existing installations	150

Small scale residential combustion

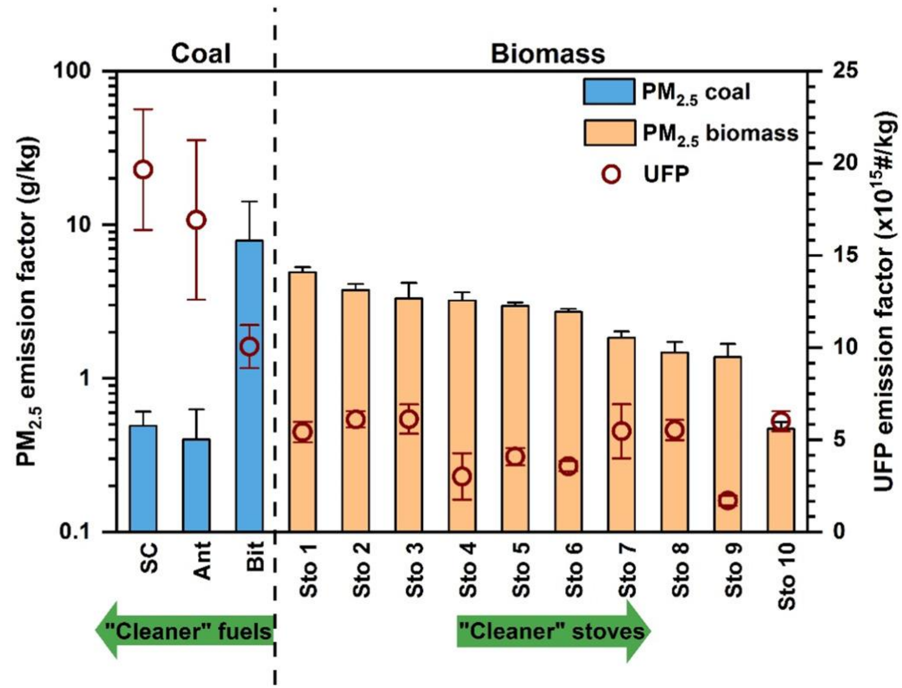
- ✓ PM emitted by biomass burning from small combustion appliances are mainly composed of carbonaceous compounds (Elemental Carbon (EC) and Organic Matter (OM).
- ✓ Most of particles are fine particles with diameter below 2.5 µm.
- ✓ A secondary production of particles is identified during the dilution of the plume and later in ambient conditions.

- ✓ Birch, Spruce and Pine often exhibit the highest emission factors of PM, BC and PAHs. Raw fir is a strong emitter of PAHs.
- ✓ Wood Oak emits the lowest BC.
- ✓ Burning wet wood is not recommended as presented in the Code of good practices for wood burning and small combustion installations (TFTEI, 2019), however some studies showed higher PM1, PAH and BC emissions using very dry wood (11%) compared to wet wood (18%) while the particulate number (PN) is lower for dry wood.

Small scale residential combustion

BC and UFP

- ✓ High emissions of **particle mass** concentration often occur at the beginning of the combustion (i.e. the first **30 min** after fire start) while high emissions of **particle number** concentration occur in a later combustion period (60–150 min).
- ✓ Notable **antagonism** between reducing PM2.5 mass-based emissions and reducing ultrafine particle number-based emissions among various control strategies that were proposed for reducing pollution from residential combustion
  - Competing processes nucleation/absorption/coagulation



Wang et al. (2020)

- ✓ Thermal Energy Storage can help to optimize the heating cycle from the start-up and the shutdown..
- ✓ Correct installation and use of appliances, as well as maintenance and service/inspection of appliances and flue gas pipes are essential to reduce emissions.

Small scale residential combustion

Effect of catalytic combustor

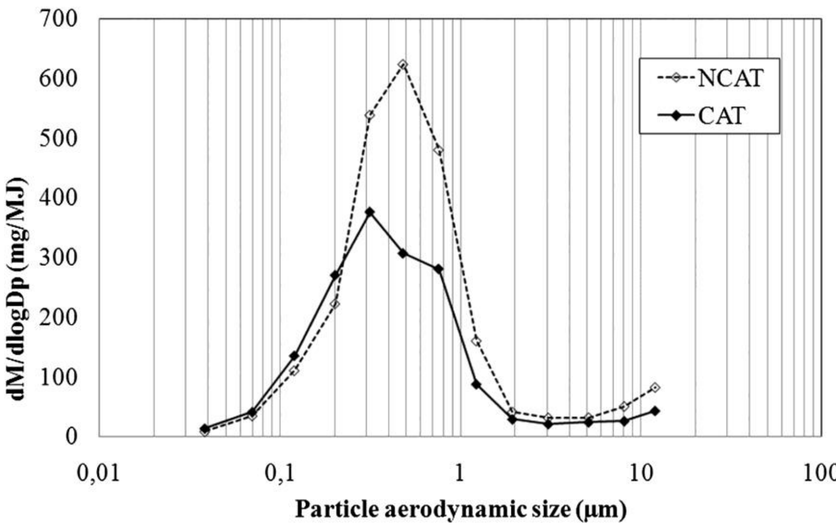
- ✓ Reduction of gaseous and particulate emissions from small-scale wood combustion with a catalytic combustor (Sauna stove in Finland)
- ✓ **PM1** (particle mass below aerodynamic size of 1 μm) was **reduced by 30%** during the whole combustion cycle.
- ✓ During gasification, a **44% reduction of PM1** was achieved but there was no reduction during burn out.
- ✓ The **organic and elemental carbon** analyzed from PM1 had reduced also only during gasification by **56% and 37%,** respectively.

However….

