Harmonizing reliable test procedures representing Real-LIFE air pollution from solid fuel heating appliances
(Real-LIFE emissions, LIFE Preparatory Project 2020: 2021-2024)

1st International Technical Workshop
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Important physical and chemical properties of particulate and gaseous emissions from small scale solid fuel combustion

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Photo: Residential Wood Combustion Simulator (SIMO) at University of Eastern Finland (UEF)

Introduction: Small scale solid fuel combustion – PM emissions

- ~ 65% of total energy consumption in Europe is used for heating, mostly comes from the combustion of solid biomass (Deutsche Umwelthilfe, 2016).
- Residential wood combustion (RWC) appliances represented more than a 35% of total PM10 emissions in EU in 2018.
- Primarily, logs with relatively low moisture content, but also with pellets, saw dust, coal, straw, bark and manure (Schwartz et al., 2020).
- Vary from medium to high temperature combustion, medium to high oxygen supply, often in single stage stoves (Schwartz et al., 2020).
- Different combustion (e.g., smouldering and complete) conditions may occur in RWC.
- Hundreds of chemical compounds emitted from RWC, some of which are unknown.
- Chemical compounds - gaseous and particulate emissions and physical parameters.
- Factors affecting residential combustion emissions: type of combustion appliances, fuels, moisture content, combustion conditions, operating conditions, sampling methods.

At SIMO: 21.03.2022

Residential combustion in winter in Finland

Real-LIFE Emissions

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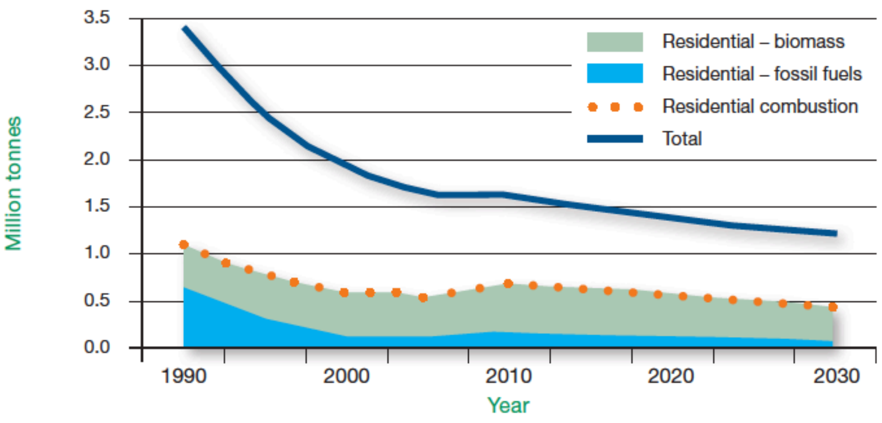
Introduction: PM emissions projections in EU-28

Future trends in residential biomass emissions

In general, if current trends continue, the relative contribution of primary $PM_{2.5}$ emissions from biomass combustion for household heating are expected to increase in the future, although declining in absolute terms (see Fig. 2).

Fig. 2. Emissions of $PM_{2.5}$ from residential sources in the EU-28, 1990–2030



Notes: EU-28 is countries belonging to the EU after July 2013; current legislation scenario as in Amann et al. (2014), using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2011).

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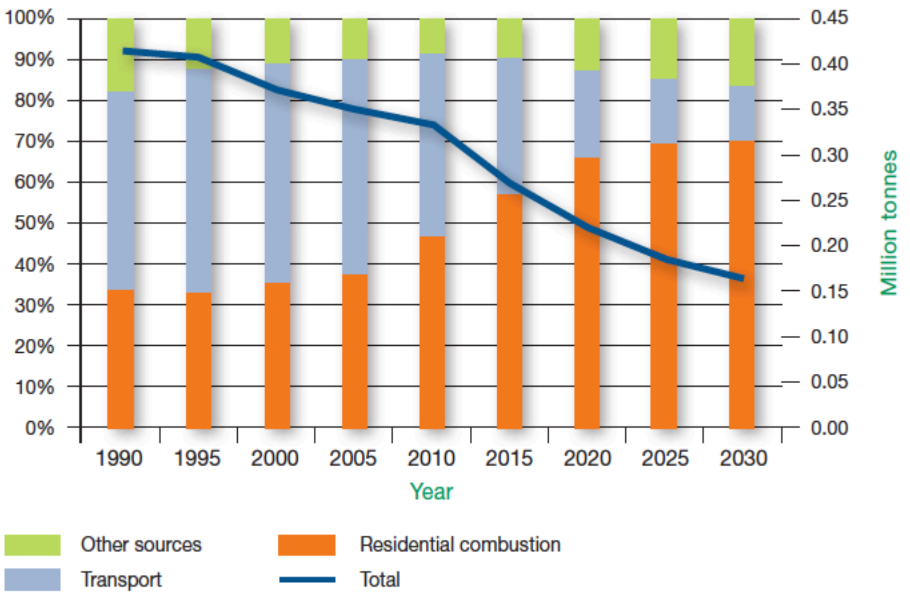
Fig. 3. Baseline BC emissions from the common major sources in the EU-28, 1990–2030



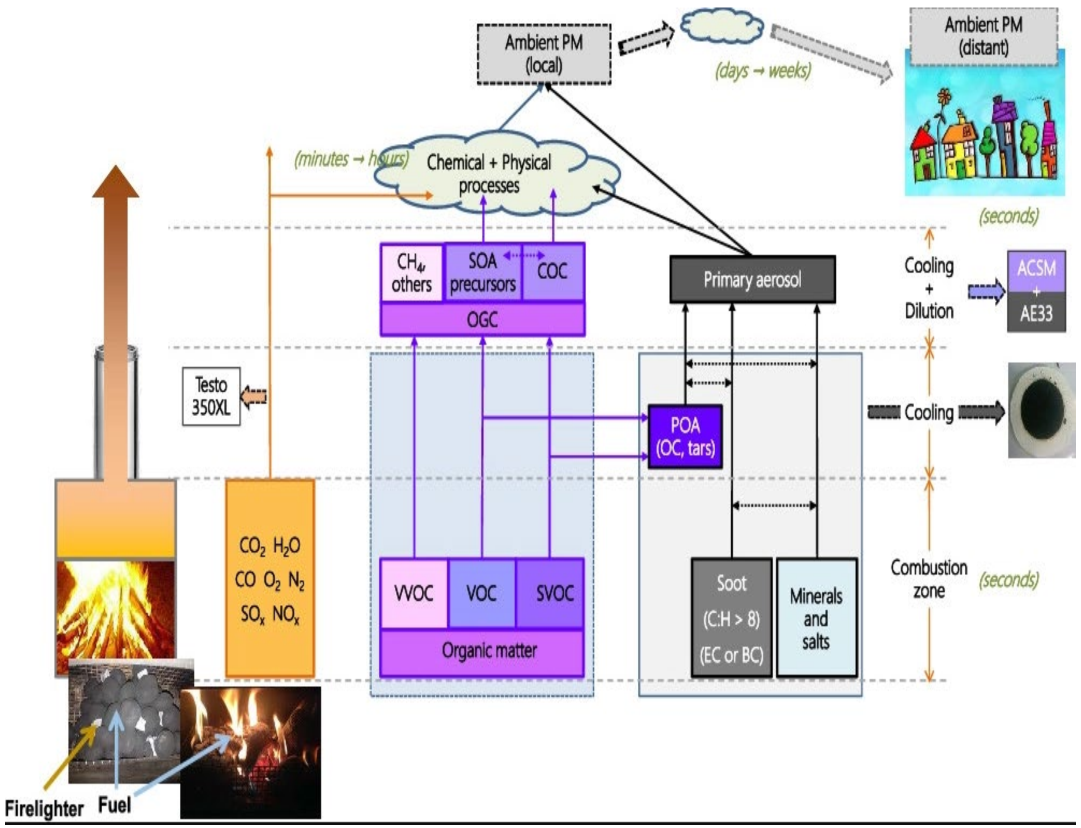
Note: EU-28 is countries belonging to the EU after July 2013; current legislation scenario as in Amann et al. (2014), using the carbonaceous particles module (Kupiainen and Klimont, 2007) of the GAINS model (Amann et al., 2011).

Source: reproduced with permission from IIASA.

