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Near-term climate impacts of Finnish residential wood combustion

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ABSTRACT

Residential wood combustion (RWC) is a major source of climate-impacting emissions, like short-lived climate forcers (SLCF) and biogenic CO_2, in Finland. In this paper, we present projections for those emissions from 2015 to 2040. We calculated the climate impact of the emissions using regional temperature potential metrics presented in literature. In our results, the climate impacts are given as global and Arctic temperature responses caused by the studied emissions in a 25 year time span. The results show that SLCF emissions from RWC cause a significant warming impact. Using our selected metrics, SLCF emissions from RWC added to the warming impact of Finland's projected greenhouse gas emissions by 28% in global temperature response and by 170% in Arctic response. When compared with other common heating methods in Finnish detached houses, using a typical Finnish stove (masonry heater) was the least climate-friendly option. Taking biogenic CO_2 emissions into account further highlighted this finding. Finally, we assessed the change in climate impact when implementing various emission reduction measures for RWC. With a time span of 25 years, early action was found to be even more crucial than the eventual reductions in annual emissions in 2040.

1. Introduction

Wood is a major source of heating energy in Finland. It is being combusted both in district heating plants and in residential heaters. Of the ~1 150 000 detached houses, 23% have a wood heater as the primary heating method (Statistics Finland, 2018). In addition, wood is being combusted in most detached houses for supplementary heating, recreational purposes or in sauna stoves. Wood is also commonly used to heat the ~500 000 recreational houses in Finland. Consumption of wood in Finnish stoves and residential-size boilers has been increasing since the end of the 70s, from 44PJ in 1980 to 58PJ in 2015 (Statistics Finland, 2017). Fuelwood accounted for 20% of the primary energy used for heating in Finland in 2015. The popularity of stoves has also increased in new detached houses, and currently almost 90% of them are being equipped with one or several stoves.

The combustion process in residential wood burning is almost always incomplete. This means that there are reasonably high amounts of unburnt compounds in the flue gases, leading to high emissions of PM and many SLCFs. Like in many other countries, residential wood combustion (RWC) is the largest single source of black carbon and many other short-lived climate forcers (SLCF), as well as fine particles in Finland (Finnish Environment Institute). Emissions from other major sectors of energy use have decreased significantly during recent years and decades due to legislation, and continue to do so. Emissions of most pollutants from residential wood combustion, however, have not been restricted by any legislation in Finland. The first legislation that will specifically target particulate emissions is the Ecodesign directive (Commission Regulations (EU) 2015/1185 and 2015/1189), coming into force in 2020 for residential boilers and in 2022 for local space heaters. Measures that reduce particulate matter (PM) will also reduce black carbon emissions.

Primary fine particles ($PM_{2.5}$) have been identified as the most harmful air pollutant for human health in Finland (Lehtomäki et al., 2018). Residential wood combustion is the biggest source of domestic $PM_{2.5}$ emissions and thus a major contributor to the negative health impacts caused by air pollution (Soimakallio et al., 2017). Black carbon and methane emissions have been proposed to be potentially significant contributors to climate change, especially in the Arctic area (AMAP, 2015). However, they are usually co-emitted with many other SLCFs, some of which have a cooling impact on climate. This is why it's important to include those other pollutants into the impact assessments on global warming. The SLCFs included in this study are Black carbon (BC), organic carbon (OC), CH_4, NMVOC, CO, NO_x, and N_2O. We use the term SLCF instead of SLCP (Short-Lived Climate Pollutant), since we

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have included both warming and cooling effects of the air pollutants (Kupiainen et al., 2019). We have also calculated emissions of $PM_{2.5}$, although it is not regarded as a SLCF. The assessment of RWC emissions builds upon the $PM_{2.5}$ and BC calculation scheme introduced in Savolahti et al. (2016).

Wood burning has been generally considered as carbon neutral, and thus a climate-friendly way of heating. Fundamentally, this is based on an assumption that CO_2 emissions released in wood combustion are sequestered back into growing trees when biomass is derived from sustainably managed forests (Koponen et al., 2018). As a result, the CO_2 emissions from biomass combustion are often calculated to be zero in life cycle assessment studies (Cherubini et al., 2011). However, it has been shown that the time lag between CO_2 emissions and carbon sequestration back into growing trees matters in terms of energy accumulated into climate system (Cherubini et al., 2011). In addition, tree harvesting may cause forgone carbon sequestration, due to losses in tree growth and soil carbon stocks, which strengthens the global warming impact related to wood burning (Helin et al., 2016). Forest management also influences surface albedo (Bright et al., 2011), as well as cloud albedo through aerosol emissions (Spracklen et al., 2008). Forest harvesting likely increases the surface albedo of the area, but decreases cloud albedo due to reduction of organic aerosols. These effects may have opposite climate impacts compared to each other.

