REVIEW OF PARTICULATE EMISSIONS PRODUCED FROM THE SMALL SCALE SOLID FUEL COMBUSTION

Summary and Key messages of Action A2 report

25 NOV 2022

Authors:
Karna Dahal (UEF) & Jarkko Tissari (UEF)

Contributors:
Hans Hartmann (TFZ), Claudia Schön (TFZ),
Isaline Fraboulet (INERIS), Benjamin Cea (INERIS),
Petr Kubesa (VSB), Juho Louhisalmi (UEF),
Jiri Horak (VSB) and Florian Couvidat (INERIS)

Real-LIFE Emissions

LIFE20 PRE/FI/000006
LIFE PREPARATORY PROJECT 2020
01/05/2021 - 30/04/2024

UNIVERSITY OF EASTERN FINLAND | KUOPIO | JOENSUU

REVIEW OF PARTICULATE EMISSIONS PRODUCED FROM THE SMALL-SCALE SOLID FUEL COMBUSTION

Summary and Key messages of Action A2 report

November 25th 2022 Kuopio, Finland

Authors: Karna Dahal (UEF) & Jarkko Tissari (UEF)
Contributors: Hans Hartmann (TFZ), Claudia Schön (TFZ), Isaline Fraboulet (INERIS), Benjamin Cea (INERIS), Petr Kubesa (VSB), Juho Louhisalmi (UEF), Jiri Horak (VSB) and Florian Couvidat (INERIS)

The Real-Life Emissions project has received funding from the European Union under grant agreement n° LIFE 20 PRE/FI/000006.

Background

Small scale combustions in households emit large quantities of gaseous and particulate emissions mainly due to poor combustion in traditional combustion appliances. Wood is the major fuel (about 43%) but pellets, peat, charcoal, coal and anthracite are also used in the residential combustion in Europe (1). The emissions produced from small scale solid fuel combustion (SSSFC) can be primary and secondary in nature.

Primary particulate matter (PM) includes black carbon (BC), also called elemental carbon (EC) or soot, organic matter (OM), and inorganic species (20,21, 22). Primary organic matter include e.g. polycyclic aromatic compounds (PAHs), sugar compounds (e.g. anhydrosugars), phenolic species, resin acids, oxygenated monoaromatics, dioxins and furans such as polychlorinated dibenzo-dioxins (PCDD/Fs), nitrophenols, dicarboxylic acids (oxalic acid, succinic acid etc.), polyol, multifunctional acids/anhydrides (fumaric acid, malic acid etc.) and fatty acids (oleic acid, decanoic acid) (4,5). The main inorganic species of the particulate emissions are metal oxides (e.g. ZnO) and alkali salts such as potassium chloride (KCl), potassium sulphate (K_2SO_4), potassium carbonate (K_2CO_3) which are formed from volatile ash constitutes (6,7).

Primary gaseous emissions from complete combustion are carbon dioxide (CO_2), nitrogen oxide (NO_x), suphur dioxide (SO_2) and hydrochloric acid (HCl), whereas pollutants from incomplete combustion are carbon monoxide (CO) and volatile organic compounds (VOCs, total amount is defined as organic gaseous carbon (OGC) or total hydrocarbons (THC). The most primary organic compounds in atmosphere are dominated by semi-volatile compounds and undergo gas-to-particle conversion when the exhaust cools down (2). There is also the production of other chlorine (Cl) compounds such as hexachlorobenzene (HCB), and polychlorinated biphenyls (PCBs) but depends on the types of fuels (8–10).

In addition, secondary organic aerosols (SOAs) are formed in atmosphere via various physical and chemical processes such as cooling and dilution, oxidation and photochemical aging of VOCs precursors (2,5,11,12). Secondary inorganic aerosols (SIAs) are also formed due to the gas to particle conversion of precursors such as SO_2 and NO_X (2,13,14).

Furthermore, particles have also physical properties such as particle mass, number, size, size distribution, surface area, volume, density, morphology and optical properties (e.g. light absorption, adsorption, and light scattering). PM and number concentration and their size distributions are widely used in literature to assess health and environmental effects (3,15). To evaluate the important components of emissions from SSSFC, it is imperative that all released emissions from combustion sources are measured with appropriate measurement techniques. At the moment, not all emissions (e.g. condensables, SOAs, some important PAHs) are not measured by individual member countries. Thus, particle emissions in the atmosphere is poorly represented in existing emission data (2). The most important issue is the exclusion of some of the health and climate affecting particulate emission components and accounting of real-life emissions. The purposes of this literature review are: a) to provide an overview of the particulate and gaseous emission components generated from SSSFC appliances, b) to understand the health and environmental effects of PM emission components and physical parameters from SSSFC, c) to evaluate and select the most important combustion emission components to be measured based on their adverse effects on health and environment.

