Atmospheric Environment 140 (2016) 495–505

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

# Black carbon and fine particle emissions in Finnish residential wood combustion: Emission projections, reduction measures and the impact of combustion practices

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## HIGHLIGHTS

- Emissions from RWC are highly dependent on the heating appliance.
- The varying appliance stock needs to be acknowledged in emission inventories.
- RWC is the biggest source of black carbon and $PM_{2.5}$ emissions in Finland.
- Technical and non-technical measures exist for reducing RWC emissions.

## ARTICLE INFO

*Article history:*
Received 10 February 2016
Received in revised form
7 June 2016
Accepted 8 June 2016
Available online 11 June 2016

*Keywords:*
Black carbon
$PM_{2.5}$
Residential wood combustion
Emission
Reduction measure

## ABSTRACT

Residential wood combustion (RWC) is a major source of black carbon (BC) and $PM_{2.5}$ emissions in Finland. Making a robust assessment of emissions on a national level is a challenge due to the varying heater technologies and the effect of users' combustion practices. In this paper we present an update of the emission calculation scheme for Finnish RWC, including technology-specific emission factors based on national measurements. Furthermore, we introduce a transparent method to assess the impact of poor combustion practices on emissions. Using a Finnish emission model, we assessed the emissions in 2000, 2010 and 2030, as well as the cost-efficiency of potential emission reduction measures. The results show that RWC is the biggest source of both $PM_{2.5}$ and BC emissions in Finland, accounting for 37% and 55% of the total respective emissions. It will also remain the biggest source in the future, and it's role may become even more pronounced if wood consumption continues to increase. Sauna stoves cause the most emissions and also show the biggest potential for emission reductions. Informational campaigns targeted to improve heater users' combustion practices appear as a highly cost-efficient measure, although their impact on country-level emissions was estimated to be relatively limited.


## 1. Introduction

Residential wood combustion (RWC) is the largest single source of black carbon (Finnish Environment Institute, 2015; Kupiainen et al., 2006) and fine particle emissions (Karvosenoja et al., 2010) in Finland. Wood combustion has a profound status in Finnish culture and it has been promoted as domestic and carbon neutral fuel. In recent years, however, there has been a rising scientific interest in the negative effects of fine particulate matter ($PM_{2.5}$) emissions from wood combustion. Emissions occurring in residential areas may deteriorate local air quality and cause adverse human health impacts (Yli-tuomi et al., 2015). In addition, black carbon (BC), an important component of $PM_{2.5}$ from RWC, is seen as a potential factor in global warming (Bond et al., 2013).

Black carbon is formed in wood burning as a product of incomplete combustion. Most particles in the atmosphere reflect sunlight and thus act as climate cooling agents, but black carbon absorbs it and has a strong warming impact (Shindell et al., 2012). It

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http://dx.doi.org/10.1016/j.atmosenv.2016.06.023
1352-2310/

also greatly decreases the albedo of a bright surface and thus accelerates the melting of ice and snow when deposited on it. In addition, black carbon has indirect climate effects as it influences the formation and properties of clouds. Uncertainties remain as to the significance of BC to global warming, but it is suggested that it's warming effect could be especially important in the Arctic area (ACAP, 2014; AMAP Assessment, 2015).

The adverse health impacts of $PM_{2.5}$, including the particles from RWC, are well documented (WHO, 2013). RWC causes considerable population exposure to $PM_{2.5}$ in Finland (Karvosenoja et al., 2010) and wood consumption has been on the rise. Most of the main economic sectors causing PM emissions, e.g. traffic and industry, are covered by strict legislation and their emissions have decreased during the past 20 years. This trend is expected to continue in the future. RWC appliances, however, are currently not under such legislation, and they will become an even more dominant source of emissions in the future. Ecodesign (2009/125/EY) requirements for solid fuel local space heaters and boilers, intended to come into force by 2022, will be the first legislation addressing these emissions in Finland.

The assessment of country-level RWC emissions involves challenges due to a diverse appliance stock, lack of comprehensive registers and the acquisition of fuels from uncommercial sources (Karvosenoja, 2008; Fountoukis et al., 2014). In addition, several studies (e.g. Frey et al., 2009; Schmidl et al., 2011; Tissari et al., 2008) have shown that smouldering combustion caused by poor heater operation practices can significantly increase the emissions. Therefore using emission factors derived from laboratory measurements with accomplished heater operation may underestimate real-world emissions. For these reasons the uncertainties in RWC emission estimates are higher than in many other major source sectors. Karvosenoja et al. (2008) estimated the uncertainty of the Finnish RWC emission inventory for $PM_{2.5}$ to be $-36\% \ldots +50\%$ (with 95% confidence interval). This uncertainty analysis was carried out for an earlier version of the emission calculation system, of which a further development is presented in this paper.

