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

Mikko Savolahti[a*], Niko Karvosenoja[a], Jarkko Tissari[b], Kaarle Kupiainen[a], Olli Sippula[b], Jorma Jokiniemi[b]

[a] Finnish Environment Institute, Mechelininkatu 34a, P.O.Box 140, FI-00251 Helsinki, Finland, firstname.lastname@ymparisto.fi

[b] University of Eastern Finland, Yliopistonranta 1 P.O. Box 1627 FI-70211 Kuopio, Finland, fistname.lastname@uef.fi

[*] Corresponding author. Tel. +358 29 5251595, Fax. +358 9 5490 2190

Abstract

Residential wood combustion (RWC) is the largest 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 emission trends to the year 2030, as well as the cost-efficiency of potential emission reduction measures. The results show that RWC will remain the biggest source of BC and $PM_{2.5}$ emissions in Finland 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 practises appear as a highly cost-efficient measure, although their impact on country-level emissions was estimated to be relatively limited.

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

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 (Shindel et al., 2012). It 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, 2015; 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; Fontoukis, 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%...+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 generally accepted standard methods to measure BC or EC in atmospheric aerosol. It has to be also noted that different methods are also sensitive e.g. to aerosol size distribution and chemical composition. However, different methods seems to generally correlate, e.g. in an urban background comparison campaign, the average values of BC and EC agreed within their standard deviations (Hintzenberger et al., 2006).

Table 1. Emission factors for the residential wood combustion appliance categories for both normal (NC) and smouldering combustion (SC), with the ranges of the measurements shown in parentheses when available. The appliances that were considered to comply with Ecodesign limits are shown in italics.

Boilers	$PM_{2.5}$ [mg MJ^{-1}]		BC [mg MJ^{-1}]		**References**
	NC	SC	NC	SC	
Wood chip boilers, automatic stoke	16 (12-19)	16	1	1	Tissari et al., 2005; Jalava et al., 2012;
Pellet boilers, automatic stoke	20 (5-55)	20	1 (0-8)	1	Tissari et al., 2005; Lamberg et al., 2011a,b;
Manually stoked boilers with accumulator tank	135 (20-422)	135	41	24	Jalava et al., 2012; Gaegauf et al., 2005
Manually stoked boilers, no accumulator tank*	700 (353-2240)	700	210	210	Johansson et al., 2004; Gaegauf et al., 2005
Manually stoked modern boilers	17 (15-18)	17	1	1	Jalava et al., 2012
Wood-fired room heaters					
Open fireplaces and other	578 (303-850)	1155	35 (22-46)	53	McDonald et al. 2000
Kitchen range	48	95	32	48	Tissari et al., 2007
Conventional masonry heaters	93 (19-311)	500 (295-660)	38 (6-96)	127	Tissari et al., 2007; 2008; 2009; Lamberg et al., 2011; Nuutinen et al., 2014
Modern masonry heaters	33 (23-67)	178	15 (8-55)	50	Tissari et al., 2007; 2009; Lamberg et al., 2011; Nuutinen et al., 2014
Masonry ovens	43 (22-86)	87	14 (5-32)	21	Tissari et al., 2007
Sauna stoves	389 (35-1567)	1166	173 (7-330)	260	Tissari et al., 2007; 2009; Lamberg et al., 2011; Hukkanen et al., 2012
Modern sauna stoves	194	583	87	130	**
Wood stoves	77 (56-94)	428	22 (9-28)	74	Tissari et al., 2005; Schmidl et al., 2011; Jalava et al., 2012
Modern wood stoves	49 (48-49)	272	14	47	Schmidl et al., 2011; Jalava et al., 2012

*Manually stoked boilers with no accumulator tank are central heating boilers
**As no emission measurements for modern sauna stoves were found, the emission factors were assumed to be 50% lower than that of conventional ones based on expert estimation.

2.2. The impact of user behavior

We created profiles for three different types of user habits to estimate the total amount of smouldering combustion (Table 2). The share of users in each profile is based on two sets of questionnaires for chimney sweeps: one covering Uusimaa in southern Finland, the other covering the whole of Finland. The share of smouldering combustion takes into account typical user mistakes, namely suboptimal batch sizes and ignition, insufficient air supply and poor quality of fuel (wet wood or waste). We estimated the impact of an informational campaign that educates heater users on proper combustion habits. In a sensitivity study, the range of efficiency for the campaign was from 5% to 50% reduction in total share of smouldering combustion. The assumed best case scenario would mean that roughly 60% of both decent and poor heater users had improved their habits and were moved to the profile above them.

Table 2. Estimation for the share of smouldering combustion in the use of Finnish room heaters. This estimation is applied to all the studied years.

User profiles	**Share of users**	**Share of smouldering combustion**
Good use of heater	55 %	0 %
Decent use of heater	30 %	10 %
Poor use of heater	15 %	50 %
Total share of smouldering combustion for wood-fired room heaters		**10.5%**

2.3. Wood use projections

The baseline scenario is built according to The National Energy and Climate Strategy (MEE, 2013), which assumes that the prevalence of wood heating remains at the current (2011) level. This supposedly leads to a decrease in wood consumption, due to increasing energy efficiency in housing. However, the statistics show that wood consumption has been increasing for the past decades (Statistics Finland, 2013), and recent questionnaires (e.g. Torvelainen, 2009; Makkonen et al., 2012) indicate that people intend to increase wood heating in the coming years. Therefore, we also studied two alternative projections: stagnation, where wood consumption stays at the 2010 level, and continued growth, where RWC increases by 50% from 2010 to 2030 (Fig 1). All scenarios assume a 15% improvement in average energy efficiency of housing from 2011 to 2030.