Health effects

Concerning the health effects of gaseous emissions, exposure to SO_2 can cause inflammation and irritation of the respiratory system can affect lung function, worsen asthma attacks, and worsen existing heart disease in sensitive groups (16). With high concentration, CO can limit the transport of oxygen in human body which can result in dizziness, over unconsciousness to eventually death (17). Exposure to NO_x can result in respiratory tract irritation (17). VOCs can cause symptoms such as irritations of the nose, throat, and eyes, cause headaches, nausea, dizziness, impaired concentration, and allergic skin reactions. In the case of chlorinated compounds, HCl is corrosive to skins, possibly carcinogenic and toxic to humans (18–20).

Particle emissions are very important in terms of health effects. PM2.5 is regarded as the most detrimental factor of the PM emissions as it can be breathed more deeply into the lungs and remains suspended for a longer period of time (3,21,22). Particle size influence lung deposition, with nano-sized particles accumulating in the cells at a faster rate than larger particles (23,24). With high particle number concentrations, acute toxicity has also been reported in murine macrophages (25–27). Lung deposition surface area (LDSA) is important parameter as many harmful constituents are on the surface of particles (28). Similarly, particle shape plays an important role in describing particle behavior at the cell membrane and inside the cell (29).

Recent studies have shown that inhalation of BC (e.g. diesel soot) is associated with production of reactive oxygen species (ROS), inflammation, respiratory and cardiovascular disease and cancer (4)(30). PAH constituents have detrimental health effects such as DNA damage, cell damage, different type of cancers and cardiopulmonary mortality (22). In short-term, PAHs can cause eye and skin irritation, nausea, vomiting and inflammation (26,31,32)._Eight PAHs considered as possible carcinogens are: benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene (B(a)P), dibenzo (a,h)anthracene, indeno (1,2,3-cd)pyrene and benzo (g,h,i) perylene (33). At the moment, the EMEP guidebook includes only four PAHs.

With regard to health effects of heavy metals and alkali salts, these substances can be responsible for both inflammatory responses and cell death in epithelial cells (31,34). Some metals such as Fe, Cu, Cr, Va, and Zn can act as catalyst to form ROS (26,32). Some other metals such as Fe and Al are related to genotoxicity (35) while Zn is also associated with cardiovascular mortality and morbidity (30). Dioxins, furans and chlorinated compounds (PCDD/Fs, PCBs) have several carcinogenic, genotoxic and dermatological effects (36).

There is complexity in the determination of health effects of SSSFC emissions. It is not easy to determine the exposure effects of individual compounds in real life due to mixing of different physical and chemical properties of PM. Most studies show that the PM2.5 mass fraction is mainly connected to health effects. Exposure of high daily PM2.5 concentrations from SSFC can easily show irritation symptoms to people with respiratory diseases, elders and small children. It can worsen the cardiovascular and respiratory symptoms and infections to heart and respiratory patients requiring hospitalization. Exposure to smoke for several years or decades increases the risk of developing chronic heart and respiratory diseases and increases premature deaths among those suffering from these long-term diseases. With continuous high concentration of particles for few days can even cause deaths related to heart and respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD). The health effects of wood smoke are similar to that of traffic exhaust and cigarette smoke, which is very similar in composition to smoke from incomplete combustion. It has not been possible to determine a concentration for particles below which health hazards would no longer occur.