- ✓ The usage of catalytic converters in RWC is controversial.
- ✓ A catalytic converter reduced the adverse products of incomplete combustion such as CO, OGC and **PAHs** on average 26%, 24%, and **24%**, respectively.
- ✓ On the other hand, there is a clear **increase** in the concentrations of **PCDD/Fs** (8.7-fold) when the catalytic converter was used

(Kaivosoja et al., 2018)

Hukkanen et al. (2012)

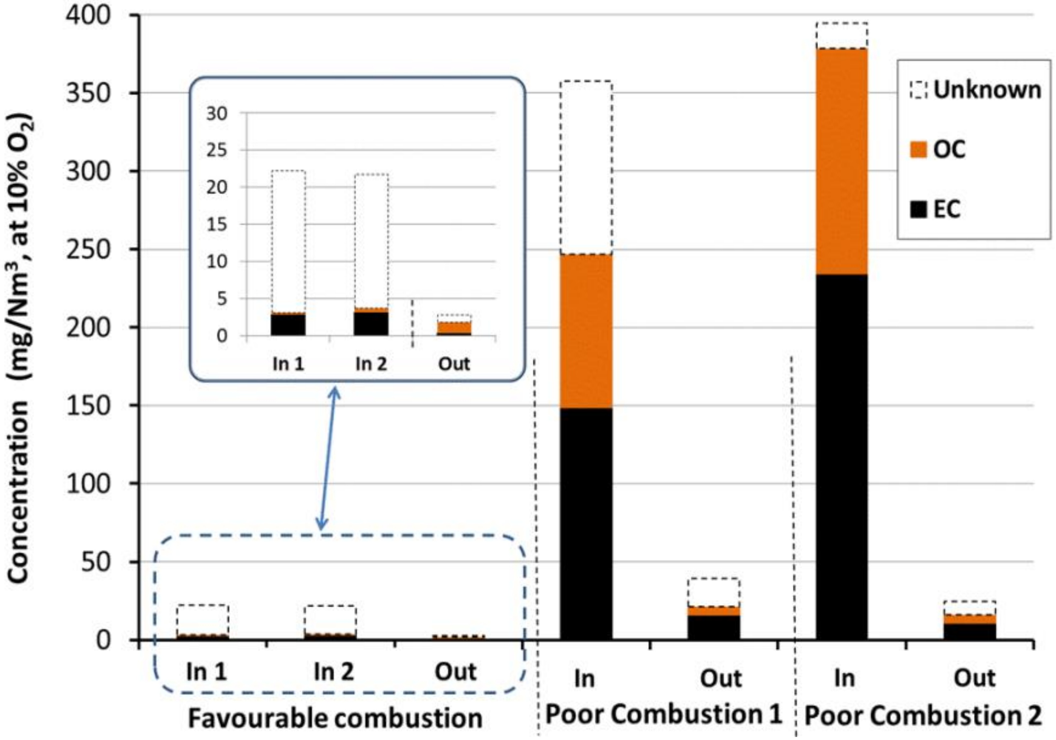


Small scale residential combustion

Electrostatic Precipitator would be a good strategy to reduce particles from existing appliances

Bäfver et al. (2012)

- ✓ Tests on wood Pellet Boiler under favorable and poor combustion
- ✓ Reduction efficiency > 90%
- ✓ Possible formation of condensable organic matter in the ESP in case of Temperature drop
- ✓ Efficiency exceeding more than 99% are commonly obtained in combustion plants, however in practice this technology is not suitable for residence appliances.



Confirmed by industrial combustion processes (Mertens et al., 2020)

Precaution: Under favorable combustion conditions, after the ESP during the cooling of the flue gas, organic matter can appear due to condensable species.

Small scale residential combustion

- ✓ The ban of not eco-labelled wood stove seems the most beneficial in some recent studies.
- ✓ The use of modern stoves implementing advanced methods to limit the emission of pollutants like catalytic combustors, wood pellets and masonry stoves enables to reach the emission standards as defined in the EU by latest eco-design standards.
- ✓ Organic gases are also largely reduced with modern wood stoves which involve a potential positive effect to reduce the secondary organic aerosol (SOA) potential formation.
- ✓ Wood pellet stoves have 2 to 3 times lower PM, EC and PAH emissions than wood logs in advanced wood stoves. However, their efficiency to reduce particle number is not as high as expected.

Small scale residential combustion

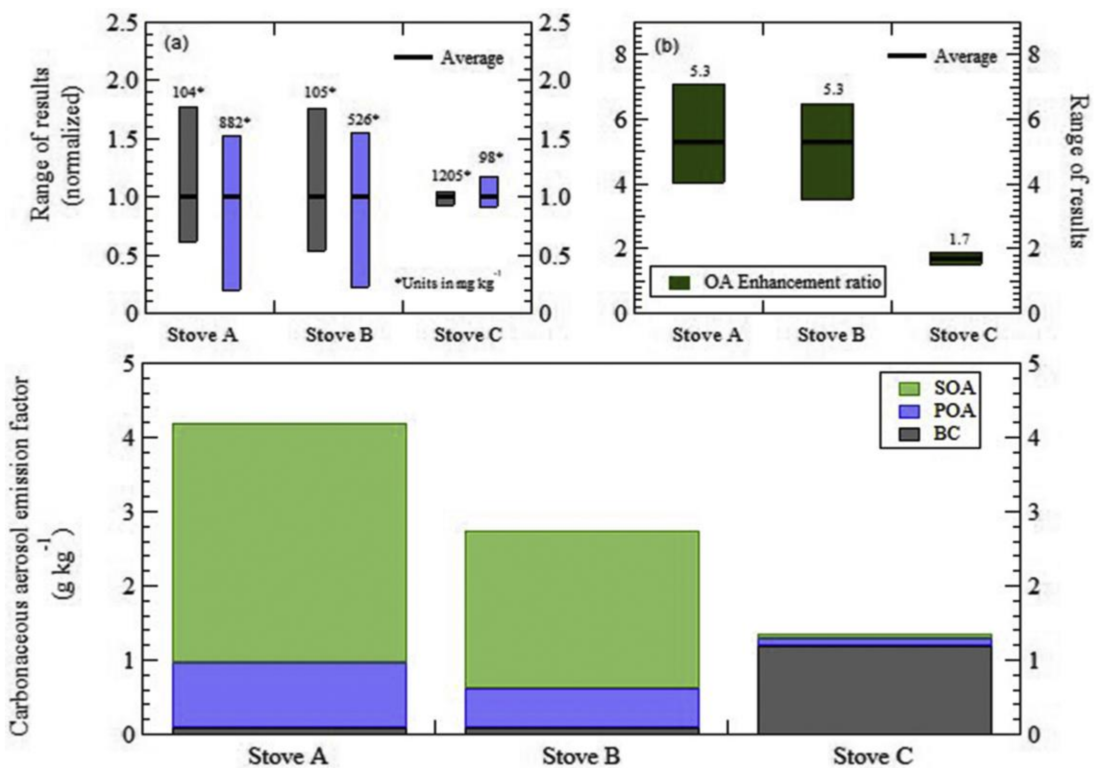
From (TFTEI, 2019), the following list of new technologies were identified and can be recommended.