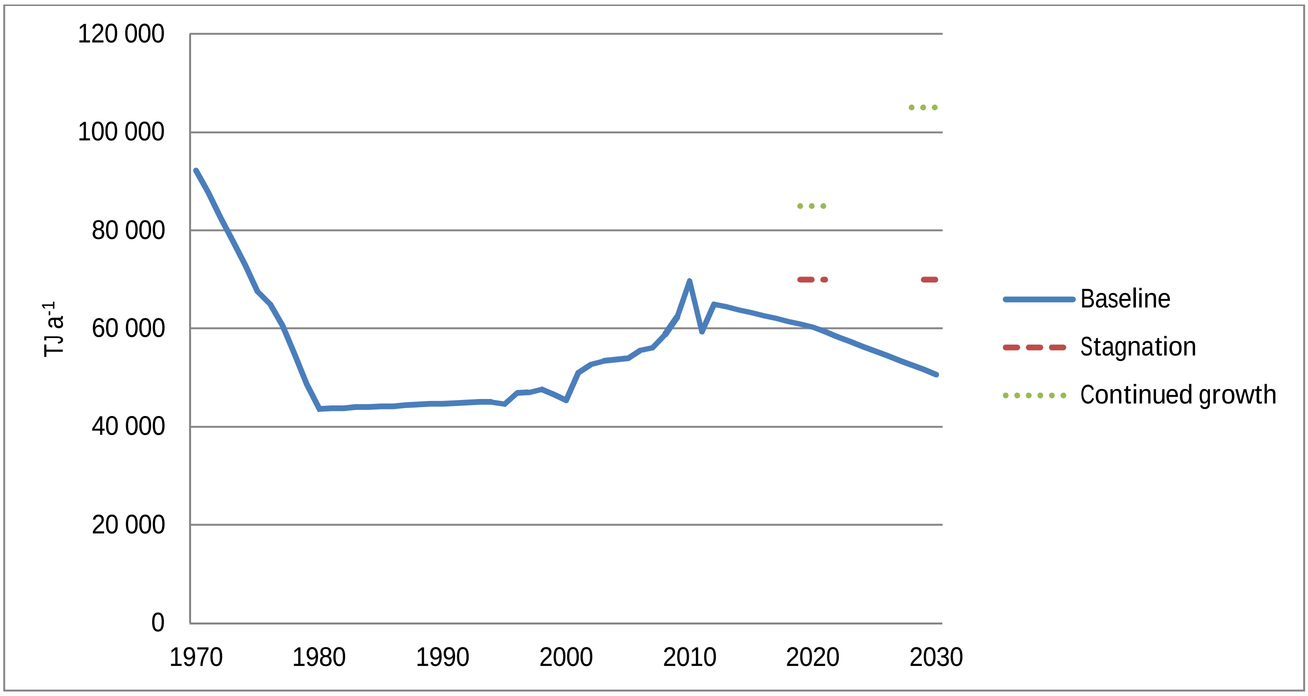

Fig 1. Annual wood use in the RWC sector (Statistics Finland 2013). Includes residential, recreational, commercial and agricultural buildings.

2.4. *Emission reduction measures and costs*

In the No measures scenario, the regeneration of heating appliance stock was assumed to lead to only minor market shares for low-emission heaters. Basically only the technologies that already play a significant role in the market, i.e. modern masonry heaters and pellet boilers, were assumed to become considerably more common by 2030.

With the Ecodesign regulation for boilers and space heaters, only the heating appliances that were estimated to comply with the regulation will stay in the market after 2022. The rest will phase out of the appliance stock as their useful life comes to an end (Table 3). Note that sauna stoves are not included in Ecodesign.

In addition to Ecodesign requirements, three other reduction measures were estimated: 1) National legislation for new sauna stoves starting from 2022: only modern appliances allowed on the market, 2) Informational campaigns for heater users to make their combustion habits cleaner, with the assumed effect ranging from 5% to 50% less smouldering combustion and 3) Additional measures directed to heating boilers, i.e., installation of electric precipitators (ESP), and banning of manually fed boilers with no accumulator tank.

The cost and technical parameters needed to estimate the efficiency and costs of the studied emission reduction measures were estimated based on literature and expert consultations (Table 3). Interest rate for investments was set to be 4%. Operating costs for heaters (Sternhufvud et al., 2004) and ESPs (Lenz et al., 2008) were also taken into account. The fuel cost for logs was estimated to be 71 €/ton (Halkoliiteri 2015), taking into account that a major part of the wood is coming from non-commercial sources. The average useful life of each appliance is used to calculate the renewal rate of the appliance stock, and thus the penetration speed of new technology.

Table 3Values used for cost calculations (Rouvinen et al., 2011; Hulkkonen & Rautanen 2004; Lenz et al., 2008; Sternhufvud et al., 2004)

Appliance	Efficiency	Investment cost [€]	Average useful life [a]	Repayment period [a]
Manually stoked modern boiler	0.9	9000	30	20
Accumulator tank to a manually stoked boiler	0.88	4000	30	20
Conventional masonry heater	0.75	4000	35	20
Modern masonry heater	0.85	6000	35	20
Wood stove	0.45	400	12.5	10
Modern wood stove	0.6	600	20	10
Sauna stove	0.45	400	12.5	10
Modern sauna stove	0.6	800	20	10
ESP	80 %*	1000	-	15

*removal efficiency for $PM_{2.5}$ and BC

An informational campaign can be used as a local as well as a national measure. We studied two cases for the scope of an assumed campaign: 1) all detached and recreational houses, and 2) all detached houses in the municipalities that contain population centers with more than 20 000 inhabitants, i.e., the 30 biggest municipalities in Finland. The cost estimation – including production, printing and distribution of information leaflets, arrangements for lecturers and the payments for experts involved – is based on a recent campaign in the Helsinki metropolitan area. The cost per household in the campaign was €0.31 (Personal communication, Maria Myllynen,Helsinki regional environment authority June 13, 2013).