Environmental effects

The pollutants from SSSFC have a lot of detrimental environmental effects. CO_2 causes acidification of sea water and affects the photosynthesis process (25). It is the most potent radiative/climate forcing greenhouse gas and strongest contributor to current global warming and climate change. N_2O shows warming effects in the atmosphere. NO_x react with VOCs resulting to the formation of tropospheric ozone (O_3) (17,37) but it can destruct the stratospheric ozone layer (17,25). NO_x also contributes to acidification, eutrophication, and photochemical smog (17,25). SO_2 has a cooling effect as it forms light reflecting particles in the atmosphere that reduces radiative forcing (38). SO_2 also induces acidification (e.g. H_2SO_4), and ozone (O_3) emissions which adversely affect on vegetation and contribute to global warming and climate change (25,39). CO does not have climate effects directly but its presence in the atmosphere can help in the production of greenhouse gases such as methane (CH_4) and CO_2 (40). VOCs can play an important role in the formation of ozone and growth of PM2.5 concentration by photochemical smog (39). Methane is a greenhouse gas having significant warming impacts [GWP (CH_4) = 25 x (CO_2)] and a precursor of ground level ozone (25). The ground level ozone causes oxidative damage in vegetation (39). PAHs emitted in the atmosphere partition between gas and particulate phases and undergo atmospheric depositions on plants and soils (41,42).

Physical properties of PM impact greatly on cloud formation, absorption and refraction of the radiation and formation of condensation sink. The shape of the particles affect various climatic parameters such as optical properties and lifetime in the atmosphere (29). Optical properties of particles are also important parameters to determine the absorbing capacity of the specific particulate emissions (e.g. BC and EC) that are directly linked to climate forcing (43,44). Ultrafine particles (< 100 nm) may affect the cloud formation and other climatic activities. Regarding particle number concentration, there is no clear answer for its direct impact to climate but in some literature it is described as an important parameter for cloud formation processes through cloud condensation nuclei (45–47).

BC particles in the atmosphere absorb sunlight and emit heat radiation to the surroundings (38). It can also alter the atmospheric temperatures profile and cloud distribution, thereby, influencing the brown cloud formation, droplet formation, and microphysical properties and precipitation of the atmosphere (38,48–50). Deposition of BC on ice or snow in cryosphere decreases the albedo of the surface which stimulates the sunlight absorption and accelerate the melting of glaciers and ice sheet (38,51). Regarding other organics, BrC is potent to light absorption (5). It also changes the optical properties and chemical composition of aerosols that can affect cloud formation (52). Organic aerosols can contribute significantly to both visibility degradation and direct aerosol climate forcing due to its effective light scattering property and play an important role in various aerosol-cloud interactions due to its water-soluble property (53,54). During the atmospheric transformation and SOA formation processes, organic aerosols are transformed which poses environmental risks extensively (55,56). It is not clearly understood about the health and environmental effects of SOAs but some studies urge SOA particles can have negative impact on the environment.

Similarly, presence of sulfate, nitrate and ammonium compounds mainly of intermediate sizes in SIAs can modify the properties of clouds and affect the climate (14). Inorganic aerosols in phase reactions with other pollutants can cause severe environmental degradations such as ozone layer depletion, air quality deterioration, smoke-fog related accidents and acid rain formation (14). For chlorinated compounds, HCl causes environmental degradation due to its acidic nature which affects food and ecosystem. In addition, HCl can also damage the combustion appliance due to corrosion.

Key Messages

Based on the literature review, it can be stated that residential combustion produces significant amount of atmospheric emissions which cause several health and environmental effects. Key points of the report are below:

- The most important emission components to be measured concerning adverse health and environmental effects are PM2.5, black carbon (BC) or alternatively elemental carbon (EC), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), particle number, particle size distribution, lung deposition surface area (LDSA) concentration, and secondary aerosols (SOAs + SIAs). All these emission compounds can be measured with available measurement systems but a single set up for the measurement needs to be established.
- PCDD/F, PCB, and HCB emissions from residential combustion in the EU are emitted in very low concentrations, this can sometimes make difficulty in measurement. Nevertheless, PCDD/F and HCB emissions have already been included in the EU guidebook.
- Only four single PAH compounds have been included in the EMEP guidebook 2019 although several other PAH elements are also harmful for health and environment which should be included in future measurement standards.
- In the case of particle number and size distribution, these are important in terms of health and environmental effects, but the particle number concentration is not correlated to other physical and chemical properties of emission compounds and cannot be used as predictors (57). Yet, particle mass concentration (PM2.5) and size distribution (e.g. ultrafine particles are important) should be reported.
- Surface area concentration/lung deposition surface area (LDSA) and optical properties (e.g. Absorption Angstrom Exponent (AAE) and single scatter albedo (SSA)) are also important parameters for determining the health and environmental effects of residential combustion emissions.
- Physical and chemical properties of the particles are mixed which makes it difficult to differentiate the effects of single properties.
- SOAs enhance the concentration of PM in the atmosphere which simultaneously increases the impacts on health and environment. However, SOA precursors and its formation process are not understood well. Thus, SOAs should be studied more extensively in research, be measured in the laboratory simultaneously with other emissions, and be included in future emission inventories.
- All targeted emissions except SOAs can be measured with various available instruments in the market, but which instruments are the best for the measurement in terms of maturity and efficacy of the technology and the costs associated with it are important.
- For short term, measurement of only particulate matter (PM) including gaseous compounds THC, NO_X and CO is appropriate for legislation but for long term, secondary aerosols or SOA formation potential via VOC precursors should be included. However, for other needs (e.g. inventory, modelling), the list of EMEP compounds, particle number and particle size, and the conversion factor for old appliances (i.e. portion of condensables of total PM) should be included for the measurement and reporting.