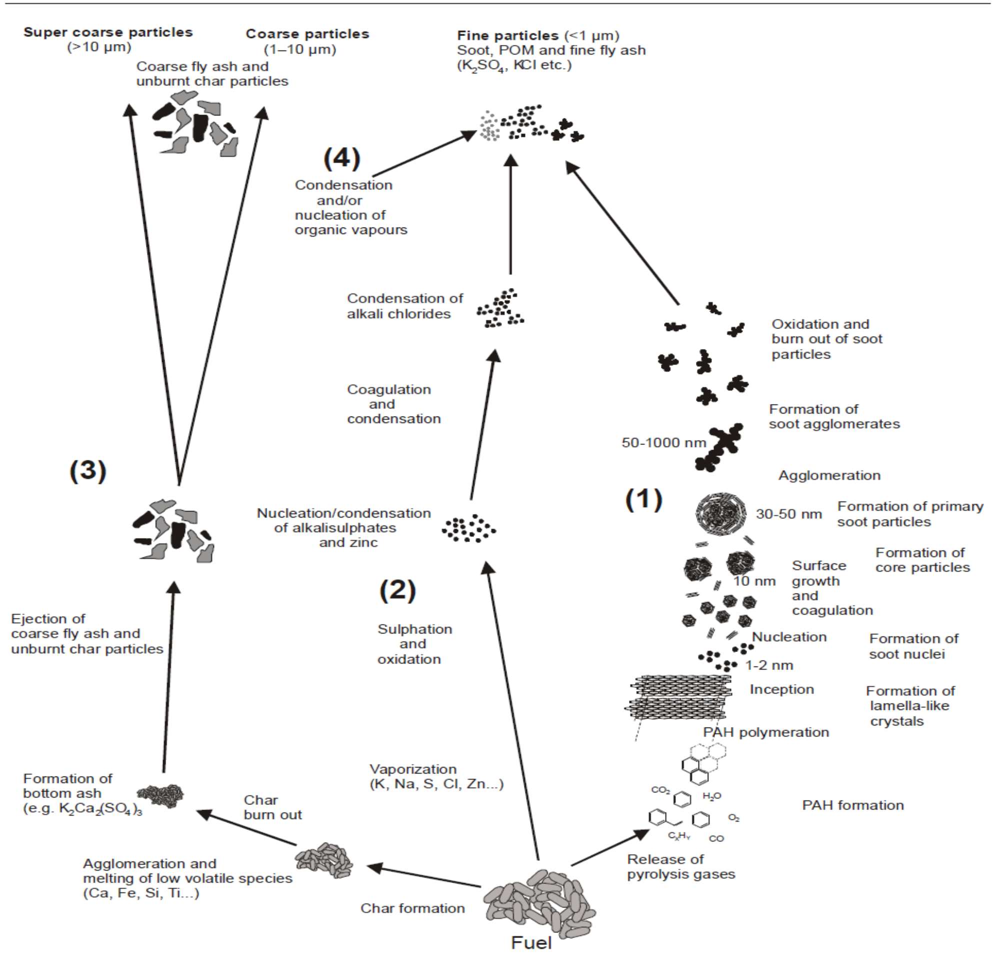
Source: WHO, 2015

Introduction: How emissions are formed in small scale combustion?

Requirement complete combustion:
a) A high combustion temperature,
b) A sufficient amount of combustion air supply,
c) Adequate mixing of combustion air and fule gas



Source: Trubetskaya et al., 2021



Source: Tissari et al., 2007

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Background and objectives of Action A2

Background

- At the moment, not all emissions are required to be reported by individual member countries.
- The most official emission measurement standards do not require to measure all condensable organic components.
- To what extent the emission inventories include organics is not clear (Simpson et al., 2020). EMEP guidebook has not defined the amount of organics to be reported (EMEP guidebook, 2019).
- Currently, only primary emissions are measured i.e., sample is taken at source, but secondary emissions are also formed in the atmosphere (Olsen et al., 2020, Bruns et al., 2016).
- The gap between model predictions and ambient air measurements of aerosol particles (Robinson et al., 2010, Simpson et al., 2020).
- The most important issue is the exclusion of some of the health and climate affecting particulate emission components from the current emission measurement standards - **real-life emissions are not accounted**.

Objectives of Action A2

- To provide an overview of the particulate and gaseous emission components generated from small-scale residential solid fuel appliances.
- To understand the health and environmental effects of PM emission components.
- To evaluate and select the most important combustion emission components to be measured based on their adverse effects on health and environment.

List of gaseous emissions from small-scale solid fuel combustion

Gaseous emissions from complete combustion	Gaseous emissions from incomplete combustion
Carbon dioxide (CO_2): the most important climate forcing effect	Carbon monoxide (CO): the most important intermediate product of fuel conversion to CO_2
Nitrogen Oxides (NO_x) - NO_X emissions are fuel derived: **NO** and NO_2	Volatile organic compounds (VOCs): Semivolatile organic compounds (SMVOCs), intermediate volatile organic compounds (IVOCs), and very volatile organic compounds (VVOCs): **methane**, ethene, propene, formaldehyde, acetaldehyde; acetylene, ethane, benzene, toluene, Xylenes
Sulphur-dioxide (SO_2): depend on sulphur content of the fuel	Hexachlorobenzene (HCB): is formed in the presence of Chlorine (Cl). Can also be other Cl compounds (e.g., HCl)

Overview: Gaseous compounds – CO, SO_2, NO_X

- *Carbon monoxide (CO)* – intermediate product – oxidize to CO_2 under appropriate temperature and oxygen availability.
- CO concentration is a function of the excess air ratio, combustion temperature and residence time of the combustion products in the reaction zone.
- CO – In residential combustion from 50 to several thousands ppm.
- Sulphur oxides (SO_x) – depends on sulphur content of the fuel, used combustion technology.
- High sulphur content coal burning in stoves could result in substantial condensable inorganic aerosols, e.g., K_2SO_4, SO_2.
- Nitrogen oxides (NO_X) – mainly nitric oxide (NO) but small portion of nitrogen dioxide (NO_2).
- Low NO_X and SO_X emissions in residential combustion compared to larger furnaces (due in part to lower furnace temperatures).
- HCB – carbon (coal or plastics), chlorine, a catalyst and oxygen with temperature between 180 °C- 500 °C.

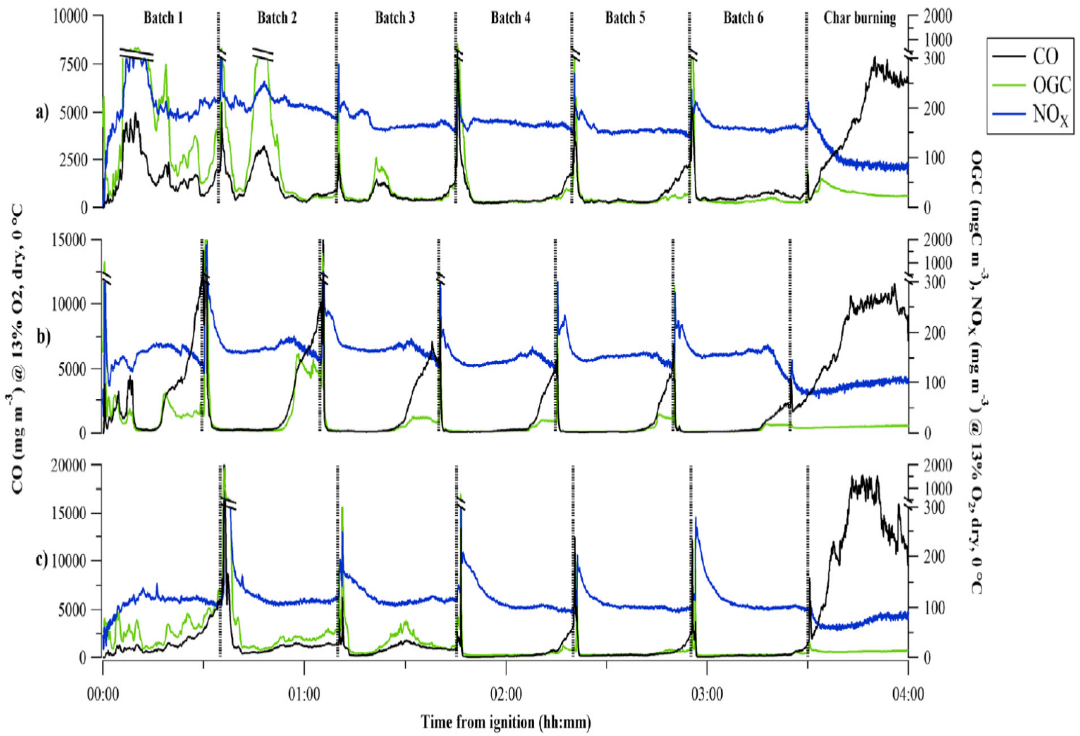


Figure: Gaseous emissions – a) beech, b) birch, c) spruce (Kortelainen et al., 2018)

Overview - Organic gaseous carbons (OGCs)

- OGC= THC= TVOCs
- OGC/VOCs - all gases or as vapors in the atmosphere.
- In RWC, VOCs are dominated by **Methane (CH_4)**.
- Non-methane VOCs (NMVOCs): ethane, acetylene, benzene, toluene, formaldehyde and acetaldehyde.
- *NMVOCs* - intermediates in the oxidation of fuels. They can adsorb on, condense, and form particles.
- VOCs types based on boiling points: very volatile organic compound (VVOC), volatile organic compound (VOC) and semi volatile organic compound (SVOC).
- VOCs- lignin structure of soft vs hard woods, e.g., hardwoods emits high syringyl compounds whereas softwoods emits guaiacyl and vanillyl compounds.
- Higher VOCs emissions at low fuel load.

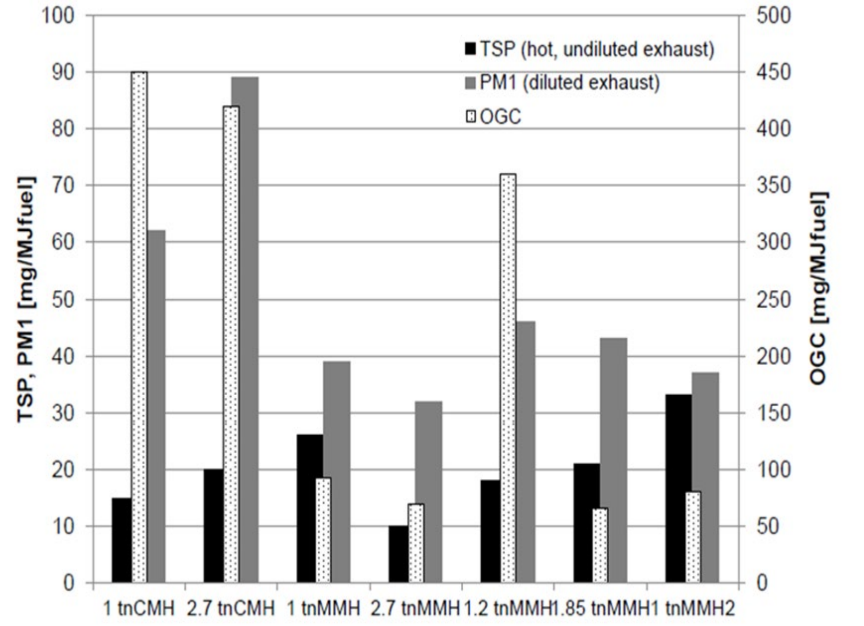


*Figure 15. Total dust mass emission TSP (hot exhaust), PM_1 mass emissions (diluted exhaust at ambient temperature) and organic gaseous carbon emissions OGC from conventional masonry heaters (CMH) and modern masonry heaters (MMH), sampled during the second batch (**IV**).*