3. Results and discussion

3.1. *Emissions in 2000, 2010 and 2030*

RWC is the biggest single source of $PM_{2.5}$ and BC in Finland, with the relative shares of the total emissions being 37% and 55% in 2010, respectively (Fig 2). Emissions from the RWC sector were 11.9 Gg a^{-1} (kilotons per year) for $PM_{2.5}$ and 3.6 Gg a^{-1} for BC in 2010 (Table 4). The respective emission estimates for the year 2000 were 8.4 Gg a^{-1} and 2.6 Gg a^{-1}, i.e. the emissions increased 43% and 40% from 2000 to 2010, while the increase in wood consumption was 49%. The slightly less intense increase in emissions compared to wood use is caused by gradual regeneration of heater stock, especially the introduction of modern masonry heaters into the market.

The biggest single source for the RWC sector's emissions were sauna stoves, causing 35% and 46% of $PM_{2.5}$ and BC emissions in 2010, respectively. The respective contribution in wood use was only 13%, which emphasizes the simple design and high emission factors of sauna stoves. Other device categories with relatively high emissions were conventional masonry heaters due to their high wood use and manually stoked boilers without a heat accumulator due to their high emission factors. Masonry heaters have a high mass that efficiently stores the heat and slowly releases it into their surroundings. Manually stoked boilers that don't have an accumulator tank are often used with low thermal output and limited air supply, causing high emissions.

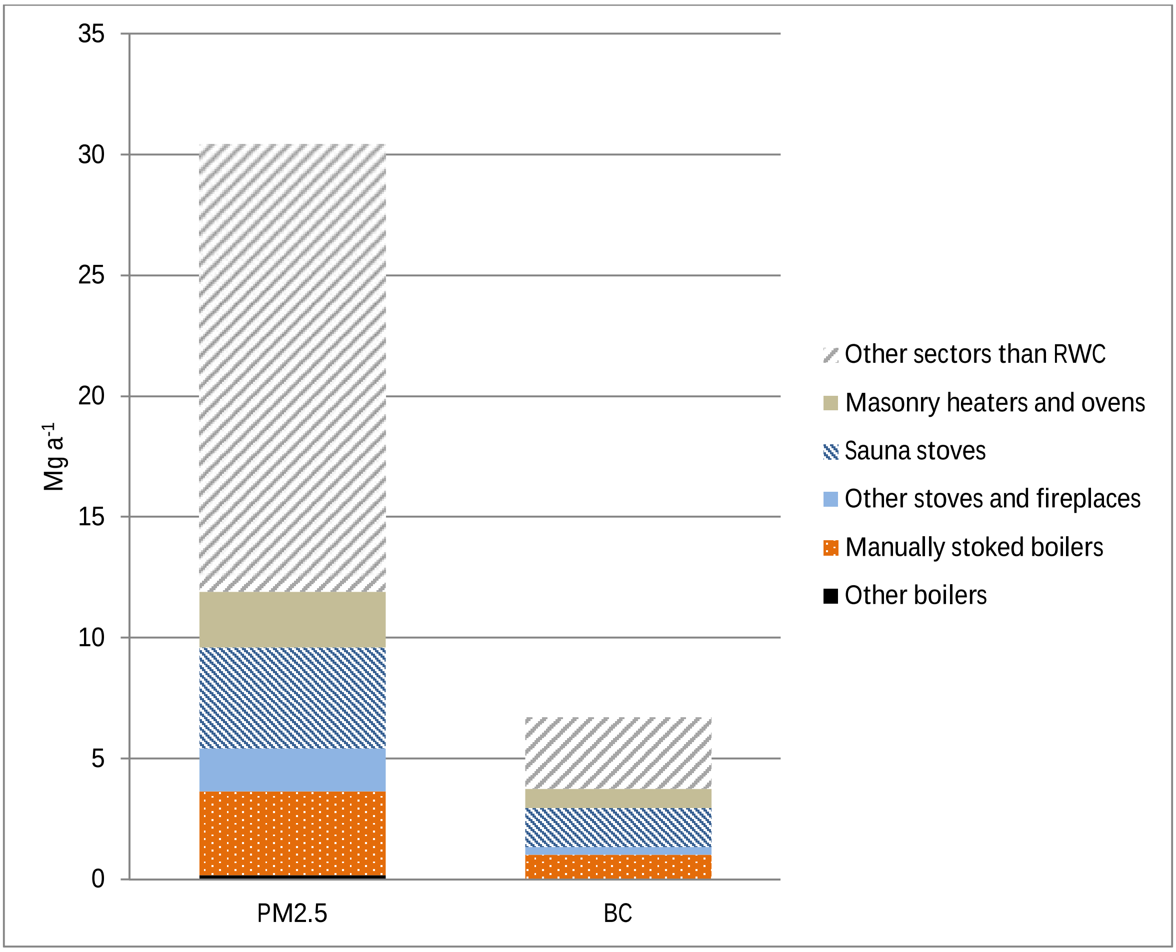

Fig 2. Finnish emissions from RWC and other sectors (Finnish Environment Institute 2014) in 2010

In the baseline scenario that assumes 28% decrease in wood use from 2010 to 2030 and no measures, the emissions are expected to decrease by 42% and 38%, to 6.9 Gg a^{-1} and 2.2 Gg a^{-1} for $PM_{2.5}$ and BC, respectively. The significant decrease in emissions is a result of decreased wood consumption, as well as further regeneration of boiler and heater stock; manually stoked boilers will become less common, especially the ones operated without an accumulation tank, while modern masonry heaters will gain popularity. The aggregated $PM_{2.5}$ emission factor over the whole sector decreases by 20% between 2010 and 2030. Without the implementation of new legislation, modern manually stoked boilers, sauna stoves or iron stoves were not assumed to break into the market by 2030. Sauna stoves remain the most important source of both $PM_{2.5}$ and BC emissions, with 35% and 45% relative share of the emissions, respectively.