- ✓ New advanced stoves equipped with improved air control, reflective materials and two combustion chambers;
- ✓ New smart stoves with automated control of air supply and combustion, thermostatic control, Wi-Fi-connected to collect and send combustion data to the manufacturer for better service;
- ✓ New advanced masonry stoves, operating at high efficiencies and low emissions;
- ✓ New advanced pellet boilers: fully automated boilers (electronic control of air supply, lambda sensors), condensing boilers, using standardised pellets;
- ✓ Wood carburettor boilers using log wood or chip wood;
- ✓ Heat accumulating equipment with heat accumulating reducing stop/start frequencies and operation at partial load, which generates higher emissions than operation at full load;
- ✓ Other: flue gas recirculation, reverse combustion, gasifier.

Small scale residential combustion

- ✓ Automatic fuel feeding and improvement of air staging combustion clearly improve the combustion efficiency.
- ✓ Low-cost strategies of retrofit air injection on traditional stoves can reduce PM and BC emissions.
- ✓ High burn rates should be avoided as they are associated to higher pollutant emissions.

Primary and secondary aerosol emission factors of carbonaceous aerosol for three types of stove (averaged over the replicates).



(a) the box encompasses the minimum and maximum values of POA and BC EF normalized to that of the average. The average value is indicated in the bolted line in the middle of the box. The actual value is noted on top.

(b) the box encompasses the minimum and maximum OA enhancement ratio (dark green). Stove A is a wood stove from before 2002, stove B is a wood stove from 2010, and stove C is an automated pellet stove from 2010 (Bertrand et al., 2017)

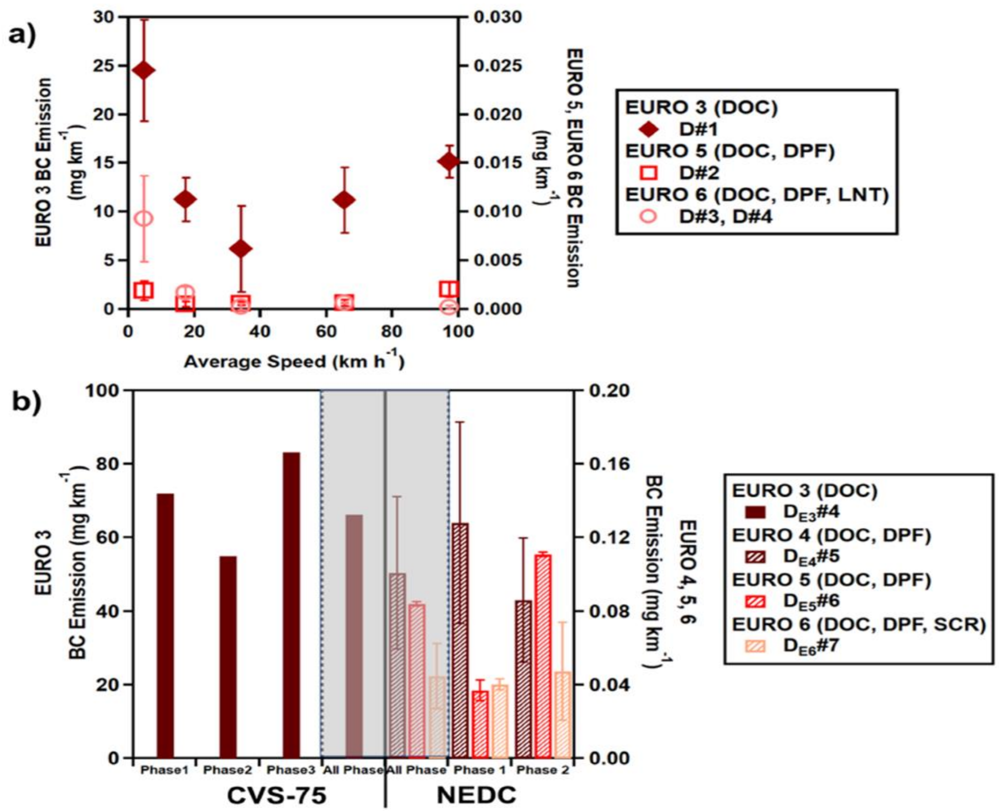
Small scale residential combustion

Going farther:

- ✓ Currently, test procedures for delivering labels are not able to characterise real conditions of use of domestic appliances. New normalised test procedures would be useful to better account for real utilisations of small-scale combustion appliances (starting phases, closing phases).
- ✓ Harmonized methods to determine the emission concentrations of PM and BC would be necessary. For PM, methods accounting for condensables like dilution tunnels are existing.
- ✓ Brown carbon (BrC) represents organic matter which can absorb solar radiation. BrC is mainly co-emitted by biomass burning or produced later during the plume dilution. So far, this species is not very well identified, and there are uncertainties in the radiative properties assigned to this species in climate models

Road transport

- ✓ PM produced by combustion emitted at the exhaust pipe are mostly fine particles below 2.5 µm and are mainly composed of carbonaceous species.
- ✓ PM, BC, PN (particle number), and PAH emissions are effectively reduced using tailpipe aftertreatment systems as Diesel Particulate Matter (DPF) or Gasoline Particulate Matter (GPF). Decreases from 90 to 100% are commonly observed for most particulate pollutants.