Nuutinen et al., 2016

Sources: Who, 2000, Hedman et al., 2006, Nuutinen et al., 2016, Tytgat et al., 2017, Obaidullah et al., 2018, EMEP guidebook, 2019, Olsen et al., 2020, Martens et al., 2021

List of physical parameters - particulate emissions from small-scale solid fuel combustion

Particle emissions: physical properties

- Particulate mass concentration, PM (mg/nm³)
- Particulate mass fraction concentration: PM10, PM2.5, PM1 and UFP (ultra-fine particulates)
- Particulate number concentration = # particles/cm³
- Surface area concentration, Lung deposition surface area (LDSA)
- Particle size distribution; mass number, surface area, volume, composition
- Morphology (shape, structure etc.)
- Density
- Optical property (Ångstrom exponent, scattering absorption) - refraction, absorption, reflection, and scattering of light

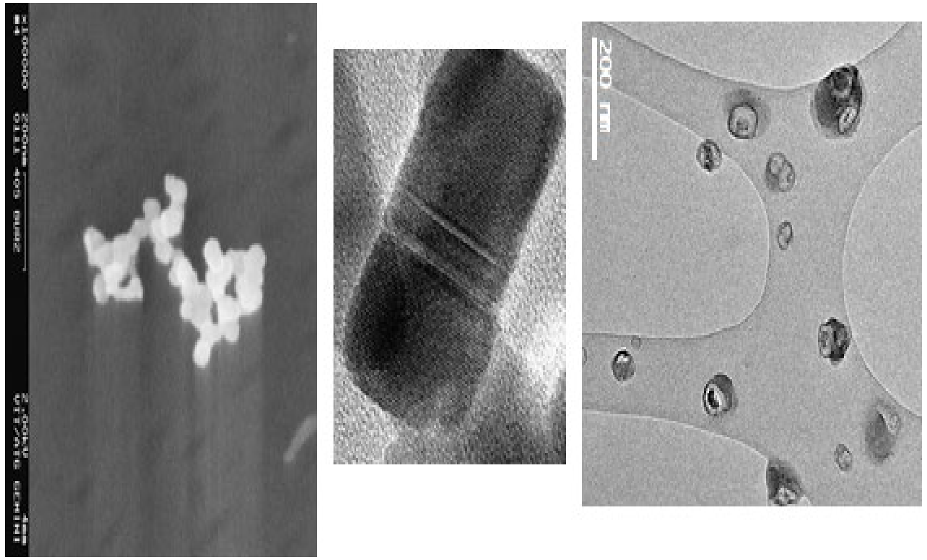


Figure: Physical appearance of particles

Overview: Physical properties - Particle mass, number and size distribution

- PM is dominated by submicrons or below 1 μm particles.
- Particle size distribution - unimodal for most of the time, vary strongly between the combustion phases, shifts towards larger particles (e.g., ignition phase) (Tissari et al., 2019).
- Particle number - does not correlate with particle mass and other parameters but with particle size (Tissari et al., 2019).
- The lowest number concentrations when highest PM1, BC, and PAH concentrations (Tissari et al., 2019).
- If concentration is higher -> collisions (= coagulation) -> size increase, number decrease
- In flue gas, number concentration is typically 10 -100 million /cm^3

PMSD: UFP = ultra fine particles, PM1 ≤ 100 nm, PM2.5 ≤ 2.5 μm, fine particles, PM10 ≤ 10 μm, course particles

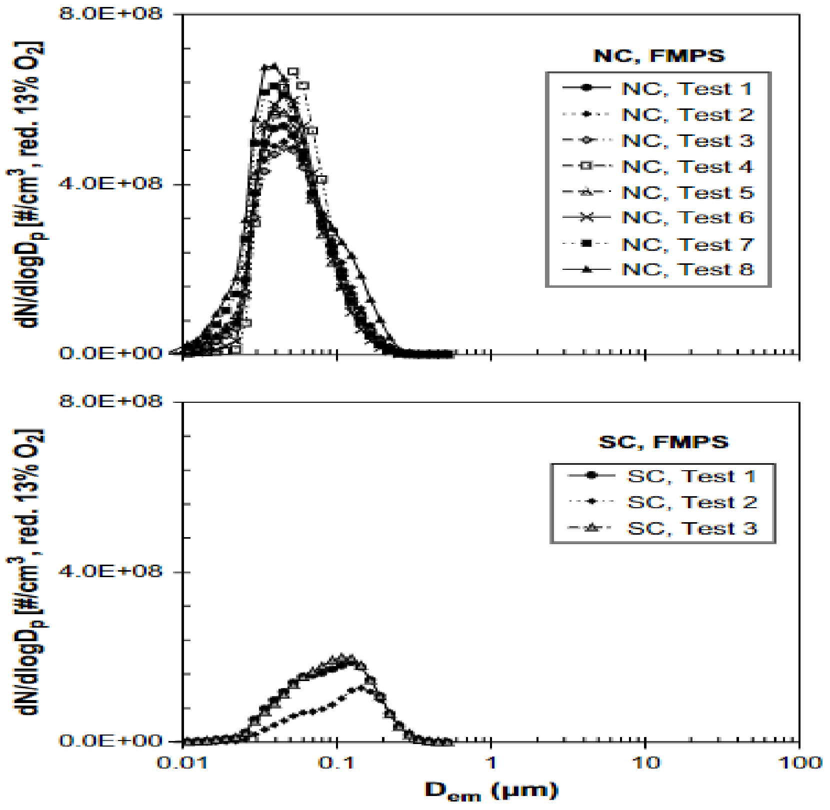
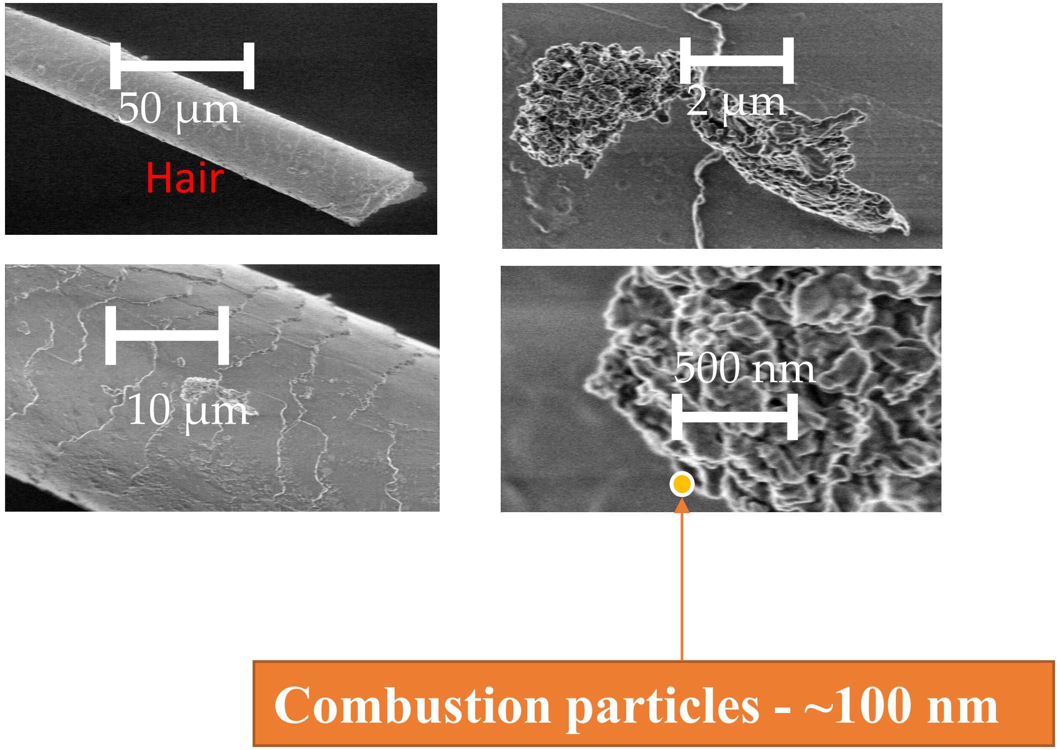


Figure: The average particle number size distributions during normal and smoldering combustion as measured by a Fast Mobility Particle Sizer (Tissari et al., 2008)

Overview: Other physical properties of particles

- Volume, shape and structure: submicron particles-compact structure; organics –spherical or irregular shaped, fine inorganic ash particles - sphere-like shape
- Surface area – Lung deposition surface area (LDSA)
- Optical properties – light scattering, absorption, backscattering, and light-extinction - e.g., absorbing capacity of e.g., BC or EC) - single scatter albedo (SSA) and the absorption Ångström exponent (AAE)
- Density - To estimate aerodynamic diameters and mass size distribution