Table 4. Estimated wood consumption and emissions for each appliance for 2000 and 2010 as well as the projection for 2030 without measures.

	Wood use [PJ a^{-1}]			$PM_{2.5}$ [Mg a^{-1}]			BC [Mg a^{-1}]		
Boilers	2000	2010	2030	2000	2010	2030	2000	2010	2030
Wood chip boilers, automatic stoke	8.1	12.1	8.6	130	190	135	4	6	4
Pellet boilers, automatic stoke	1.3	1.3	3.4	26	26	67	1	1	2
Manually stoked boilers with accumulator tank	6.9	10.6	6.9	930	1440	935	280	430	280
Manually stoked boilers, no accumulator tank	1.9	2.9	0.6	1330	2030	385	400	610	115
Manually stoked modern boilers	0	0	0	0	0	0	0	0	0
Room heaters									
Open fireplaces and other	1.3	2	0.5	830	1280	330	48	74	19
Kitchen range	4	6.1	2.6	210	320	140	135	205	89
Conventional masonry heaters	8.6	12.9	6.9	1170	1750	940	405	610	330
Modern masonry heaters	0	1.1	4.4	0	54	210	0	21	82
Masonry ovens	6.9	10.5	8.5	330	505	405	100	155	125
Sauna stoves	7	8.9	6.8	3290	4180	3210	1275	1620	1240
Modern sauna stoves	0	0	0	0	0	0	0	0	0
Iron stoves	1.1	1.6	1.5	125	180	170	30	44	41
Modern iron stoves	0	0	0	0	0	0	0	0	0
Total	47.1	70	50.7	8370	11950	6930	2680	3780	2330

The emission development by 2030 for RWC and other sources has been investigated in a national report that studied the Finnish position in relation to the proposals of the EU National Emission Ceilings directive (Suoheimo et al., 2015). Considering all Finnish emission sources, the emissions of $PM_{2.5}$ and BC will continue to decline significantly in the future in many of the major emission source sectors, especially traffic exhaust. However, the emissions will increase for traffic induced non-exhaust dust, which contributes to $PM_{2.5}$, but not significantly to BC. Assuming the Baseline projection, i.e., decrease in wood consumption, RWC's share of the Finnish total $PM_{2.5}$ emissions would remain at 37% in 2030 (Suoheimo et al., 2015), but the share of BC emissions would rise to 85% (Kupiainen et al., 2013).

3.1.1. Comparison to earlier results

The emissions from the RWC sector have been earlier estimated in Karvosenoja et al. (2008) for $PM_{2.5}$ and Kupiainen et al. (2006) for BC. At that time there were fewer representative national measurements existing compared to this paper. Furthermore, the earlier calculation for BC was more aggregated in terms of combustion appliance categorization. The earlier $PM_{2.5}$ emission estimate for the year 2000 was 7580 Mg a^{-1}, which is close to the current estimate, 8370 Mg a^{-1}. However, there are considerable differences in emission factors within different stove type categories (see Figure 3) that partly rule out each other as total emissions. Previously the emission factors for masonry heaters, masonry ovens, kitchen ranges and sauna stoves were based mostly on measurements for masonry heaters.

Using the relative BC shares of PM2.5 presented in Kupiainen et al. (2006), BC emission estimate for 2000 would be 1340 Mg a^{-1}, and thus considerably lower than the current estimate (2680 Mg a^{-1}). This is due to the fact that PM emissions from Finnish appliances tend to be relatively rich in BC. Typically the share of BC increases along with combustion efficiency. Kupiainen et al. (2006) estimated the share of BC in Finnish RWC to be 16% of PM2.5 emissions. whereas the current calculation scheme gives an average BC share of 32%.