(a) Results of BC emission of EURO 3, 5, and 6 on five different NIER modes.

(b) (b) BC Emission from EURO 3 on CVS-75 mode, and EURO 4, 5, and 6 on NEDC mode as presented in (Park et al., 2020)

Road transport

- ✓ Since emission factors of solid particles have decreased by at least 2 orders of magnitude, the counter part is an increase of the part of the OM due to the dilution and cooling effects producing mainly organic condensable species.
- ✓ However, the cooling and dilution effects in the exhaust plumes produce less and less absolute emissions of condensables with the implementation of successive Euro legislations.
- ✓ Aftertreatment systems reduce the intermediate volatility organic compounds (IVOC) emissions but there are still several gaps in the knowledge of these compounds and their chemical transformation after emissions and in ambient conditions
- ✓ With the decrease of PM emissions, gasoline vehicles even recent, can now produce more particles.

Road transport

- The use of GPF for gasoline is a key technology to reduce PN and PM emissions. However, a study has reported larger genotoxic PAH emissions from gasoline vehicles (mainly Gasoline Direct Injection vehicles) even equipped with DPF compared to diesel equipped with DPF (2 orders of magnitude higher).
- Recent research findings show that different after-treatment technologies have an important effect on the level and the chemical composition of the emitted particles, and highlight the importance of the particle filter device conditions and their regular checking to maintain the best performances.
- For non-equipped diesel vehicles, the use of biofuels can reduce BC emissions by 30% and could be an option to achieve sooner the legal air quality thresholds.

Road transport

- ✓ Even if brake, tire and road wear emit mainly coarse particles, a non-negligeable fine fraction of PM is emitted.
- ✓ The TSP emissions per km are larger than current Euro 6/VI emissions and a similar fraction of BC is observed either in exhaust and not-exhaust PM emissions.
- ✓ Brakes also produce ultrafine particles, metals and PAHs, the temperature greatly affect the PM emissions. BC emissions from brakes are very correlated to PM1 emissions.
- ✓ There is no widely used after-treatment system to control brake, tire and road wear emissions. The type of materials, and the behaviour of the driver is often cited as a key to reduce emissions. Some companies have developed brake particles collection system that would reduce by 80% to 90 % respectively the brake mass and number emissions.

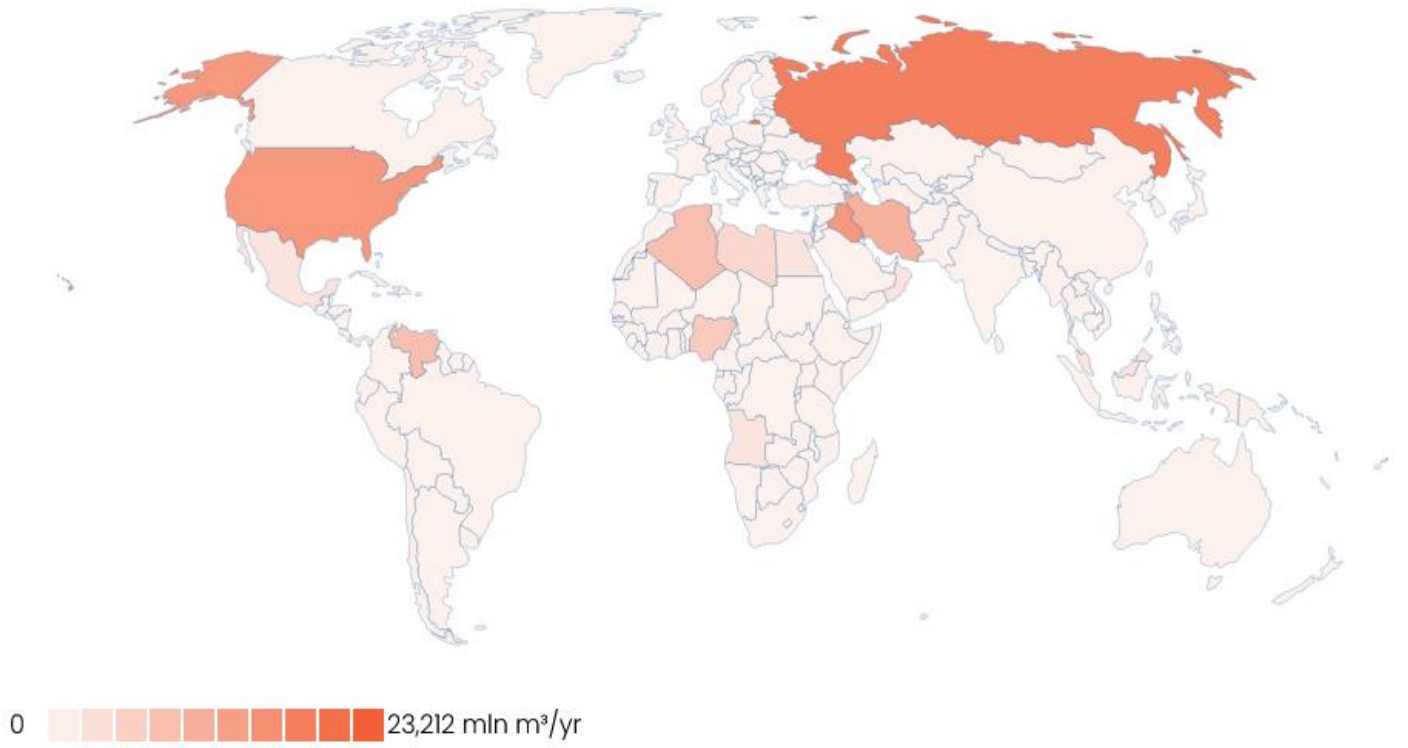
	Tires	Brakes	Road wear
TSP EF (mg km^{-1})	4.6 – 16.9	3.7 – 11.7	6 - 15
Fraction (%)			
TSP	100	100	100
PM10	60	98	50
PM2.5	42	39	27
PM1	6	10	-
PM0.1	4.8	8	-

Emission factors ranges for vehicles from two-whelled to light heavy duty vehicles according to the Tier 2 methodology (Ntziachristos and Boulter, 2019)

- ✓ PM resuspension from the road are also significant. This emission is responsible for a large fraction of total road traffic emissions. It depends on meteorology (wind, temperature, humidity, precipitation) and the site climatology (land use in the vicinity)

Gas Flaring

- ✓ Black carbon emissions from the oil & gas industry by Gas Flares is an important source and particularly in areas surrounding the Artic zone as they affect the radiative budget and enhance snow melting.
- ✓ Russia, USA, Africa and some Middle East countries are among the largest emitting countries.