List of particulate chemical emissions from small-scale solid fuel combustion

Particulate emissions from complete combustion	Particulate emissions from incomplete combustion
Metals: **Non-volatile metals**: Calcium (Ca), Silicon (Si), Magnesium (Mg), Ferrous (Fe), Aluminum (Al) and **Easily volatile heavy metals**: Zinc (Zn), Lead (Pb), Cadmium (Cd), Nickel (Ni), Mercury (Hg), Chromium (Cr), Cupper (Cu), Selenium (Se) **Alkali salts**: KCl, K_2SO_4, K_2CO_3	Black carbon (BC): Soot, elemental carbon (EC) and black smoke (BS)
	➢ Particulate organic matter (POM)s: different types of compounds - Polycyclic aromatic compounds (PAHs): Benzo (a) pyrene (BaP), Benzo (b) fluoranthene, and Benzo (k) fluoranthene, Phenanthrene, fluoranthene, Napthalene, pyrene, fluorene, anthracene, OH-PAHs, O-PAHs, Allkylated PAHs - Anhydrosugars: Levoglucosan, mannosan and galactosan - Phenolic Species (Syringol, Vanillin, Isoeugenol) - Resin acids (Pimaric acid, Isopimaric acid etc.) - Oxygenated monoaromatics (Guiacol, Syringol and Phenols etc.) - Polychlorinated dibenzo-dioxins (PCDD/Fs) ➢ Other organic components: Nitrophenols/brown carbon (BrC), dicarboxylic acids (oxalic acid, succinic acid etc.), polyol, multifunctional acids/anhydrides (fumaric acid, malic acid etc..) and fatty acids (oleic acid, decanoic acid

Overview: Particulate emissions- Polycyclic Aromatic Hydrocarbons (PAHs)

- PAHs - condensed benzene cores; bound to particles or in the gas phase.
- Phenanthrene, fluoranthene, pyrene, Benzo (a) pyrene (BaP), fluorene, and anthracene have been reported in high concentrations during wood combustion experiments.
- In the EMEP guidebook: Benzo (a) pyrene (BaP), Benzo (b) fluoranthene and Benzo (k) fluoranthene. Limit value = 1 ng/m^3 for BaP by European air quality monitoring program.
- Typically, a small fraction (1.7 - 3.2% of total OA) of the PM mass.
- PAHs: can degrade during atmospheric transport; also produced by other sources and are chemically unstable in PM captured for offline analysis.
- PAH derivatives: oxygenated (OPAH) and nitrated compounds (NPAH) are emitted either directly during the combustion process or during gas-phase oxidation by atmospheric oxidants or on the particle surface.

Sources: Boman et al., 2005, Nuutinen et al., 2016, EMEP guidebook 2019, Nyström et al., 2017, Tytgat et al., 2017, Olsen et al., 2020.

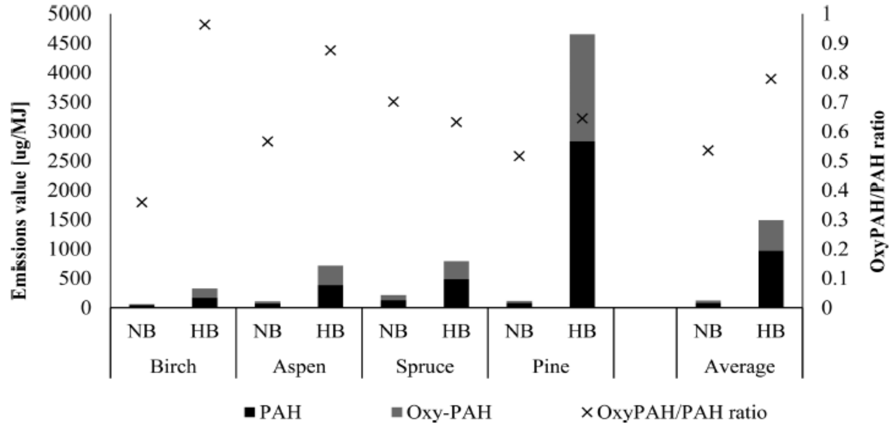
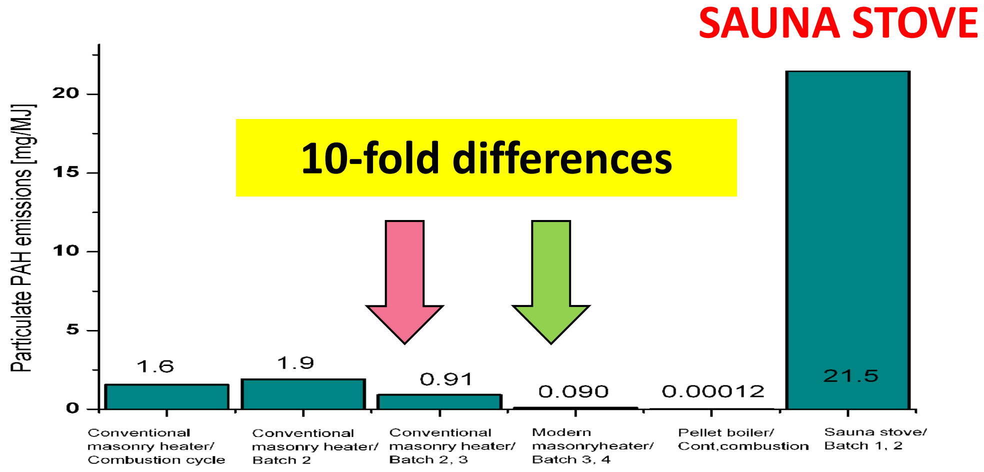


Figure: Total emissions of particulate PAH and oxy-PAH during NB and HB combustion for all fuels, as well as the oxy-PAH/PAH ratio (Nyström et al., 2017)



PAH emissions from different combustion appliances (Lamberg et al., 2011)

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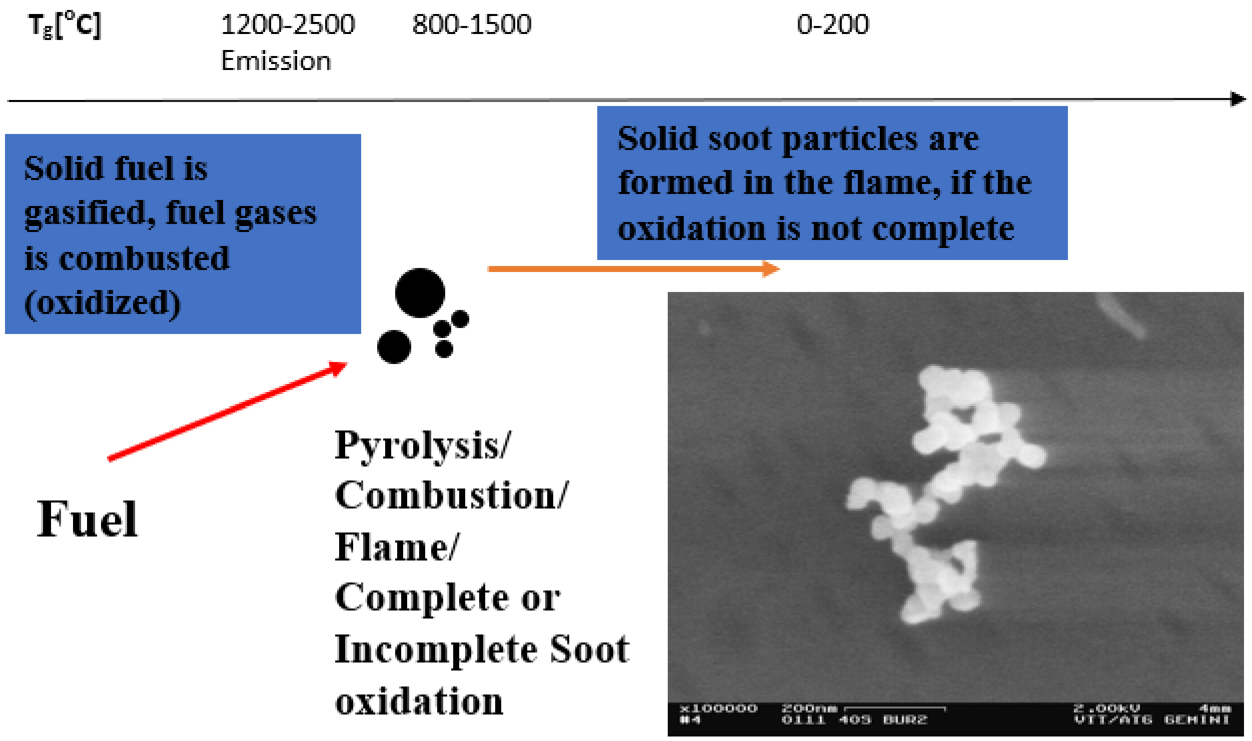
Overview- Particulate emissions- Black carbon (BC)

- BC- also called soot and EC: Strong light absorbing and refractory material.
- BC - a range of carbon containing compounds, covers partly large polycyclic species, charred to highly graphitized soot.
- Mass fraction of BC ≤ 10% of atmospheric aerosol. The BC or EC is only present in the solid (filterable) part.
- ~56% of the BC soot in Europe is caused from RWC and 70% by 2030.
- BC strongly absorbs all wavelengths of visible light. It is refractory in nature.
- BC - direct radiative forcing (climate forcing of +1.1 W/m^2) - net positive radiative forcing (i.e., warming effect) of climate.
- BC has very low chemical reactivity in the atmosphere.



Agglomerates 50 nm to 1000 nm

Sources: EMEP guidebook 2019, Bond et al., 2013, Trojanowski & Fthenakis, 2019

Overview - Other particulate organic compounds

- BrC - light absorbing organic aerosol - includes wide range of species with different absorption characteristics. **Mainly from biomass combustion**.
- BrC represents a substantial part of SOA formed during atmospheric oxidation of biomass burning.
- PCDD/F - carbon, chlorine, a catalyst and oxygen with temperature between 180 °C - 500 °C.
- Dioxins and furans - mainly from the combustion of coal and plastic wastes.
- Resin acids - Isopimeric, dehydrobietic, abietic, and pimaric acids are result of softwood combustion - high in ignition phase, and decay during more effective combustion.
- Anhydrosugars/**Levoglucosan** is high in start-up phase and addition of each batch and died away thereafter during the flaming phase-> further decomposed in complete combustion.
- **Levoglucosan** - suitable tracer for manually fired systems and less suitable for the automated fired wood combustion techniques.