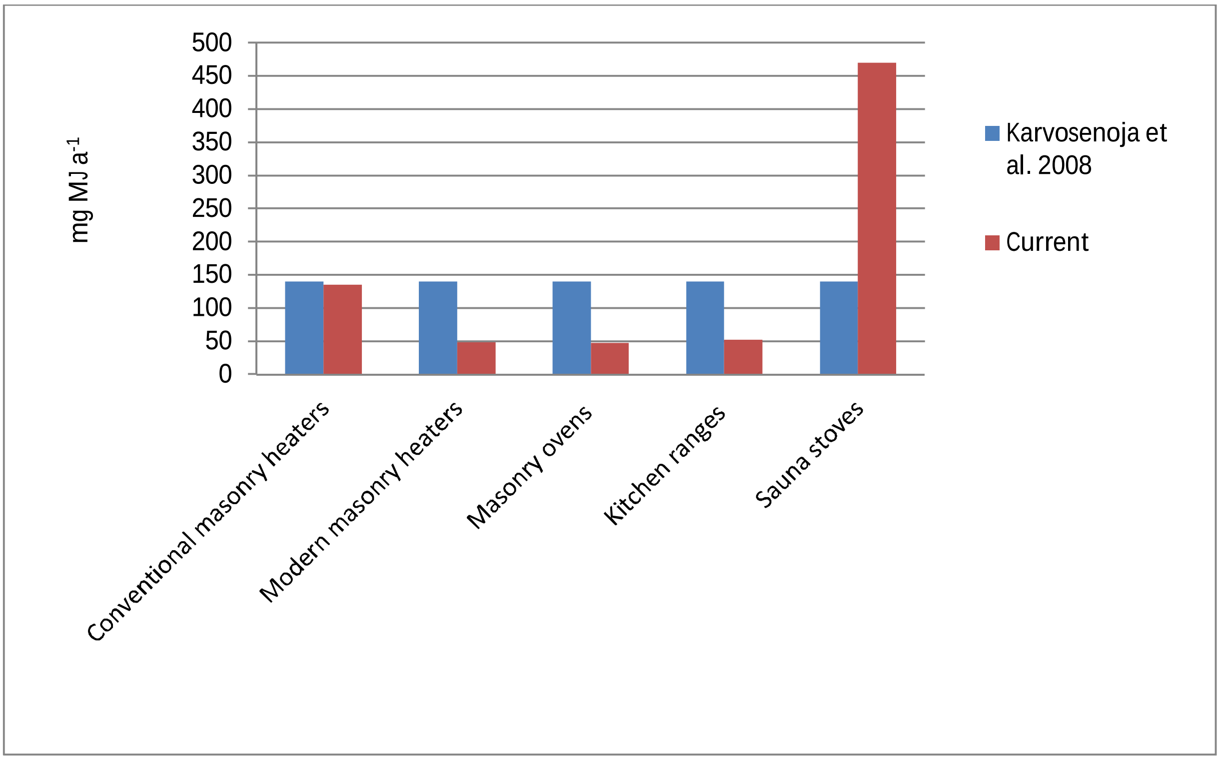

Fig 3. $PM_{2.5}$ emission factor for an aggregated stove group "other stoves and ovens" in Karvosenoja et al. (2008), compared to the appliance-specific emission factors in the current calculation scheme.

3.1.2. Effect of alternative wood use estimates in 2030

The impact of wood consumption on emissions can be seen in the Stagnation and Continued growth scenarios. In the scenario with stagnant wood use, the decrease of $PM_{2.5}$ and BC emissions from 2010 to 2030 is less than half compared to that of the baseline case. Continued growth of wood consumption at the current rate would increase both $PM_{2.5}$ and BC emissions by 25 % in 2030 (Table 5).

Table 5. Emissions in the alternative scenarios for wood consumption in 2030

	Wood use [PJ a^{-1}]		$PM_{2.5}$ [Mg a^{-1}]		BC [Mg a^{-1}]	
	Stagnation	Continued growth	Stagnation	Continued growth	Stagnation	Continued growth
Boilers	27	40	2080	3130	550	830
Room heaters	43	65	7890	11830	2610	3910
Total	70	105	9970	14970	3150	4740

3.2. *Emission reduction potential*

The effect of the studied measures on emissions in the three wood use projections is presented in Table 6. For the Ecodesign directive the estimated effect was a reduction of 400 to 790 Mg ($PM_{2.5}$) a^{-1} and 90 to 180 Mg (BC) a^{-1} in 2030, depending on the wood use scenario, or approx. 4% to 6% of the total RWC emissions. This relatively limited impact is due to several reasons. The most common installations that are affected by the directive, i.e. conventional masonry heaters and manually stoked boilers, have a long lifetime and the stock renewal is slow. Some important appliance categories are assumed to already comply with the directive, i.e. automatic stoked boilers, kitchen ranges and masonry ovens. In addition modern masonry heaters already have a significant market share and are assumed to further increase it in the future without directive requirements. More than half of the effect of Ecodesign originates from the modernization of the boiler stock.

Sauna stoves have a shorter life span and are changed more frequently than masonry heaters and boilers. Furthermore, sauna stoves have relatively high emission factors, making them a potential target for effective emission reductions. In 2030, the reduction potential for the assessed requirements, i.e. 50% lower emission factors for new sauna stoves, would be up to 19% of the total RWC emissions for $PM_{2.5}$ and 23% for BC.

Informational campaigns aim to improve heater users' behavior and thus reduce emissions caused by poor combustion. The effectiveness of such campaigns changing behavior and reducing emissions is highly uncertain; therefore a range from 5% to 50% reduction in smoldering combustion was studied in a sensitivity analysis. The maximum effect of the sensitivity analysis for the informational campaigns was estimated to lead to 8% and 4% reduction of the total RWC emissions for $PM_{2.5}$ and BC, respectively, i.e. approximately the magnitude of the Ecodesign legislation. The campaigns are typically targeted to urban areas to improve local air quality; therefore the effect of the measure was also calculated also for the case where it is implemented in only the 30 biggest cities in Finland. Emission reductions in this case are minor when compared to the country's total emissions, but the impacts at the municipality or local levels would naturally be more significant.

The measures targeted to heating boilers, i.e., installing ESPs and requiring heat accumulator tanks for manually stoked boilers show a combined reduction potential of up to 17% of RWC emissions for $PM_{2.5}$ and 11% for BC. Installing ESPs was assumed for the whole boiler stock and produced 75% of the emission reductions, while 25% came from installing heat accumulator tanks. The number of boilers without an accumulator was assumed to decrease significantly by 2030 even without measures, so this measure would be more effective if it was to be implemented immediately.

Some of the measures overlap, so the cumulative reduction potential is slightly smaller than the sum of single measures. The cumulative reduction potentials for $PM_{2.5}$ in the three wood use scenarios are shown in Figure 4. Maximum reduction potential, if all the studied measures were implemented in 2030, would equal to 3.1 – 6.4 Gg a^{-1}, depending on the wood use projection. This accounts for 43 – 45% of the Finnish emissions from RWC, or 17 – 24% of the Finnish total $PM_{2.5}$ emissions. For BC, the respective reductions would be 0.9 – 1.7 Gg a^{-1}, accounting for 39% of RWC emissions and 26 – 30% of Finnish total emissions.