Upstream Gas Flaring 2019 - million cubic meters for flaring - mln m3 yr-1 (GGFR, 2016)

Gas Flaring

- ✓ Usually, at least 90% of carbonaceous species in the Gas Flare flue gas is made of Black Carbon.
- ✓ Emission factors from GF are uncertain since the combustion conditions can vary and can be not monitored enough. The emission factors (EF) can vary over several order of magnitude generally in the range 0.2 to 2.27 g m^{-3} .
- ✓ Emission inventories deriving from these EF are therefore uncertain and often gap filled or assessed by Satellite observations.
- ✓ Routine flaring from a lack of gas utilisation sources is the most important and largest source of BC emissions from flaring, however, intermittent flaring and continuous flaring for operational reasons can also be significant sources.

Pollutant	Value	Unit	95% confidence interval		Reference
			Lower	Upper	
TSP*	0.89	g GJ^{-1}	0.3	3	(CONCAWE, 2015)
PM10*	0.89	g GJ^{-1}	0.3	3	(CONCAWE, 2015)
PM2.5*	0.89	g GJ^{-1}	0.3	3	(CONCAWE, 2015)
Benzo(a)pyrene*	0.67	µg GJ^{-1}	0.134	3.35	(CONCAWE, 2015)
Benzo(b)fluoranthene*	1.14	µg GJ^{-1}	0.228	5.70	(CONCAWE, 2015)
Benzo(k)fluoranthene*	0.63	µg GJ^{-1}	0.126	3.15	(CONCAWE, 2015)
Indeno(1,2,3-cd)pyrene*	0.63	µg GJ^{-1}	0.126	3.15	(CONCAWE, 2015)
BC as 24% of PM2.5**	0.624	g kg^{-1} throughput	-	-	(McEwen and Johnson, 2012; Villasenor, 2003)

Emission factors for source category "1.B.2.c Venting and Flaring" (Plejdrup et al., 2019).

- Tier2 and
- **Tier1

Gas Flaring

	Steam-assisted	Air-assisted	Pressure-assisted	Non-assisted
Method	Steam is introduced into the combustion zone to enhance mixing.	Air is introduced from a blower to enhance the mixing and turbulence of the fuel gas in the combustion zone	The vent pressure of the gas flow is used to enhance mixing at the tip of the flare burner	No assistance is given to the combustion process
Efficiency	Most efficient in terms of suppressing soot formation. Some of the CO formed can be oxidized to CO_2	Less efficient than the steam assisted flare but relatively efficient that the other two types	Not as efficient as steam and air-assisted but can equally suppress sooting.	Only efficient for non-sooting combustion especially in light hydrocarbons
Benefits	Fuel with high heat value, and hence, high sooting propensity can be disposed of with relatively less soot	Prolongs the life span of the flare tip. Less expensive than steam-assisted and easy to maintain, hence, it is the most commonly used.	Enhance combustion efficiency when the gas flux pressure is sufficiently high enough without the additional cost of steam and air generation	Can be used for occasional emergency flaring of near smokeless gas
Relative size	They are often large flares as they include the steam generator and are usually employed in large gas facilities.	Not as large as the steam assisted.	May be of same size as air-assisted flare depending on the flow capacity of the facility	Often smaller in size compared to the other types
Shortcoming	Over-steaming can result in reduced efficiency of flare. It is also expensive to maintain on a large-scale	Over- aeration can also result in less efficiency. A limit of air assist to gas ratio must be maintained for effectiveness of the flare.	The fluctuation of gas flow pressure has a bearing consequence on the efficiency of the combustion. Requires large space in a remote area.	Cannot be used for dense fuels with high sooting propensity which are typical gas in oil and gas processing facilities

Summary of the properties of flare types by (Fawole et al., 2016)

Gas Flaring

- ✓ Using associated gas for on-site application or export (Power, heat, gas generation) is a natural solution to reduce BC and other flaring emissions by avoiding the flue gas emission.
- ✓ Associated gas utilization virtually eliminates BC emissions, however, flaring and low gas utilization rates are often common during the first years of production in new fields because decisions on gas infrastructure construction are often made only after production starts.
- ✓ Even when it is economically interesting to utilize Associated Petroleum Gas (APG), there will typically be some degree of flaring for safety or other operational reasons.
- ✓ In some cases, no gas recovery solution will be available or considered feasible.
- ✓ Under these conditions, other options to minimize BC emissions exist: extraction of heavy components from the flared gas stream.

Gas Flaring

- ✓ A flare with multiple tips seems a good example showing good performances on BC emission reductions.
- ✓ Steam-assist flares are clearly the most efficient in terms of suppressing soot formation.
- ✓ High pressure-assisted flares can be an efficient technique if water is not available on site.
- ✓ Steams assisted flares show less emission of very small particles (below 50 nm) compared to air steam assisted flares.
- ✓ The optimization of flare design and combustion conditions is an option thanks to the use of Computational Fluid Dynamic (CFD) model.
- ✓ Model and control systems can be used to monitor the flue gas characteristics and control the input data.
- ✓ New models based on Artificial Intelligence techniques can be used to set optimized input parameters to lower emission flaring and therefore reduce BC emissions

✓ Key messages

Measures to reduce PM and BC:

Residential wood combustion:

- The use of advanced or eco-labelled stoves and boilers
- The quality and the type of wood is also important and dry wood is usually recommended

Precaution: The decrease of available mass for condensation and lower temperature can increase nucleation processes and then increase the number of particles.