Sources: Who, 2000, Hedman et al., 2006, Obaidullah et al., 2018, EMEP guidebook 2019, Olsen et al., 2020

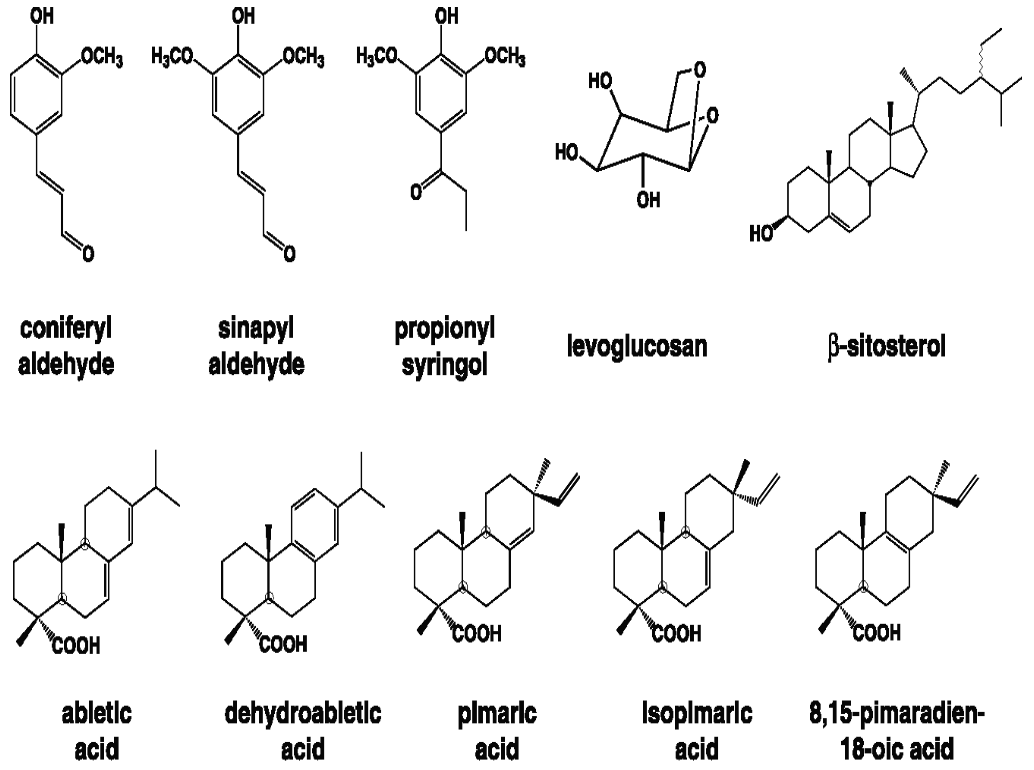
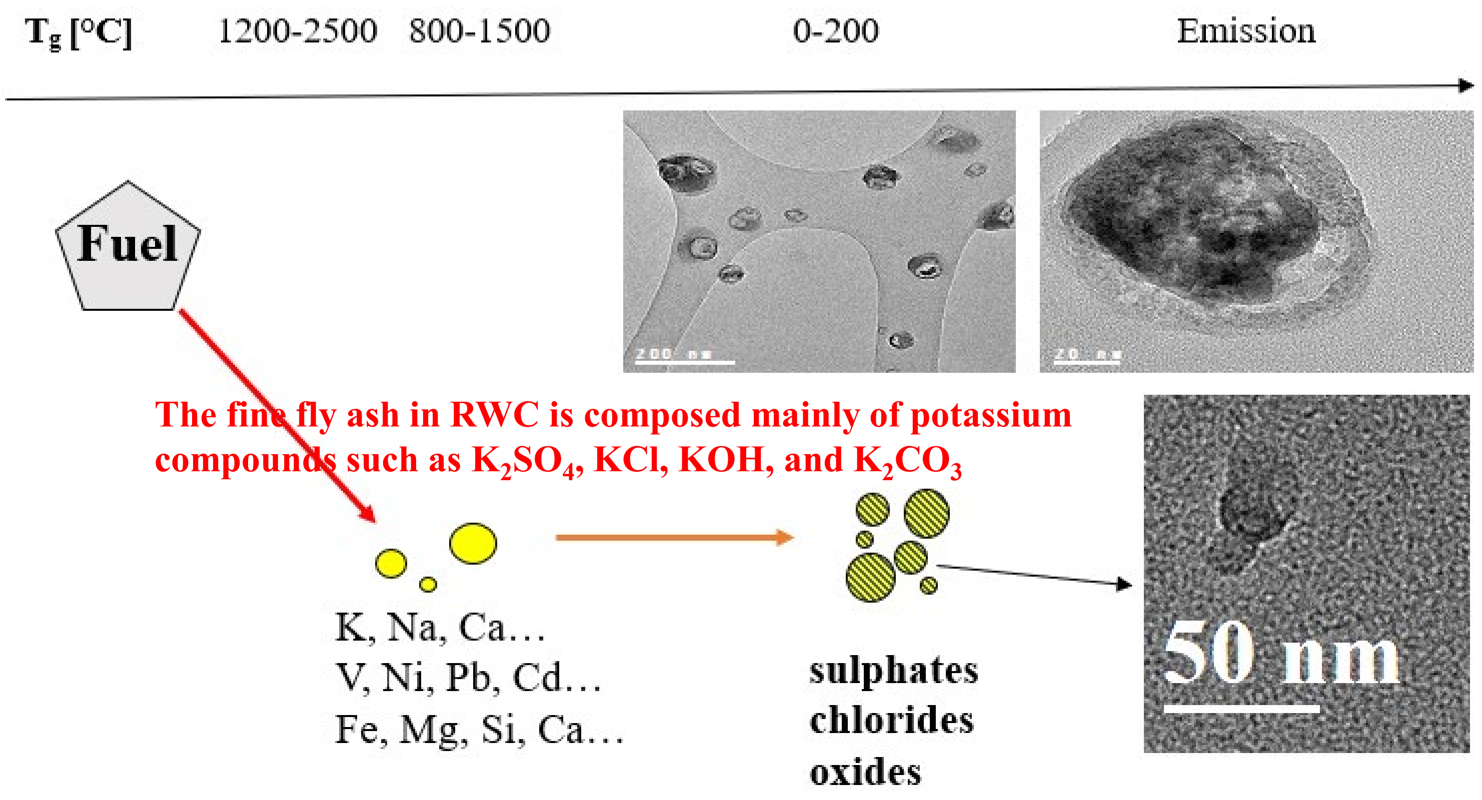


Figure: Selected organic compounds from residential wood combustion (Fine et al., 2002)

Overview: Particulate emissions – Heavy Metals and Fine Ash Particles

- Heavy metals: The content of heavy metals depends on the type of biomass. Dominant heavy metals: As, Cd, Cr, Cu, Hg, Ni, Pb, Se, and Zn are associated and/or adsorbed with particles (e.g., sulphides, chlorides or organic compounds).
- Hg, Se, Cd, As and Pb are at least partially present in the vapour phase. Thus, fuel ash partly vaporized always in combustion.
- Less volatile metal compounds tend to condensate onto the surface of smaller particles in the exhaust gases.
- Contamination of biomass fuels (e.g., impregnated or painted wood), may cause higher amounts of heavy metals emitted (e.g., Cr, As) (Pye et al., 2005).
- Vaporized ash compounds nucleate or condensate, when the temperature decreases.



Sources: Pye et al., 2005, Tissari, J., 2007, EMEP guidebook, 2019

Ash particles are formed albeit complete combustion conditions!

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Overview: Particle emissions from different combustion sources and fuels

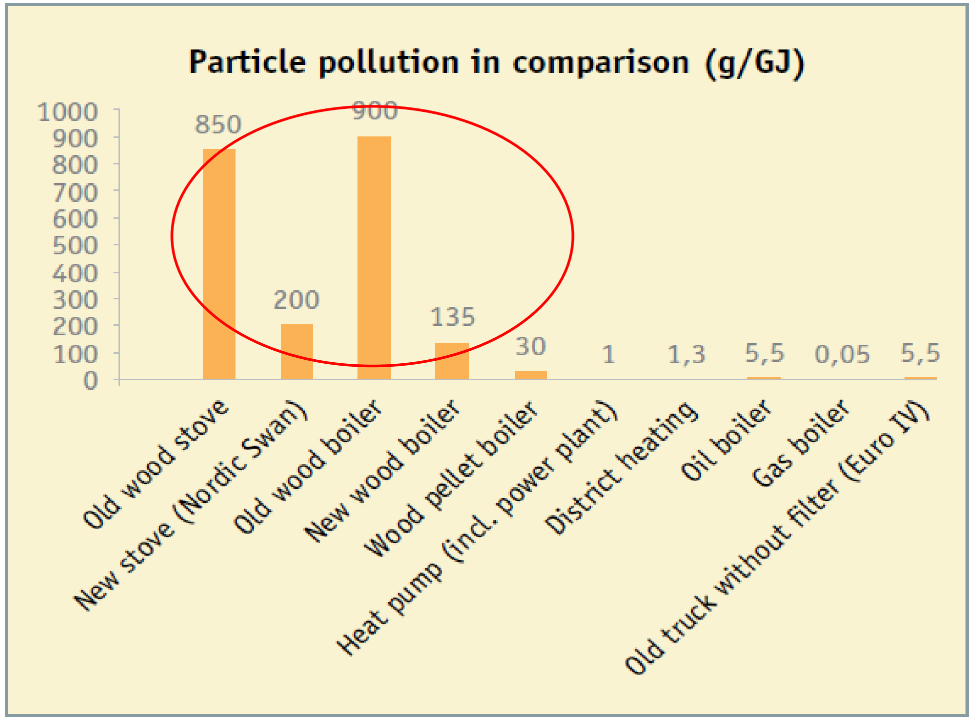

Figure 5: Particle pollution ($PM_{2.5}$) of different heat sources compared with a diesel truck (data from Denmark). | Sources: Helge Rørdam Olesen, DCE, University of Aarhus, Denmark.