The climate impacts of RWC have been studied before, but typically with global GWP_{100} metrics for air pollutants. Ekholm et al. (2014) compared climate and other environmental impacts of various Finnish RWC methods to those of light fuel oil heaters. They concluded that wood heating caused comparable or smaller climate impact than using light fuel oil (although social costs were often higher in wood heating, due to negative health impacts). Robinson (2011) studied the climate impacts of RWC heaters in Australia, and concluded that emissions from wood heating cause a larger climate impact than those from gas heating or reverse cycle air conditioning. The study did not assess BC emissions, but included other SLCFs like CH_4 and CO. Both studies also assessed the impacts of biogenic CO_2 emissions, but with different methods.

The choice of climate metrics influences the perceived impacts of various pollutants. The most common climate parameters examined by metrics are radiative forcing and temperature response. AMAP (2015) concluded that regional temperature potential is a more accurate metric than radiative forcing for quantifying the climate impact of SLCFs in the Arctic. Shindell et al. (2017) proposed a near-term goal to reduce SLCFs "enough to slow projected global warming by 0.5°C over the next 25 years." The Arctic area is especially sensitive to warming climate. It will likely suffer irreversible change and trigger amplifying feedbacks even if the global goal of less than 2 °C warming is met (Overland et al., 2018). Time horizon of 25 years was assessed to be serviceable in our scenario work and relevant in estimating climate impacts, especially near the Arctic. In our study, we use regional temperature potential for SLCFs and GHGs, to calculate a cumulative climate impact of emissions and emission reductions projected for a 25 year time span. Our chosen method also takes into account the way annual emissions change between the start and the end of the study period, which emphasizes the importance of timing of reduction measures. In addition, we present the temperature changes both globally and in the Arctic area. To our knowledge, this is the first study to assess the climate impact of all relevant emissions from the RWC appliances of a whole country, including current and future emissions, as well as the regional aspect of responses.

The objectives of this study are to 1) calculate the climate impacts of Finnish RWC emissions in a baseline projection from 2015 to 2040, 2) compare the climate impact of wood heating to that of alternative heating methods, 3) analyze the climate benefits of RWC emission reduction measures designed for mitigating harmful health impacts and 4) discuss other relevant mechanics in assessing the climate impact of wood combustion.

2. Materials & methods

The emissions in this paper were calculated with the recently updated version of the Finnish Regional Emission Scenario (FRES) model (Karvosenoja, 2008). The calculation scheme for RWC emissions has been presented in Savolahti et al. (2016), though it only included $PM_{2.5}$ and BC. Emissions of other SCLPs, including those from the RWC sector were first presented in Kupiainen et al. (2019). In the model, emissions are a product of wood use activity and emission factors for a given appliance type.

2.1. Wood use projection

The estimation of wood consumption in the residential sector in 2015 is taken from Statistics Finland (2017). The allocation of wood use to various appliance types was based on national questionnaire surveys carried out by the former Finnish Forest Research Institute, Metla (Torvelainen, 2009). In 2018, a new wood use survey was carried out by the Natural Resources Institute Finland. Results of the survey weren't available at the time of the preparation of the calculations in this paper. However, they are well in line with the wood consumption assumptions we have used. The projection of wood use between 2015 and 2030 is based on the baseline scenario of the latest national Energy and Climate Strategy (Huttunen, 2017) (Table 1). The fuel use projection for each appliance type is based on available information in the strategy, historical trends and expert opinion. Consumption in 2040 was extrapolated as a continued trend of the development between 2015 and 2030, since no projection was available. For pellet use, this trend was not used to create the projection to 2040, since the assumed increase by 2030 in the strategy was already significant. As there are no clear signs of a notable increase in pellet consumption in the next decade, we did not extrapolate further increase after 2030. Instead we assumed the use of pellets to continue at 2030 level.

2.2. Emission factors for other SLCFs than BC

Since Savolahti et al. (2016), the FRES model has been updated and new emission factors added. Current emission factors are shown in appendix (Table A1). For this work, we included the emission factors for $PM_{2.5}$, BC, OC, NO_x, NMVOC, CO, SO_2, CO_2, CH_4 and N_2O. These were estimated to be the most important emission in terms of climate impact. $PM_{2.5}$ is not considered a climate forcer as such, but its components, mainly BC and OC are.