References

1. Malico I, Nepomuceno Pereira R, Gonçalves AC, Sousa AMO. Current status and future perspectives for energy production from solid biomass in the European industry. Renew Sustain Energy Rev [Internet]. 2019;112:960–77. Available from: https://www.sciencedirect.com/science/article/pii/S1364032119304150

2. Robinson AL, Grieshop AP, Donahue NM, Hunt SW. Updating the conceptual model for fine particle mass emissions from combustion systems. J Air Waste Manag Assoc. 2010;60(10):1204–22.

3. M. Obaidullah SB and JDR. An Overview of PM Formation Mechanisms from Residential Biomass Combustion and Instruments Using in PM Measurements. Vol 12. 2018;12(May):41–50.

4. WHO. Residential heating with wood and coal: Healaath impacts and policy options in Europe and North America. UN City; 2015.

5. Olsen Y, Nøjgaard JK, Olesen HR, Brandt J, Sigsgaard T, Pryor SC, et al. Emissions and source allocation of carbonaceous air pollutants from wood stoves in developed countries: A review. Atmos Pollut Res [Internet]. 2020;11(2):234–51. Available from: https://doi.org/10.1016/j.apr.2019.10.007

6. Sippula O. Fine particle formation and emissions in biomass combustion [Internet]. University of Eastern Finland; 2010. Available from: https://www.atm.helsinki.fi/faar/reportseries/rs-108.pdf

7. Ozgen S, Becagli S, Bernardoni V, Caserini S, Caruso D, Corbella L, et al. Analysis of the chemical composition of ultrafine particles from two domestic solid biomass fired room heaters under simulated real-world use. Atmos Environ [Internet]. 2017;150:87–97. Available from: http://dx.doi.org/10.1016/j.atmosenv.2016.11.048

8. Ulrich Quass, Fermann M, Bröker G. The European Dioxin Emission Inventory Stage II [Internet]. Nordrhein-Westfalen; 2000. Available from: https://ec.europa.eu/environment/archives/dioxin/pdf/stage2/volume_2.pdf

9. Nielsen O-K, Plejdrup MS, Dore C, Nielsen M, Kubica K, Paradiz B, et al. EMEP/EEA air pollutant emission inventory guidebook 2019. Αγαη. 2019;8(5):55.

10. Hedman B, Näslund M, Marklund S. Emission of PCDD/F, PCB, and HCB from Combustion of Firewood and Pellets in Residential Stoves and Boilers. Environ Sci Technol [Internet]. 2006 Aug 1;40(16):4968–75. Available from: https://doi.org/10.1021/es0524189

11. Tkacik DS, Robinson ES, Ahern A, Saleh R, Stockwell C, Veres P, et al. A dual-chamber method for quantifying the effects of atmospheric perturbations on secondary organic aerosol formation from biomass burning emissions. J Geophys Res. 2017;122(11):6043–58.

12. Bruns EA, El Haddad I, Slowik JG, Kilic D, Klein F, Baltensperger U, et al. Identification of significant precursor gases of secondary organic aerosols from residential wood combustion. Sci Rep. 2016;6(February):1–9.