Table 6. Emission reduction potential for single measures in 2030, compared to the base case of no measures given as bolded letters for each wood use scenario.

Wood use scenario/reduction measure	**$PM_{2.5}$ [Mg a^{-1}]**	**Black carbon [Mg a^{-1}]**
1) Baseline	**6930**	**2330**
EcoDesign	-400	-130
Requirements for sauna stoves	-1330	-520
Informational campaign, all detached and recreational houses (-5…-50% smouldering combustion)	-53…-530	-8…-80
Informational campaign, detached houses in the 30 biggest municipalities (-5…-50% sc)	-8…-77	-1…-12
Measures for boilers: ESPs, ban of manually stoked boilers without accumulator tank	-1190	-370
2) Stagnation	**9970**	**3150**
EcoDesign	-500	-160
Legislation for sauna stoves	-1750	-680
Informational campaign, all detached houses and recreational houses (-5…-50% smouldering combustion)	-72…-720	-11…-110
Informational campaign, detached houses in the 30 biggest municipalities (-5…-50% sc)	-10…-100	-2…-16
Measures for boilers: ESPs, ban of manually stoked boilers without accumulator tank	-1630	-460
3) Continued growth	**14960**	**4740**
EcoDesign	-790	-260
Legislation for sauna stoves	-2630	-1020
Informational campaign, all detached houses and recreational houses (-5…-50% smouldering combustion)	-100…-1040	-15…-150
Informational campaign, detached houses in the 30 biggest municipalities (-5…-50% sc)	-15…-150	-2…-22
Measures for boilers: ESPs, ban of manually stoked boilers without accumulator tank	-2450	-700

If a measure affects the current appliance stock, as is the case with the informational campaign and additional measures for boilers, it can produce results faster (Fig 4). Adding a heat accumulator tank to manually stoked log boilers would reduce more emissions in 2020 than 2030, as these boilers are expected to eventually become less common. Informational campaigns will also have more effect early on, when the general quality of the appliance stock is lower.

Measures on new appliances in the market take time to affect. By implementing Ecodesign directive requirements, the share of modern appliances would increase by 30 percentage points for log boilers, 7 for masonry heaters and 70 for iron stoves by 2030. Respectively, additional national requirements would bring the share of modern sauna stove from zero to 70 percentage points. There are examples of measures to speed up the regeneration of the heating appliance stock, e.g. economic incentives (Levander & Bodin, 2014; Welles et al., 2012). For Finnish masonry heaters, this kind of change-out program was not estimated to be cost-efficient (Savolahti et al., 2012). In a theoretical estimate, a complete modernization of the whole appliance stock by 2030 would decrease $PM_{2.5}$ emissions by 60% compared to the case with no measures. The different wood consumption scenarios show that in addition to reduction measures, the prevalence of RWC also plays a key role in future emissions.

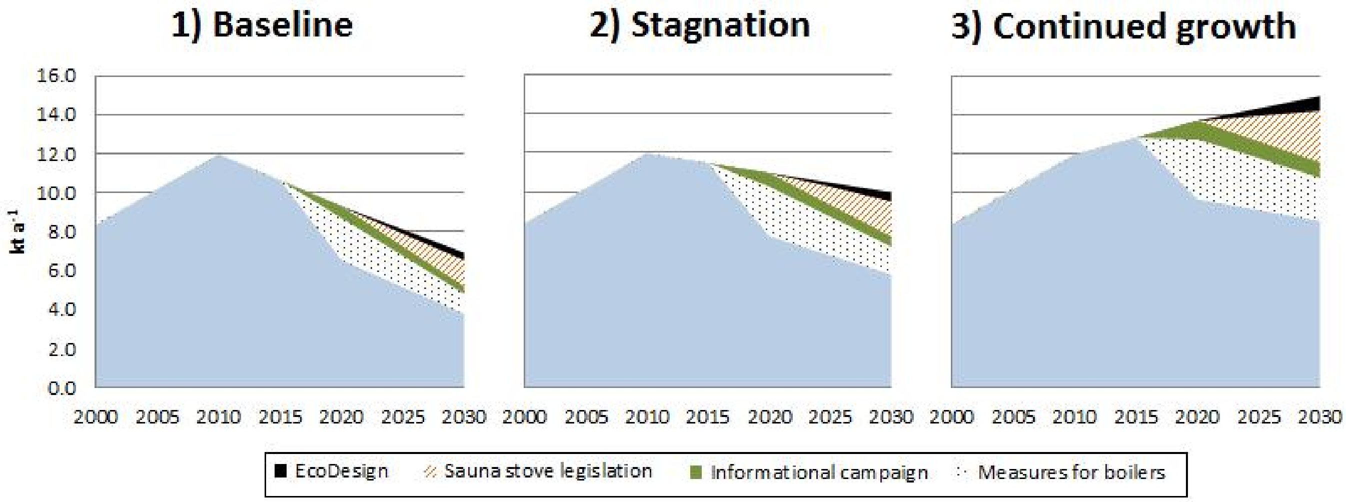

Fig 4.Cumulative $PM_{2.5}$ reduction potentials for the measures in 2020 and 2030, depending on the assumption of wood consumption (MFR = Maximum Feasible Reduction). For the informational campaign, the maximum assumed effect is shown (50% reduction in smouldering combustion).