Road transport:

- More stringent regulations applied to vehicles at the exhaust pipe
- The choice of pad material is the main technical way to decrease brake emissions

Gas Flare:

- Steam assist Flares are clearly the most efficient in terms soot emission reductions
- High pressure-assisted Flares can be an efficient technique if water is not available on site
- New model based on neural networks could help to better assist the Flaring operations to better control soot formation

Going farther: the emission of Brown Carbon (BrCa) is light-absorbing

particulate matter mainly co-emitted by biomass burning or produced later during the plume dilution

Thank you very much for your attention! Questions?

TFTEI Technical Secretariat

https://unece.org/environment/documents/2020/12/informal-documents/Review on BC and PAH emission reductions

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MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE
Liberté
Égalité
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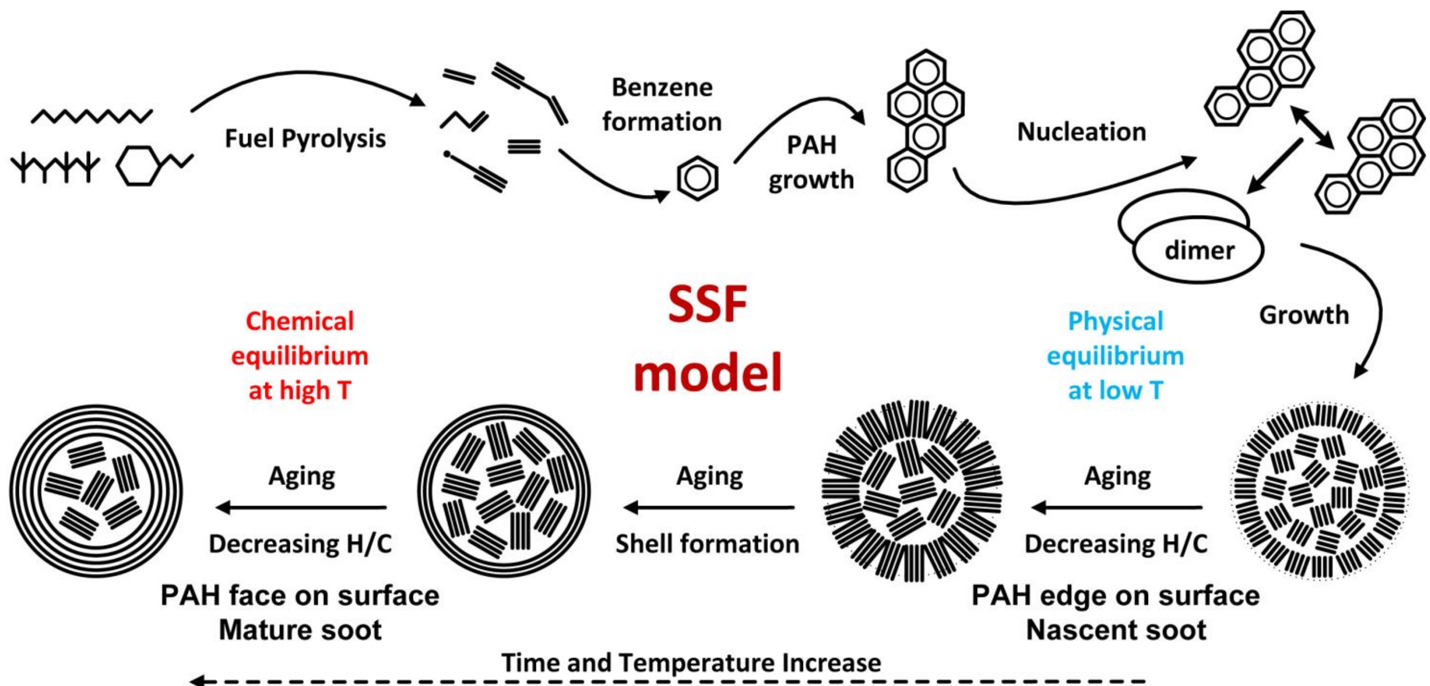
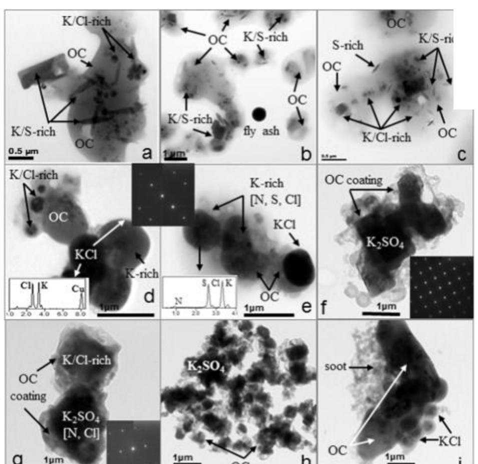
Some recent key findings

Soot and ash formation pathway

Kholghy et al. (2016)