13. Fu X, Wang S, Chang X, Cai S, Xing J, Hao J. Modeling analysis of secondary inorganic aerosols over China: pollution characteristics, and meteorological and dust impacts. Sci Rep [Internet]. 2016;6(1):35992. Available from: https://doi.org/10.1038/srep35992

14. Allen SAA, Ree AG, Ayodeji SAM, Deborah SAE, Ejike OM. Secondary inorganic aerosols:

impacts on the global climate system and human health. Biodivers Int J [Internet]. 2019;3(6). Available from: http://medcraveonline.com/BIJ/secondary-inorganic-aerosols-impacts-on-the-global-climate-system-and-human-health.html

15. Miettinen M, Tissari J, Jokiniemi J. Determination of particulate matter emissions of solid 1fuel burning appliances and boilers: Dilution methods and the effect of dilution on partitioning of semivolatile organics between Gas and particle phase. University of Eastern Finland; 2012.

16. National park services. Sulfur Dioxide Effects on Health [Internet]. Webpage. 2018. Available from: https://www.nps.gov/subjects/air/humanhealth-sulfur.htm

17. Tytgat T, Walpot G, Cools J, Lenaerts S. Literature review of emissions of modern wood combustion devices and emissions reducing technologies , under real-life conditions FINAL REPORT [Internet]. Flanders Enviromental Agency. 2017. Available from: https://en.vmm.be/publications/literature-review-of-emissions-of-modern-wood-combustion-devices-and-emissions-reducing-technologies-under-real-life-conditions

18. EPA. Hydrochloric Acid (Hydrogen Chloride) [Internet]. 2016. Available from: https://www.epa.gov/sites/default/files/2016-09/documents/hydrochloric-acid.pdf

19. Department of Health. Summary of Possible Health Effects Exposure : How can a person come in contact with it ? How is HCB used ? Toxicity : What are its possible health HCB has been classified as possibly carcinogenic [Internet]. Vermont; Available from: https://www.healthvermont.gov/sites/default/files/documents/pdf/ENV_CDP_118_74_1_Hexachlorobenzene.pdf

20. EPA. Hexachlorobenzene [Internet]. 2000. Available from: https://www.epa.gov/sites/default/files/2016-09/documents/hexachlorobenzene.pdf

21. Pope CA, Dockery DW. Health effects of fine particulate air pollution: Lines that connect. J Air Waste Manag Assoc. 2006;56(6):709–42.

22. Nuutinen K. Polycyclic Aromatic Hydrocarbon Emissions From Residential Wood Combustion [Internet]. Vol. 184, Report Series in Aerosol Science. 2016. 184 p. Available from: http://www.atm.helsinki.fi/FAAR/

23. Corsini E, Marinovich M, Vecchi R. Ultrafine particles from residential biomass combustion: A review on experimental data and toxicological response. Int J Mol Sci. 2019;20(20).

24. Yue H, Wei W, Yue Z, Lv P, Wang L, Ma G, et al. Particle size affects the cellular response in macrophages. Eur J Pharm Sci [Internet]. 2010;41(5):650–7. Available from: https://www.sciencedirect.com/science/article/pii/S0928098710003180

25. Jalava PI, Happo MS, Kelz J, Brunner T, Hakulinen P, Mäki-Paakkanen J, et al. Invitro toxicological characterization of particulate emissions from residential biomass heating systems based on old and new technologies. Atmos Environ. 2012;50(2012):24–35.

26. Dilger M, Orasche J, Zimmermann R, Paur HR, Diabaté S, Weiss C. Toxicity of wood smoke particles in human A549 lung epithelial cells: the role of PAHs, soot and zinc. Arch Toxicol. 2016;90(12):3029–44.

27. Tapanainen M, Jalava PI, Mäki-Paakkanen J, Hakulinen P, Happo MS, Lamberg H, et al. In vitro immunotoxic and genotoxic activities of particles emitted from two different small-scale wood combustion appliances. Atmos Environ [Internet]. 2011;45(40):7546–54. Available from: https://www.sciencedirect.com/science/article/pii/S1352231011003360

28. Kocbach Bølling A, Pagels J, Yttri KE, Barregard L, Sallsten G, Schwarze PE, et al. Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties. Part Fibre Toxicol. 2009;6(May 2014).

29. Leskinen J, Ihalainen M, Torvela T, Kortelainen M, Lamberg H, Tiitta P, et al. Effective density and morphology of particles emitted from small-scale combustion of various wood fuels. Environ Sci Technol. 2014;48(22):13298–306.