Source: Environmental Action Germany, 2016

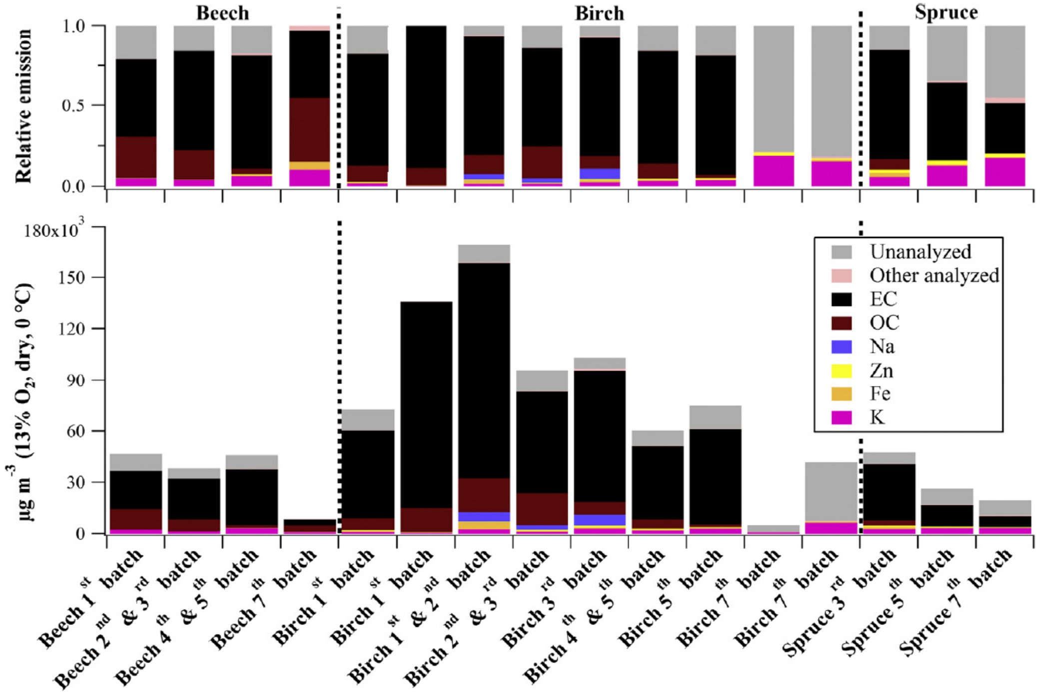

Figure: PM1 chemical composition analyzed from filter samples (Kortelainen et al., 2018)

Overview: Particulate emissions- Secondary organic aerosols (SOAs)

- SOAs are produced mainly from VOCs (e.g., terpenes, NMVOCs) but also from aliphatic and aromatic hydrocarbons, phenol derivatives (e.g., BrC), monoterpenes, and sesquiterpenes.
- Upto 85% of all SOA are related to low (semi) volatile species (< C12 n-alkanes).
- 31–78% of SOA by aromatic compounds (mainly single ring aromatics and oxygenated aromatics) from the selected fuels (Hatch et al., 2015).
- The main pathways to form SOAs include a) the oxidation of VOCs precursors via radicals with chain reactions; b) oxidation, functionalization, and oligomerization of VOCs and c) gas to particle conversion via nucleation, condensation, and aqueous phase SOA formation.
- Factors to influence SOA formation: precursor mixture, organic aerosol concentration, oxidant type [ozone (O_3), hydroxyl (OH^-) and nitrate (NO_3^-)] as well as concentration and duration of aging, multiphase chemistry, temperature, relative humidity, and radical branching.
- During aging/oxidation of biomass emissions: the POA to SOA mass increases by factor of 3 -7.

Sources: Hatch et al., 2015, Bruns et al., 2016, Titta et al., 2016, Tkacik et al., 2017, Kumar et al., 2018, Olsen et al., 2020

22 precursor molecules

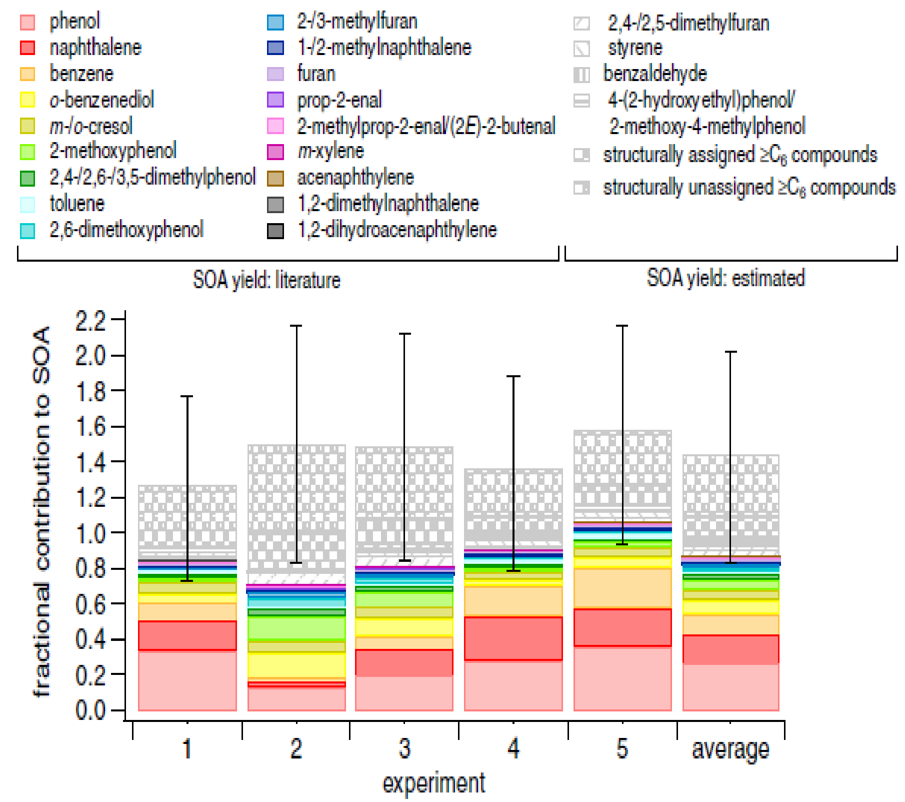

Figure: Fractional contribution of 22 individual NMOGs and two lumped NMOG categories to observed SOA for each experiment and the average of all experiments.(Bruns et al., 2016)

The most important precursors: phenol, naphthalene, and benzene

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Overview: Health effects of gaseous emissions

- Excessive CO_2 exposure: inflammation, reductions in higher-level cognitive abilities, bone demineralization, kidney calcification, oxidative stress, and endothelial dysfunction.
- Excessive exposure to SO_2: inflammation and irritation of the respiratory system resulting symptoms such as pain when taking a deep breath, coughing, throat irritation, and breathing difficulties (National park services). It can also affect lung function, worsen asthma attacks, and worsen existing heart disease in sensitive groups (National park services).
- CO has more lethal effects: with higher concentrations, it limits the transport of oxygen in human body which can result in dizziness, over unconsciousness to eventually death (Tytgat et al., 2017).
- VOCs: acute symptoms such as irritations of the nose, throat, and eyes, cause headaches, nausea, dizziness, allergic skin reactions, and can also damage liver and kidneys (Department Environment, 2021).
- Toluene and xylene can result in serious neurosis, dementia (Department Environment, 2021). Chronic xylene -headaches, extreme tiredness, tremors, impaired concentration, and short-term memory, long term exposure of chloroform - effects on central nervous systems including hepatitis, jaundice, depression, and irritability (Department Environment, 2021).
- HCB is a possibly a carcinogenic to humans (Department of Health, 2022).
- HCl is corrosive - eye, nose, and respiratory tract irritation and inflammation and pulmonary edema in humans. Long-term exposure - gastritis, chronic bronchitis, dermatitis, and photosensitization (EPA, 2016).

Real-LIFE Emissions

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Overview: Health impact of chemical compounds of PM emissions

Transition and heavy metals - both inflammatory responses and cell death in epithelial

Fe, Cu, Cr, Va, and Zn - **oxidative stress**). Fe and Al – **genotoxic**, K and Zn - cardiovascular mortality and morbidity

BC - indicator of toxic constituents - carry a wide variety of chemicals to the lungs, the body's major defense cells and possibly to the circulatory system

BC can: cause cardiovascular mortality and cardiopulmonary hospital admissions, also cause other respiratory diseases and lung cancer and drive to form reactive oxygen species (ROS) and inflammation

Eight PAHs, **possible carcinogens** are: benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene (BaP), dibenzo (a,h)anthracene, indeno (1,2,3-cd)pyrene and benzo (g,h,i) perylene. BaP is classified as carcinogenic

PAHs, short-term effects: eye and skin irritation, nausea, vomiting and inflammation. Long-term effects: cancer (lung, skin, bladder, gastrointestinal), DNA damage, cataracts, kidney and liver damage, gene mutation, and cardiopulmonary mortality

Chronic exposure to PAHs - induces reactive oxidative stress (ROS) and a strong cellular response, immunologic and reproductive issues, cause genotoxicity and downregulation of neutrophils in the lungs

Levoglucosan - causes inflammatory effect due to the production of interleukin-8

Dioxins (e.g., PCDD/F): dermatological response chloracne, toxin, immunotoxin, and carcinogenic. High exposure during pregnancy causes subcutaneous oedema, gastrointestinal hemorrhage and decreased fetal growth and prenatal mortality in primates and rodents, DNA damage in rat peritoneal cells, and mutations in the mouse cells

SOA - Increment in the number and sizes of the particles due to SOA formation poses more health risks

SIA - morbidity and mortality but health effects depend on varied sizes and chemical composition in different locations

Sources: Hedman et al., 2006, Srogi et al., 2007, Jalava et al., 2012, WHO, 2015, Nuutinen et al., 2016, Kasurinen et al., 2016, Corsini et al., 2017, Allen et al., 2019, Ihantola et al., 2020

Overview: Health impact of physical parameters of PM emissions

Physical parameters determine **deposition probability and deposition site** of the particles .