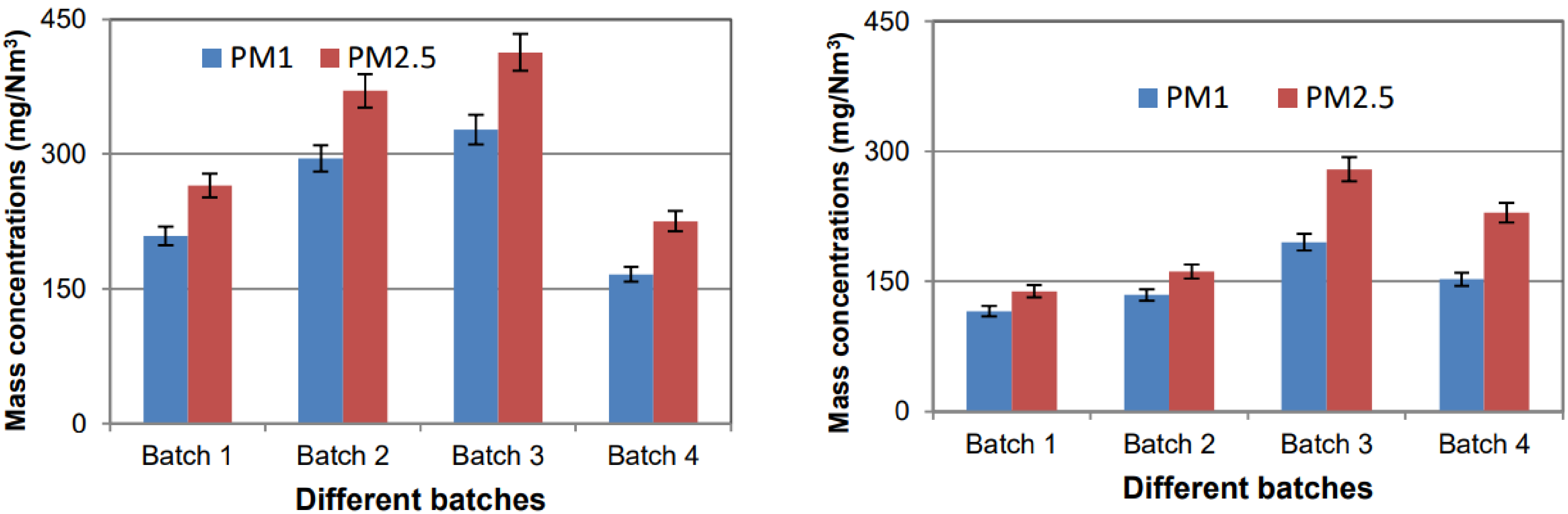
Chen et al. (2017)



SSF: soot surface shell formation

Some recent key findings

PM concentrations in flue gas from two Belgian modern wood stoves



(a) (b)

Fig. 4. PM$_1$ and PM$_{2.5}$ emissions from different batches, (a) for the 10 kW stove, (b) for the 20 kW stove

Obaidullah et al. (2019)

Small scale residential emissions

EF for carbonaceous species

Seay et al. (2020)

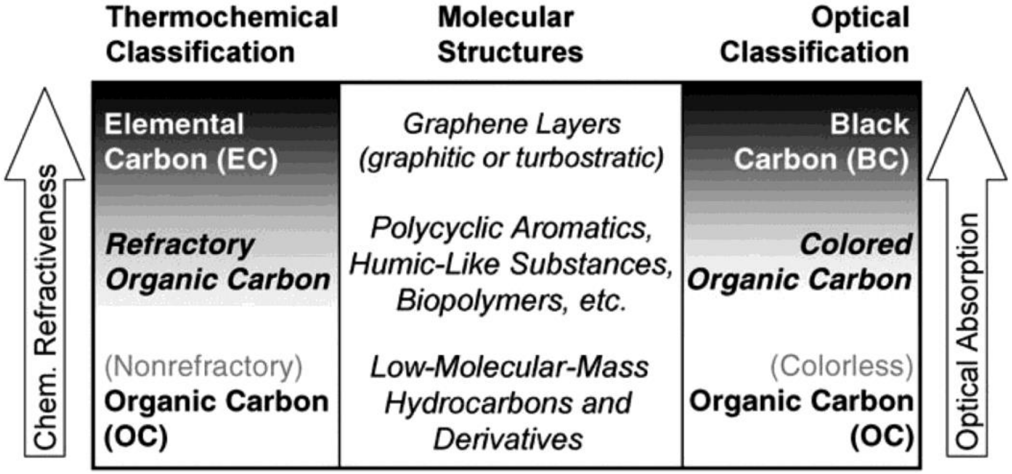
Appliance (efficiency) [a]	Description	Aerosol wood combustion EFs [e]			
		$PM_{2.5}$, g/GJ [b]	BC, g/GJ (%) [c]	OC, g/GJ (%) [c]	SO_x, g/GJ
Open fireplaces (20%)	Simplest combustion device, including a basic combustion chamber directly connected to a chimney and a large opening to the fire bed. Devices are characterized by high, non-adjustable excess of combustion air.	820	57.4 (7)	352.6 (43)	11
Conventional stoves (45%)	Includes both closed fireplaces and conventional radiative stoves. Closed fireplaces are equipped with front doors and have air flow control systems. Because of their design and combustion principles, they more closely resemble and are grouped with conventional stoves rather than open fireplaces. Conventional radiative stoves include both downburning and upburning techniques with poorly organized combustion processes.	740	74 (10)	333 (45)	11
Conventional boilers < 50 kW (60%)	Devices that heat water for indirect heating. Over-fire boilers are characterized by non-optimal supply of combustion air caused by natural draft, which causes incomplete combustion. Under-fire boilers include manual feed systems, stationary grates, and a two-part combustion chamber.	470	75.2 (16)	178.6 (38)[d]	11
High-efficiency stoves (65%)	Covers traditional stoves with improved utilization of secondary air in the combustion chamber. Also includes catalytic converter stoves, which reduce emissions from incomplete combustion.	370	59.2 (16)	140.6 (38)[d]	11
Advanced / ecolabelled stoves and boilers (70%)	Characterized by multiple air inlets and pre-heating of secondary combustion air by heat exchange with hot flue gases. Ecolabelling schemes assign a standard for improved efficiency and reduced emissions and are largely based around European standards. Also includes state of the art downdraft multi-chamber boilers.	93	26.04 (28)	28.83 (31)	11
Pellet stoves and boilers (85%)	An advanced stove that uses an automatic feed for pelletized fuels, which are distributed to the combustion chamber by a fuel feeder. These stoves are often equipped with active control systems for combustion air supply. Category also includes automatic pellet-fired boilers, which include fully automatic systems for feeding fuel and for supply of combustion air.	60	9 (15)	7.8 (13)	11