30. Janssen NAH, Hoek G, Simic-Lawson M, Fischer P, van Bree L, Brink H Ten, et al. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with pm10 and pm2.5. Environ Health Perspect. 2011;119(12):1691–9.

31. Uski O, Jalava PI, Happo MS, Leskinen J, Sippula O, Tissari J, et al. Different toxic mechanisms are activated by emission PM depending on combustion efficiency. Atmos Environ [Internet]. 2014;89:623–32. Available from: http://dx.doi.org/10.1016/j.atmosenv.2014.02.036

32. Ihantola T, Di Bucchianico S, Happo M, Happo M, Ihalainen M, Uski O, et al. Influence of wood species on toxicity of log-wood stove combustion aerosols: A parallel animal and air-liquid interface cell exposure study on spruce and pine smoke. Part Fibre Toxicol. 2020;17(1):1–26.

33. Srogi K. Monitoring of environmental exposure to polycyclic aromatic hydrocarbons: A review. Environ Chem Lett. 2007;5(4):169–95.

34. Kasurinen S, Jalava PI, Happo MS, Sippula O, Uski O, Hanna Koponen, 1 J€urgen Orasche, 2, 3 Ralf Zimmermann, 2, 3, 4 Jorma Jokiniemi 1, et al. Particulate Emissions from the Combustion of Birch, Beech, and Spruce Logs Cause Different Cytotoxic Responses in A549 Cells. Environ Toxicol. 2016;1487–99.

35. Corsini E, Ozgen S, Papale A, Galbiati V, Lonati G, Fermo P, et al. Insights on wood combustion generated proinflammatory ultrafine particles (UFP). Toxicol Lett. 2017;266:74–84.

36. Hedman B, Näslund M, Marklund S. Emission of PCDD/F, PCB, and HCB from combustion of firewood and pellets in residential stoves and boilers. Environ Sci Technol. 2006;40(16):4968–75.

37. Czech H, Miersch T, Orasche J, Abbaszade G, Sippula O, Tissari J, et al. Chemical composition and speciation of particulate organic matter from modern residential small-scale wood combustion appliances. Sci Total Environ [Internet]. 2018;612:636–48. Available from: https://doi.org/10.1016/j.scitotenv.2017.08.263

38. Savolahti M. Climate and health impacts of residential wood combustion in Finland [Internet]. Aalto University; 2020. Available from: https://aaltodoc.aalto.fi/handle/123456789/43035

39. Department Environment For Rural Affairs Food. Emissions of air pollutants in the UK – Non-methane volatile organic compounds (NMVOCs) [Internet]. National statistics. 2021. Available from: https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs

40. Adam Voiland. Fourteen years of carbon monoxide from MOPITT [Internet]. News. 2015. Available from: https://climate.nasa.gov/news/2291/fourteen-years-of-carbon-monoxide-from-mopitt/

41. Desalme D, Binet P, Chiapusio G. Challenges in Tracing the Fate and Effects of Atmospheric

Polycyclic Aromatic Hydrocarbon Deposition in Vascular Plants. Environ Sci Technol [Internet]. 2013 May 7;47(9):3967–81. Available from: https://doi.org/10.1021/es304964b

42. Prince U. Environmental Effects of Polycyclic Aromatic Hydrocarbons. J Nat Sci Res. 2015 Jan 1;5.

43. Roden CA, Bond TC, Conway S, Pinel ABO. Emission Factors and Real-Time Optical Properties of Particles Emitted from Traditional Wood Burning Cookstoves. Environ Sci Technol [Internet]. 2006 Nov 1;40(21):6750–7. Available from: https://doi.org/10.1021/es052080i

44. Collaud Coen M, Andrews E, Asmi A, Baltensperger U, Bukowiecki N, Day D, et al. Aerosol decadal trends – Part 1: In-situ optical measurements at GAW and IMPROVE stations. Atmos Chem Phys. 2013 Jan 1;13.

45. Denier Van Der Gon HAC, Bergström R, Fountoukis C, Johansson C, Pandis SN, Simpson D, et al. Particulate emissions from residential wood combustion in Europe - revised estimates and an evaluation. Atmos Chem Phys. 2015;15(11):6503–19.