Particle size influences lung deposition: nano-sized particles accumulates in the cells at a faster rate and promotes the secretion of Th1-specific molecule signals.

High number of particle concentrations - acute toxicity in murine macrophages.

Shape: describes particle behavior at the cell membrane and inside the cell.

Surface area of particle - affects on the lung deposition – Lung deposition surface area (LDSA).

Density - influences the transport and deposition of the particles in the human respiratory tract.

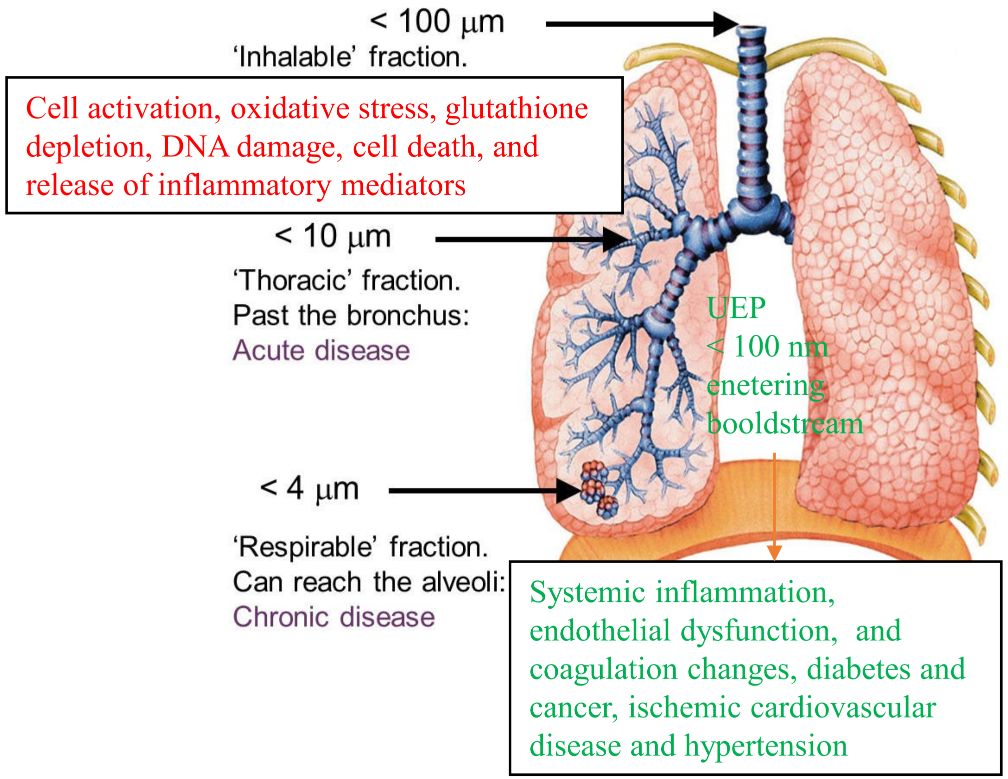

Figure: Grain size dependence of penetration of airborne particulate matter (Wikimedia)

Sources: Ristimäki et al., 2002, Yue et al., 2010, Tapanainen et al., 2011, Jalava et al., 2012, Leskinen et al., 2014, Dilger et al., 2016,, Corsini et al., 2019

Overview: Environmental Effects - Chemical compounds: Gaseous emissions

Warming species:

CO, CH_4, CO_2 , VOC

VOCs/NMVOCs + other air pollutants + UV sunlight -> ground-level ozone: harmful for environment e.g., causes oxidative damage in vegetation

The total climate forcing of wood combustion - slightly cooling, due to strong cooling impact of co-emitted species

Cooling species:

OC, NO_x, SO_2 and NH_3 form light reflecting particles - reduce radiative forcing

NO_x contributes to tropospheric ozone formation, acidification, eutrophication, and photochemical smog.

N_2O destructs the stratospheric ozone layer

SO_2 induces acidification

Sources: Kupiainen et al., 2019, Savolahti et al., 2020, Department Environment For Rural Affairs Food, 2021

Overview: Environmental Effects - Chemical compounds: particulate emissions

Black carbon (BC)

BC emits heat radiation to surrounds. A net positive radiative forcing: warming effect.

Can alter the atmospheric temperatures profile and cloud distribution, influence the formation and properties of clouds (e.g., brown cloud formation, droplet formation, and microphysical properties) and precipitation.

Deposition of BC on ice or snow decreases the albedo of the surface - increases the amount of sunlight absorption, and accelerate the melting of glaciers and ice sheet.

Organic compounds

Light scattering property - contribute to both visibility degradation and direct aerosol climate forcing.

Water-soluble property : important role in various aerosol-cloud interactions.

PAHs - atmospheric depositions on plants and soils.

BrC - changes the optical properties and chemical composition of aerosols that can affect the cloud formation.

Inorganic compounds

Sulfate, nitrate and ammonium compounds - modify the properties of clouds and affect the climates.

Undergo homogenous and heterogeneous-phase chemical reactions - a severe environmental degradations, including ozone layer depletion, air quality deterioration, smoke-fog related accidents and acid rain formation.

Secondary aerosols

SOA particles: more particles increases the air pollution, can travel to long distance and form the cryosphere ozone reacting with other pollutants present in the atmosphere.

SIA particles: impacts on climate is largely governed by size and chemical composition. Due to the short lifetime of SIA (days/weeks), their effects are more regional and less persistent into the future.

Sources: Smita et al., 2012, Prince et al., 2015,Kuang et al., 2016, Allen et al., 2019, Trojanowski et al., 2019, Olsen et al., 2020, Savolahti et al., 2016, 2020

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Overview: Environmental impact from physical parameters of PM emissions

- Fine (PM2.5) particles – the most important sizes for urban air pollution - consist of organics and condensable to produce various compounds which are harmful to environment and surrounding atmosphere.
- Ultrafine particles (< 100 nm) may affect the cloud formation and other climatic activities.
- The size distribution and number concentration affect the fate of condensable vapours and overall OA enhancement ratios.
- Number concentration – no clear direct effects on climate - some literatures describe it causes cloud formation processes through cloud condensation nuclei (CCN).
- Quantity of particles in intermediate size - crucial for climate effects than the mass of inorganic particles.
- The density of particles influences on the transport and deposition of the particles in air and surfaces.
- Optical properties (e.g., absorption, scattering) of particles - Cloud formation, absorption and refraction of the radiation and formation of condensation sink.

Sources: Ristimäki et al., 2002, Leskinen et al., 2014, Denier Van Der Gon et al., 2015, Lim et al., 2015, Janhäll et al., 2018, Allen et al., 2019, Olsen et al., 2020

Indoor air emissions and their health effects from small-scale combustion emissions

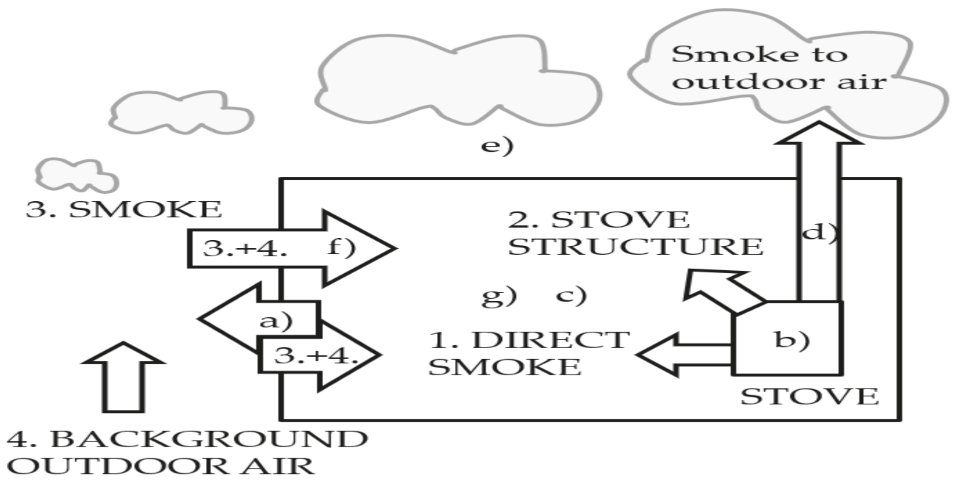

Figure 2. Schematic picture of the indoor air emission sources and affected factors in house equipped with small scale wood stove.

Combustion emissions are originated 1) directly from the stove, 2) from stove structure, 3) from stove emissions via outdoor air and 4) from background outdoor air.

Concentrations in indoor air depends on a) ventilation machine and ventilation rate, b) stove type, c) stove operational practices, d) draught conditions, e) weather conditions, f) open windows or doors and g) other indoor air sources.

- The most hazardous indoor air pollutants : benzene, 1,3-butadiene, and formaldehyde which are carcinogenic and phenols, cresols, acrolein, acetaldehyde are ciliatoxic (Naeher et al., 2007).
- Increased upper respiratory infection (URI) and low level of lower respiratory infection (LRI) and the increment in the cancer risk due to indoor air emissions (Guercio et al., 2020).
- Epidemiological and toxicological results in relation to indoor combustion emissions -lack of enough data and actual dose is rarely considered (Vicente et al., 2021).