In this study, we present the updated RWC emission calculation scheme for black carbon and primary $PM_{2.5}$. We also introduce a novel method for transparent estimation of varying combustion practices and their effect on emissions. Emission calculations by appliance type are made for the years 2000 and 2010, as well as projections for 2030. In addition to the Finnish official future projection, we developed and studied two alternative wood use estimates for 2030. Furthermore, we assess the potential and cost-efficiency of reduction measures that could be applied to the RWC sector.

The objectives of the study were (1) to evaluate the future evolution of the emissions and the contribution of different heater and boiler types, using the updated calculation scheme with latest national emissions measurements, (2) to estimate the impact of user behavior on emissions and (3) to assess the plausibility of various measures for emission reductions.

## 2. Materials & methods

The update of the RWC emission calculation presented in this paper was done in the Finnish Regional Emission Scenario (FRES) model (Karvosenoja, 2008). The model includes a coherent calculation for multiple pollutants from anthropogenic emission sources with the ability to disaggregate emissions spatially and temporally. The main features of the FRES model are presented in Karvosenoja (2008) and Karvosenoja et al. (2010). The earlier version of the calculation for the RWC sector is presented in Karvosenoja et al. (2008) for $PM_{2.5}$ and Kupiainen et al. (2006) for BC. The following presents country level calculation parameters for the RWC sector with appliance-specific emission factors and the new approach addressing the impact of user practices.

The estimation of wood consumption in the residential sector in 2000 and 2010 is from Statistics Finland (2013).The total consumption values in the statistics are based on national questionnaire surveys carried out by the Finnish Forest Research Institute, Metla (Torvelainen, 2009). The latest Metla survey for the heating season 2007/2008 was also used in the FRES model to estimate the wood consumption in different types of boilers and heaters.

### 2.1. Emission factors

We added the technology specific emission factors for BC and updated the emission factors for $PM_{2.5}$ in the FRES -model as the basis for emission calculations. As the renewed emission calculation scheme aims to estimate the effect of operating practices on emissions, we estimated emission factors for both normal and smouldering combustion for each type of heater. The calculation of the applied emission factors using assumptions on user profiles is explained in the next chapter. Emission factors for smouldering combustion were based on measurements when available and expert opinions in other cases. The emissions from boilers were assumed to be less dependent on the users' behavior and only one emission factor per appliance type was used. Emission factors for each appliance type are shown in Table 1.

The emission data for this study was mainly collected from the database obtained from the measurements at the University of Eastern Finland in 2003–2014. In the selection of emission factors, data from literature was also taken into account in order to complete the database.

For particle measurements, a partial flow from the stack was led through an externally insulated steel pipe. The sample flow was diluted typically in two stages with a porous tube and ejector diluter with filtered air in order to minimize particle losses, to have a well-defined dilution and cooling process and to decrease the particle concentrations and sample temperatures to a sufficiently low degree for the particle analyzers. The sampling system is discussed in more detail in, for example Tissari et al. (2007, 2008, 2009) and is successfully used during varying processes (e.g. Nuutinen et al., 2014), as well as high and low particle concentrations (e.g. Tissari et al., 2015; Lamberg et al., 2011b; Hukkanen et al., 2012) and it is also suitable for different emission sources (e.g. Jalava et al., 2010; Kaivosoja et al., 2013; Kortelainen et al., 2015).

The $PM_1$ samples were collected on filters from diluted gas using a pre-impactor. The filters for gravimetric analysis were kept for 24 h at a constant temperature and a relative humidity before weighing, and were weighed using a microbalance. Most of the particles from small-scale biomass combustion are $PM_1$. The conversion to $PM_{2.5}$ was made using a coefficient of 93/90, based on measurements (Meyer, 2012). The determination of organic carbon (OC) and elemental carbon (EC) concentrations of particle matter were performed from quartz filter samples with a thermal-optical method using a carbon analyzer constructed by Sunset Laboratories (Tissari et al., 2007). The analyses were performed according to the National Institute for Occupational Safety and Health (NIOSH) method 5040. Correction of pyrolytic conversion of OC to EC (Pyrol C) was done by laser transmission measurement.

The measured EC emission factors were assumed to be directly BC, because comparison of light absorbing/scattering properties of particles is very complex and varies between emission sources (e.g. Frey et al., 2014). BC is a term, that describes carbon as measured by light absorption whereas EC is formally defined as a substance containing only carbon and it is usually measured from filter samples with thermal-optical methods (Petzold et al., 2013). Despite intensive efforts during the last few decades, there are no