3.3. Emission reduction costs

The costs of the studied measures were assessed in the baseline wood consumption projection (Table 7). The cost-efficiency of emission reductions is expressed as unit cost, i.e. cost per reduced ton of emissions. The most cost-effective technical emission reduction measures (i.e. measures involving new installations) were the modernization of boilers and sauna stoves, due to their high emissions per appliance. The emission factor of sauna stoves is especially high for BC, resulting in cost-efficient reductions. The change of masonry heaters from conventional to modern ones, on the other hand, brings relatively small reductions in emissions with high cost.

Informational campaigns was estimated to be the cheapest measure in total costs, and it is also potentially the most cost-effective. The unit cost was low compared to the technical measures, even when the effect on combustion habits was assumed to be small. Informational campaigns can be used to increase the heater users' awareness of environmental effects, as well as economic aspects that could be gained by avoiding poor combustion. In addition, the campaigns could be executed in a relatively short time span and the effect could potentially cover the whole heater stock, including existing devices. However, in the long run informational campaigns alone without other measures would only have a limited effect because conventional heater technologies will entail relatively high emissions even when operated in an optimal way. Therefore informational campaigns appear as highly feasible for improving local air quality as an immediate measure; however they should be complemented with measures that influence the technologies that lead to incomplete combustion.

Two different measures targeted to boilers were studied: banning the use of manually stoked boilers without a heat accumulator tank and installing ESPs to the whole boiler stock. Installing a heat accumulator tank to boilers appears to be a cost-efficient reduction method. Installing ESPs to boilers, by contrast, manifests as very high annual and unit costs. Both of these measures entail high uncertainty in the cost estimates, as well as their technical and social feasibility. These aspects are discussed in the next chapter.

Table 7. Emission reduction costs in 2030

Measure	Annual cost [M€ a^{-1}]	Unit cost of emission reduction [k€ Mg^{-1}]	
		$PM_{2.5}$	BC
EcoDesign	14	35	110
-boilers	4	15	45
-masonry heaters	8	100	310
-iron stoves	2	30	130
Requirements for sauna stoves	22	17	43
Informational campaign, all detached houses and recreational houses (-5…-50% smouldering combustion)	0.3	0.6 – 6	4 – 37
Informational campaign, detached houses in the 30 biggest municipalities (-5…-50% sc)	0.08	1 – 10	7 – 66
Measures to boilers	44	29	170
-installing accumulator tanks	1	3	9
-installing ESPs	43	45	250

3.4. Uncertainties and restrictions regarding the studied measures

The emission reduction effect of Ecodesign was estimated to be relatively minor by 2030 and the uncertainties in this conclusion are small. It is more unclear how the legislation will affect Finnish masonry heater and wood boiler manufacturers, as the standards are still under preparation and the practicalities of the measurement process are unknown. The implementation of Ecodesign will probably also raise the average price of appliances on the market, and that can change the behavior of users. It could increase the use of current applications beyond their useful life, or in the case of room heaters, increase the amount of self-assembled appliances.

For the political relevance of this study it is important to address the main uncertainties in the calculations. As for the emission inventory, we find the uncertainty analysis of the previous version of the $PM_{2.5}$ calculation scheme (Karvosenoja et al. 2008) still relevant. Using corresponding sources for activity data, that study showed uncertainty estimates of ±10% (with 95% confidence interval) for total wood use and between ±25% and ±40% due to different heating and combustion appliance types in residential buildings. The uncertainties for emission factors were higher, between -54% and +88%. These factors resulted in total emission uncertainty of -36%...+50% (with 95% confidence interval) for the $PM_{2.5}$ inventory. The same assumptions are valid for the current system, and the uncertainty of BC emissions factors are of the same order as for $PM_{2.5}$.

In this study, the legislation for sauna stoves was estimated to be the most significant measure in terms of reduction potential. The calculation of sauna stove emissions also include the most significant uncertainties. Available measurement data on the emission levels of conventional sauna stoves constantly show high emission compared to masonry heaters. The wood consumption estimate in sauna stoves is also on a relatively solid base. However, variations in the emission levels are large and even small improvements in sauna stove structure might decrease the emissions. Reports from manufacturers and chimney sweeps indicate that current models have already improved from the conventional ones that are used to estimate future emissions in this study. This means that the emission projections for sauna stoves with no further measures might be overestimated. Also, we currently don't have emission measurements to validate our assumption of 50% reduction in emission levels between a conventional and a modern appliance. An up-to-date emission measurement study would improve the reliability of the reduction potential estimate. Another appliance category with high emissions and uncertainties is manually stoked boilers. Especially BC measurements from these appliances are scarce, although the few available ones suggest the share of BC in PM to be relatively high.

Informational campaigns have been performed in some major urban areas in recent years, and are seen as a relevant measure to improve local air quality. The calculating method for user behavior is simplified and the estimation of shares in table 2 is highly uncertain. However, the introduced method should be seen as a first step to include the effects of combustion habits transparently in an emission inventory. As seen in Table 1, the $PM_{2.5}$ emission factor for some room heaters can be almost six times higher in smouldering combustion. However, this fluctuation is considerably smaller in total emissions. Combustion practices are assumed to have smaller or no impact in most applications, and people generally try to use their heater in a reasonably efficient way. In a theoretical sensitivity study, changing the total share of smouldering combustion (Table 2) from 1% to 50% would increase total $PM_{2.5}$ emissions by 69%. For BC the effect would be significantly smaller, since less efficient combustion generally produces a smaller relative share of BC. The evaluation of an informational campaign's effect is also challenging, and little proof of their influence on people's behavior exists. The best case scenario, a 50% decrease in smouldering combustion, is seen as a very optimistic assumption.