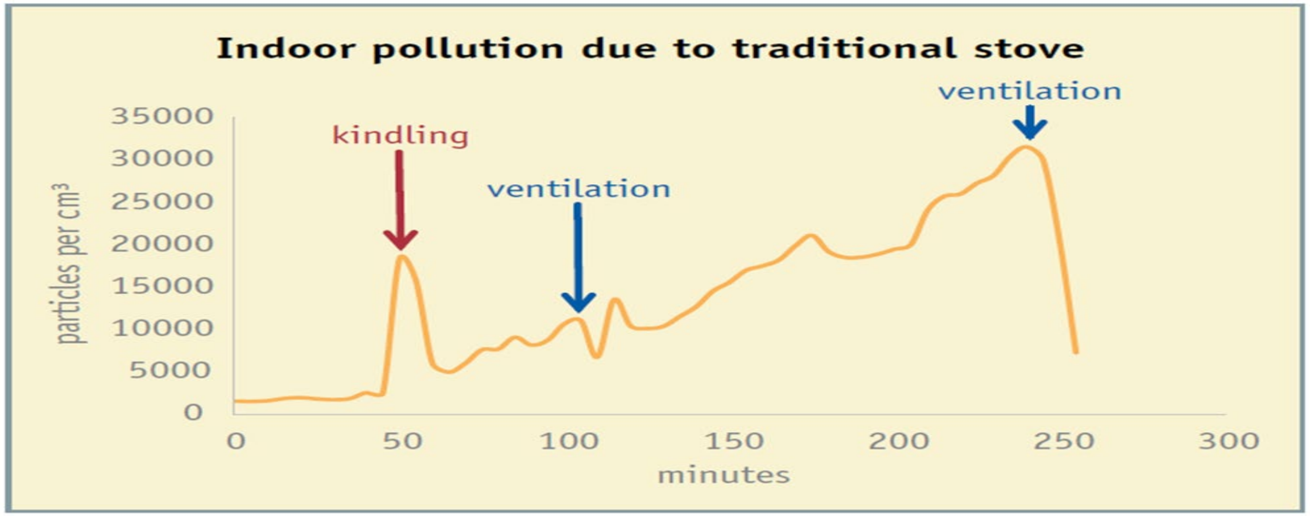

Figure :Concentration of indoor ultrafine particles by a traditional Danish firewood stove (Deutsche Umwelthilfe, 2016)

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Results: Summary table from literature study

Table 4: Evaluation of chemical components and particulate physical parameters of emissions from residential combustion based on the significance of health and climate effects [Degree of significance for health is indicated by '+ and -' sign: + = small effect, ++ = intermediate effect, +++ = high effect, - = no effect or no direct effect and for climate - = small cooling effect. -- = intermediate cooling effect, --- = high cooling effect, + = small warming effect, ++ = intermediate warming effect, +++ = high warming effect and N/A – not appicable]

Parameter	Health effects	Climate effects - Cooling + warming	Measurable/non-measurable (Online)	Location of sampling	Remarks
Carbon dioxide (CO_2)	N/A	+++	Easily measurable (Online)	Hot flue gas Diluted flue gas (as a definition of dilution ratio)	Not important for residential wood combustion Important for fossil fuel combustion
Nitrogen Oxide (NO_x)	++	-	Easily measurable (Online)	Hot flue gas	Concentration depends on nitrogen content of the fuel
Sulphur dioxide (SO_2)	++	- -	Easily measurable (Online)	Hot flue gas	Depends on S content of the fuel. Coal is the main source of SO_2 but insignificant for biomass combustion
Carbon monoxide (CO)	++	+	Easily measurable (Online)	Hot flue gas	Intermediate product, no direct effect to climate and affects, health effects if the concentration is high in indoor air
Methane (CH_4)	+	+++	Easily measurable (Online)	Hot flue gas	
Volatile organic compounds (VOCs) - Benzene, toluene, Fluorene - Phenol, Cresols, Guiacol - Furan, Furfural, Benzofuran - Formaldehyde, Acetaldehyde - Isoprene, Monoterpenes	++	++	Easily measurable,, Offline collection need laboratory analyses (Online/Offline)	Hot/diluted flue gas	Different health impacts for different constituents of VOCs, Some VOCs have significant adverse effects to health and they produce ozone, VOCs are precursors of SOAs
Hexachlorobenzene (HCB)	++	-	Not easily measurable, need specific chemical analyses (Offline)	Hot flue gas	

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Results: Summary table from literature study

Parameter	Health effects	Climate effects - Cooling + warming	Measurable/non-measurable (Online)	Location of sampling	Remarks
PM	++	--	Easily measurable (Mainly offline)	Hot/diluted flue gas	Measurement technique affects largely to the emission factor
PM2.5	+++	--	Easily measurable (Offline)	Diluted flue gas	Need cut off devices such as impactor
Mass size distribution	++	--	Not easily measurable, need dilution (Offline)	Diluted flue gas	Information important for health and climate needs
Number concentration and number size distribution	++	--	Measurable, need dilution (Online)	Diluted flue gas	Number concentration and number size distributions have climate effects but they transform during aging, particle deposition to lungs is dependent on particle sizes- important health parameter, useful information for climate modelling,
Surface area concentration/ lung deposition surface area (LDSA)	+++	-	Measurable, need dilution (Online)	Diluted flue gas	Many harmful constituents are on the surface of particles
Morphology	+	-	Not easily measurable, need dilution, need specific electron microscopy analyses (Offline)	Diluted flue gas	Rod liked shapes are harmful for health, impacts to optical properties
Density	+	-	Not easily measurable, need dilution and several different scientific instruments (Offline)	Diluted flue gas	Affects to the deposition of particles
Optical properties [e.g. wavelength-dependent light scattering (e.g. single scatter albedo), backscattering, and absorption coefficient (e.g. the absorption Ångström exponent)	N/A	++/---	Measurable (online/Offline)	Diluted flue gas	The data of optical properties e.g. absorption and scattering of the particles are useful for climate modelling, mainly BC is measured for optical properties

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Results: Summary table from literature study

Parameter	Health effects	Climate effects - Cooling + warming	Measurable/non-measurable (Online)	Location of sampling	Remarks
Primary inorganic particles (e.g. metals, alkali salts, H_2SO_4)	+/++	- - -	Measurable, need chemical analyses (Offline)	Diluted flue gas	Some inorganic particles (metals, H_2SO_4)are very important parameters in terms health
Black carbon, Elemental carbon, Soot particles	++	+++	Measurable, need dilution, need specific instrument or analyses (Online/Offline)	Diluted flue gas	(EC or BC will be more or less the same if collected in hot or cold/diluted flue gas
Primary organic particles/Primary organic matter (POM)/Organic carbon (OC)	++	---	**OC is measurable (Offline)**	**Diluted flue gas)**	**The concentration of all OC compounds will be different, higher if collected in cold flue gas without thermal post treatment**
Polycyclic Aeromatic Hydrocarbons (PAHs)	+++	--	Measurable, need specific chemical analyses (Offline)	Diluted flue gas	Can be in both particulate and gaseous form, PAHs transform in the aging
Anhydrosugars and other organics (e.g. resin acids)	+	--	Measurable, need specific chemical analyses (Offline)	Diluted flue gas	Levoglucosan is the tracer of poor wood combustion.
Polychlorinated dibenzo-para-dioxins and Furans (PCDD/F) and polychlorinated biphenyls (PCBs)	+++	--	Not easily measurable, need specific chemical analyses (Offline)	Diluted flue gas	Depends on the Cl content of fuels and need poor combustion condition
Brown carbon (BrC)		++/-	Not easily measurable, need specific chemical analyses (Offline)	Diluted flue gas	This needs more studies at least for residential combustion

Results: Summary table from literature study

Parameter	Health effects	Climate effects - Cooling + warming	Measurable/non-measurable (Online)	Location of sampling	Remarks
Secondary organic aerosols (SOAs)	+	- -	Only scientifically measurable (Offline)	Diluted flue gas	Due to the transformation from POAs to SOAs, particles have different health impacts. Difficult to measure all compositions of SOAs due to the lack of knowledge on how they are formed. More basic studies are required. SOA emission factors may be estimated based on specific VOCs.
Secondary inorganic aerosols (SIAs)	++	- -	Only scientifically measurable (Offline)	Diluted flue gas	Important information for climate modelling.

Concluding remarks

PM emissions obliged to measure now	Other Important PM emission parameters	Measurability
Ecodesign regulation 2022: PM, NO_x, OGC/THC, CO – for boilers and wood stoves but not e.g. for sauna stoves. **Construction product regulation (CPR):** Emission testing for new appliances based on testing standards – standards are under review, after review Ecodesign compounds will be needed to measure.	PM2.5, black carbon (BC) or alternatively elemental carbon (EC), individual volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), particle mass, Particle size distribution (PSD), and secondary aerosols (SOAs + SIAs)	**Measurable in type tests**: PM, CO, THC, NOx **Also measurable**: PM2.5, BC, EC, OC, number, size distributions, LDSA, PAHs, single VOCs, SOA potential!
EMEP guidebook suggestions: Solid biomass: NO_X, CO, NMVOC, SO_X, NH_3, TSP (total particles), PM10 (total particles, 95% of TSP), PM2.5 (total particles, 93% of TSP), BC (based on total partciels, 10%), PB, Cd, Hg, AS, Cr, Cu, Ni, Se, Zn, PCBs, PCDD/F, Benzo (a) pyrene, Benzo (b) fluoranthene, Benzo (k) fluoranthene, Indeno (1,2, 3-Cd) Pyrene, HCB	**Important for health**: PM2.5, UFP, PSD, BC, PAH, Metals… **Important for climate**: BC, BrC, AAE, OM2.5, PSD,	**Not easily measurable**: Real-time chemical composition, specific compounds (PCDD/F)… real SOA

- Large gaps between needed and important parameters
- Final evaluation of the PM emission components
- Instrumentations – Cost effective, appropriate and analogous instruments

Please send your proposal about the parameters to be measured at karna.dahal@uef.fi

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Thank you for listening!

Time for discussions!

https://sites.uef.fi/real-life-emissions/

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