Some recent key findings

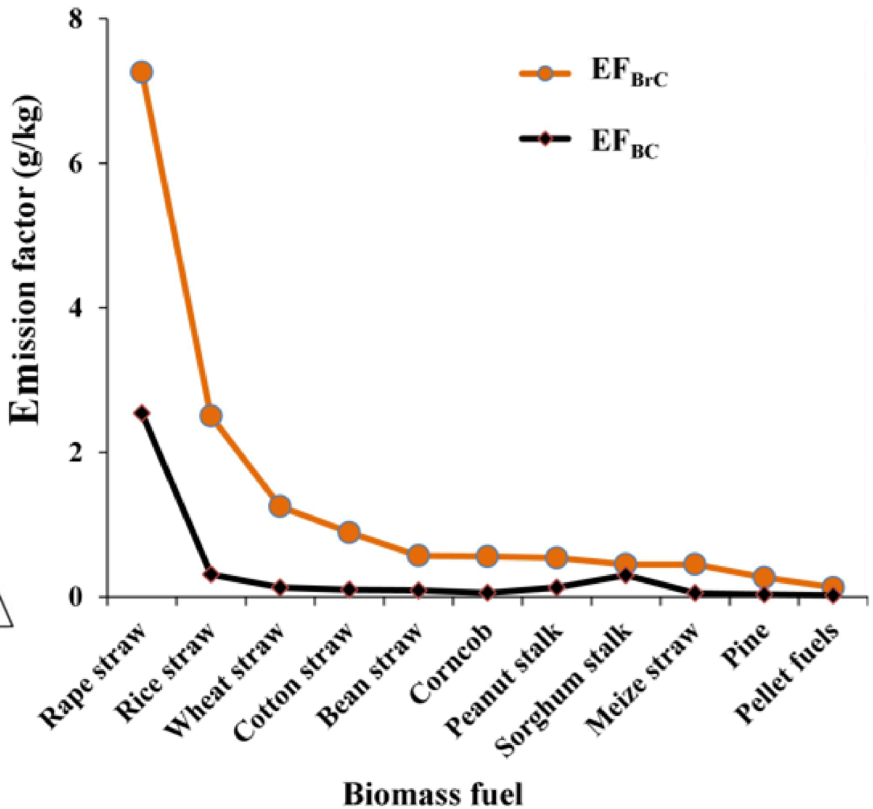
Black/Elemental/Brown Carbon

- ✓ Black or Brown Carbon?
- ✓ BC carbon c/should include BrC and then a part of Organic Matter

- Possible double counting
- EC is relevant for health issues
- BC more relevant for climate impacts



Laskin et al. (2015)

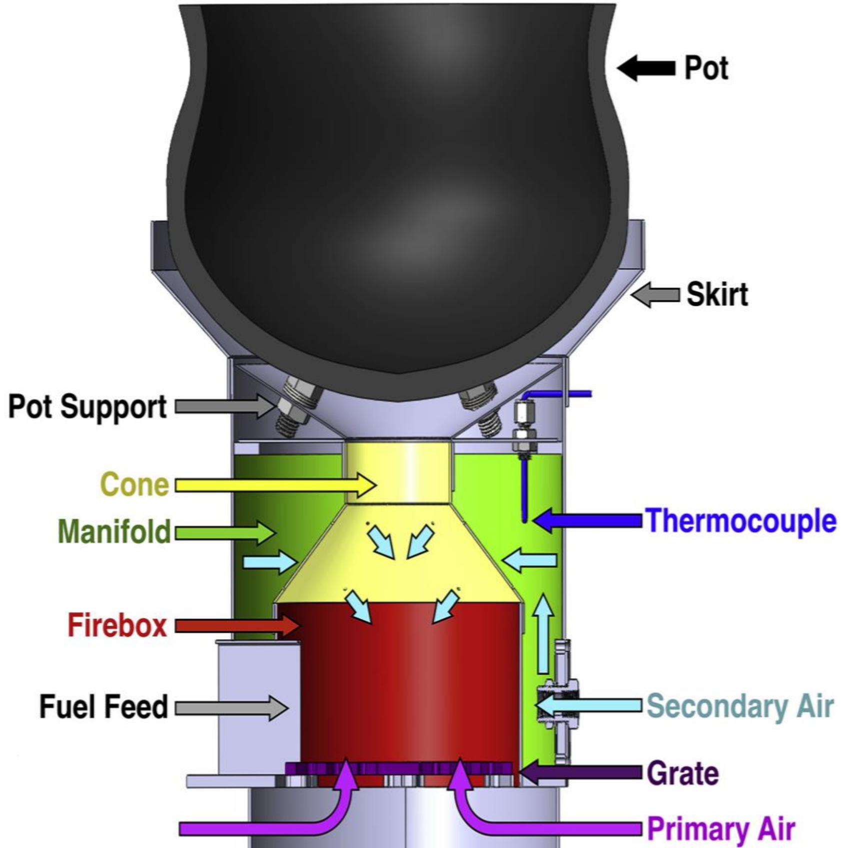


Sun et al. (2020)

Small scale residential combustion

Secondary air injection in wood-burning cook stoves

- ✓ Low-cost (<$10) fans and blowers are available to drive the secondary flow, and can be independently powered using an inexpensive **thermoelectric generator** mounted nearby.
- ✓ The size-resolved PM measurements show that secondary air injection inhibits particle growth, but the total **number of particles generated remains relatively unaffected or can increase**.
- ✓ Reduction of mass emissions of particulate matter (PM), carbon monoxide (CO), and black carbon (BC) by at least 90% relative to a traditional cooking fire
- ✓ Possible improvements for UFP:
  - ✓ Better calibration of air staging and fuel feeding
  - ✓ Turbulent conditions



Caupel et al. (2020)

Precautions:

- ✓ The formation of solid particulate matters is highly sensitive to secondary air distance and uniformity of air distribution in the secondary air modules.
- ✓ Air staging can be optimized to reduce air pollutant emissions.
- ✓ Air staging strategy in combination to reburning in order to reduce NOx can produce nitro-PAH known to have a high carcinogenic potential.

Small scale residential combustion

A low cost retrofit solution for conventional wood stoves

- ✓ PM EF decrease from 8.9 to 6.9 g/kg$_{fuel}$ but far from the reference limit
- ✓ Energy savings involved 30% in cost saving
- ✓ Expected similar performances on BC

Carvalho et al. (2018)