46. Lim MT, Phan A, Roddy D, Harvey A. Technologies for measurement and mitigation of particulate emissions from domestic combustion of biomass: A review. Renew Sustain Energy Rev [Internet]. 2015;49:574–84. Available from: http://dx.doi.org/10.1016/j.rser.2015.04.090

47. Janhäll S, Bäckström D, Gustavsson L. Emissions of particles and organic compounds from small and medium scaled biomass combustion [Internet]. 2018. Available from: http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1252254&dswid=-7429

48. Savolahti M, Karvosenoja N, Tissari J, Kupiainen K, Sippula O, Jokiniemi J. Black carbon and fine particle emissions in Finnish residential wood combustion: Emission projections, reduction measures and the impact of combustion practices. Atmos Environ [Internet]. 2016;140:495–505. Available from: http://dx.doi.org/10.1016/j.atmosenv.2016.06.023

49. Smita S, Gupta SK, Bartonova A, Dusinska M, Gutleb AC, Rahman Q. Nanoparticles in the environment: assessment using the causal diagram approach. Environ Heal [Internet]. 2012;11(1):S13. Available from: https://doi.org/10.1186/1476-069X-11-S1-S13

50. Trojanowski R, Fthenakis V. Nanoparticle emissions from residential wood combustion: A critical literature review, characterization, and recommendations. Renew Sustain Energy Rev [Internet]. 2019;103(March 2018):515–28. Available from: https://doi.org/10.1016/j.rser.2019.01.007

51. Bhattarai H, Saikawa E, Wan X, Zhu H, Ram K, Gao S, et al. Levoglucosan as a tracer of biomass burning: Recent progress and perspectives. Atmos Res [Internet]. 2019;220(November 2018):20–33. Available from: https://doi.org/10.1016/j.atmosres.2019.01.004

52. Kuang Y, Shang J, Chen Q. Effect of ozone aging on light absorption and fluorescence of brown carbon in soot particles: The important role of polycyclic aromatic hydrocarbons. J Hazard Mater [Internet]. 2021;413:125406. Available from: https://www.sciencedirect.com/science/article/pii/S0304389421003691

53. Li Liu, Ye Kuang, Miaomiao Zhai, Biao Xue, Yao He, Jun Tao, Biao Luo, Wanyun Xu, Jiangchuan Tao, Changqin Yin, Fei Li, Hanbing Xu, Tao Deng, Xuejiao Deng, Haobo Tan and MS. Strong light scattering of highly oxygenated organic aerosols impacts significantly on visibility degradation. Atmos Chem Phys [Internet]. 2022; Available from:

https://acp.copernicus.org/preprints/acp-2022-218/

54. Graham B, Mayol-Bracero O, Guyon P, Roberts G, Decesari S, Facchini M, et al. Water-soluble organic compounds in biomass burning aerosols over Amazonia - 1. Characterization by NMR and GC-MS. J Geophys Res v107. 2002 Sep 1;107.

55. Hodzic A, Kasibhatla PS, Jo DS, Cappa CD, Jimenez JL, Madronich S, et al. Rethinking the global secondary organic aerosol (SOA) budget: stronger production, faster removal, shorter lifetime. Atmos Chem Phys [Internet]. 2016 Jun 29;16(12):7917–41. Available from: https://acp.copernicus.org/articles/16/7917/2016/

56. Hartikainen A, Tiitta P, Ihalainen M, Yli-Pirilä P, Orasche J, Czech H, et al. Photochemical transformation of residential wood combustion emissions: Dependence of organic aerosol composition on OH exposure. Atmos Chem Phys. 2020;20(11):6357–78.

57. Wåhlin P, Olesen HR, Bossi R, Stubkjær J. Air pollution from residential wood combustion in a Danish village. International Centre for Indoor Environment and Energy Department of Civil Engineering Technical University of Denmark. 2010. 1–18 p.

UNIVERSITY OF EASTERN FINLAND

Harmonizing reliable test procedures representing real-LIFE air pollution from solid fuel heating appliances - **Real-LIFE Emissions** project.

Project Partners

- University of Eastern Finland (UEF)
- Technical University in Ostrava (VSB)
- The French National Institute for Industrial Environment and Risks (INERIS)
- Technology and Support Centre in the Centre of Excellence for Renewable Resources (TFZ)

VSB TECHNICAL UNIVERSITY OF OSTRAVA | ENERGY AND ENVIRONMENTAL TECHNOLOGY CENTRE | ENERGY RESEARCH CENTRE

TFZ

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

INERIS
maîtriser le risque
pour un développement durable