The use of electrostatic precipitators in small-scale installations has not been thoroughly tested in practice. Test measurements give promising results and reasonably high emission reduction efficiencies, but there are major uncertainties in the practicalities in continuous use and the net costs. The enforcement of such legislation would be difficult as well, unless the ESP comes as a pre-installed part of the new boiler. The possibility to install a heat accumulator tank to manually stoked boilers without one is also highly situational. The prices vary depending on the current system and often there is no space for the tank, in which case the easier solution would be to install a new boiler. Annual cost and total emission reductions are also highly sensitive to the assumption of wood use in such appliances, and in this study they are supposed to be almost phased out by 2030.

Small scale ESPs could also be used with space heaters, but it was estimated that the unit cost for such a measure would be an order of magnitude higher than with boilers, because of considerably smaller produced heat per year. The operating conditions would also be more challenging than with boilers. There are also other measures to reduce emissions from the use of heaters, e.g. installing a pellet insert into the firebox of an existing appliance. Batch combustion of pellets (Obernberger et al., 2012) or staged combustion of wood logs typically produce considerably lower particulate emissions than wood log combustion of in conventional appliances, but these technologies are still rarely used or experimental.

In addition to technical and educational measures, it is possible to reduce emissions and population exposure by restricting RWC in certain areas. However, outright banning of combustion appliances in Finland, either constant or occasional, could be challenging in terms of public acceptance due to the strong cultural role of wood burning. Also meteorological conditions that increase the population's exposure to local emissions typically occur in winter, when supplementary heating is most needed.

3.5. Characteristics of Finnish RWC and generalizability of the results

Fuel use, fuel mix and combustion technologies vary between countries. The design and nature of the operation of a heater have consequences to the emission characteristics, and this should be taken into account in emission inventories. The appliances most commonly used in Finland, masonry heaters and sauna stoves, are operated for a short time and with a high combustion rate, which is in contrast to e.g. wood stoves, where heat is needed to be generated for a long time at low power (Tissari et al., 2007). This might explain the relatively high share of BC in Finnish RWC emissions compared to other countries where iron stoves are more common. Major Finnish masonry heater manufacturers, such as Tulikivi and Nunnauuni, operate at international markets and the results presented in this paper can be applied wherever similar appliances are used.

4. Conclusions

The updated emission calculations support the previous finding that residential wood combustion is the biggest single source of both black carbon and $PM_{2.5}$ emissions in Finland. Technology-specific BC emission factors shows that Finnish RWC emissions are considerably richer in BC than previously thought. The significant increase in wood consumption in the 2000s has made RWC's role even more pronounced as a source of $PM_{2.5}$ and BC.

Sauna stoves cause the biggest emissions, accounting for 35% of $PM_{2.5}$ and 45% of BC emissions from RWC in 2010, and these shares are expected to increase by 2030. Other major sources are manually stoked boilers and masonry heaters. The impact of user behavior on country-level emissions appears to be relatively modest, compared to other factors like wood consumption and the state of the appliance stock.

Of the studied emission reduction measures, the most effective was requirements for sauna stoves. Although the average emission levels of currently sold sauna stoves are somewhat uncertain, this conclusion seems robust. In the baseline scenario for wood consumption, the measure could reduce Finnish RWC emissions by 1.3 Gg ($PM_{2.5}$) and 0.5 Gg (BC) in 2030. This accounts for 19 % ($PM_{2.5}$) and 23 % (BC) reductions Finnish RWC emissions. Measures for heating boilers could also bring considerable emission reductions., However, they seem to be the most challenging and least plausible of the studied measures. The introduction of the Ecodesign directive, which is expected to come into force in 2022, was found to be less effective, with only 0.4 Gg ($PM_{2.5}$) and 0.1 Gg (BC) reductions in 2030.

Informational campaigns are an inexpensive measure to influence heater users and thus potentially reduce emissions. The campaigns are flexible in targeting to urban areas and thus bringing notable air quality and health benefits. Their impacts on country-level emissions were estimated to be relatively limited and very uncertain. Reducing the assumed share of poor combustion by 50% resulted in in a reduction of less than 8% in the $PM_{2.5}$ emissions of the baseline scenario.However, in terms of cost-efficiency, informational campaigns appear to be favorable, even in the case which assumes the impact on heater users' behavior to be small. The legislation for sauna stoves was the most cost-efficient technical measure. The reasons for this are the high number and poor energy efficiency of appliances, as well as a relatively short useful life. Depending on the wood use scenario, combining all the measures would produce estimated reductions of 3.1 – 6.4 Gg a^{-1} for $PM_{2.5}$ and 0.9 – 1.7 Gg a^{-1} for BC in 2030, compared to no measures. This accounts for up to 24% ($PM_{2.5}$) and 30% (BC) of Finnish total emissions from all sectors.

A robust calculation system to assess future emissions and possibilities for emission reductions is relevant in terms of complying with various international legislations, e.g. the revision of the National Emission Ceilings Directive (2001/81/EC). However, in order to assess the negative impacts on human health and the climate caused by the emissions, more information than annual country-level emissions is needed. This requires spatial and temporal allocation of the emissions, as well as atmospheric modellings for the assessment of population exposure and effects on radiation. In earlier studies, it has been shown that the population exposure caused by Finnish RWC emissions vary considerably depending on the location of the emission (Karvosenoja et al. 2010). From a health point of view, measures targeted to urban areas, such as informational campaigns, would be considerably more efficient than those in sparsely populated areas, e.g. measures targeted to boilers. Considering the climate impacts, wintertime BC emissions in the North have considerable effect because of snow deposition. In the future, the emissions calculation scheme presented in this paper will be expanded to assess both human health and climate considerations of the cost-efficient reduction opportunities in the Finnish RWC sector.

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