The emission factors are based on emission measurements at the University of Eastern Finland during 2003-2016. The main papers applied are Sippula et al. (2007), Tissari et al. (2007a,b, 2008a,b, 2009), Lamberg et al. (2011a,b, 2013), Hukkanen et al. (2012), Leskinen et al.

Table 1
Wood consumption by appliance type [PJ a^{-1}].

	2015	2020	2030	2040
Wood chip boiler	11	11	11	11
Pellet boiler	1.1	1.1	5.1	5.1
Manually fed boiler with accumulator[a]	9.3	8.5	6.9	5.2
Manually fed boiler without accumulator	2.1	1.6	0.8	0
Manually fed modern boiler	0	1	3.3	5.5
Open fireplace	1.7	1.7	1.8	1.9
Kitchen range	5.1	5.3	5.6	5.9
Conventional masonry heater	10	9.1	7	4.8
Modern masonry heater	1.5	3	5.9	8.8
Masonry oven	8.8	9	9.7	10
Conventional sauna stove	8.9	8.6	8.2	7.7
Conventional iron stove	1.3	1.1	0.5	0
Modern iron stove	0	0.3	1	1.7
Total	61	61	67	68

[a] *hot water tank.*

(2014), Nuutinen et al. (2014) and Kortelainen et al. (2015). Both laboratory conditions and field measurements have been used to obtain the emission factors. Particulate emissions have been measured from the diluted flue gas, collected to the filters and analyzed afterwards for mass, elemental carbon and organic carbon. The NO_x, CO and CO_2 compounds have been measured with single gas analyzers and NMVOCs, CH_4 and N_2O with a Fourier Transform Infrared analyzer (FTIR). Experimental set-ups are described more detail in the above-mentioned papers.

To estimate the impact of stove user practices on the emissions, we used the method explained in Savolahti et al. (2016). It includes separate emission factors for *normal* and *smouldering* combustion (representing poor combustion practices), as well as the assumed initial share of *smouldering* combustion amongst all users. The share of *smouldering* combustion determines the applied emission factors.

2.3. Emission reduction measures

The baseline scenario includes the assumed developments in the appliance stock, including the impact of the Ecodesign directive. In addition to the baseline projection, we assessed the impact of four separate emission reduction measures in five scenarios: 1) Informational campaign for stove users on better combustion practices, 2) national legislation setting emission limits for new sauna stoves in the market from 2022 onwards, 3) installing electrostatic precipitators (ESPs) to residential boilers, 4) implementing combustion bans to population centres of more than 20 000 residents and 5) maximum feasible reduction (MFR), where all the previous measures are combined. These measures are explained in more detail in Savolahti et al. (2016) and Savolahti et al. (2019), where the emission reduction potential of these measures are assessed for 2030. In this paper, we have extrapolated those emission development trends up to 2040. The emission scenarios were assessed independently, excluding the MFR, where they had a cumulative effect.

2.4. Climate metrics used for short-lived climate pollutants

The warming or cooling impact of each short-lived climate pollutant was estimated using the mean absolute regional temperature potential (mean ARTP) for 25 years (Table 2), as presented in Table 3 of Kupiainen et al. (2019). Impacts of SCLPs are heavily influenced by location of the emission source, and Kupiainen et al. (2019) estimated the presented metrics to be the most representative numbers available for Finnish emissions. The metric values are based on central European emissions (Aamaas et al., 2017) and scaled to better represent emissions from Finland. This scaling has been done using the Arctic temperature response of Norwegian SLCF emissions (Sand et al., 2016), as Norway is located on roughly the same latitudes as Finland. The climate models behind the metrics included snow albedo as well as the semi-indirect effect of BC. Kupiainen et al. (2019) presented the climate metrics for both global and Arctic (60-90° N) temperature responses. The annual average is composed of winter time (November–April) and summer time (May–October) emissions. Winter time emissions of BC have a notably higher warming response per unit, and over 70% of the Finnish RWC emissions are produced during this period (Kupiainen et al., 2019).

Table 2
Mean(ARTP(1-25yrs)) climate metrics used with Finnish emissions (Kupiainen et al., 2019).

	Mean(1-25yrs), global response [°C/Tg]	Mean(1-25yrs), Arctic response [°C/Tg]
CO_2	5.7E-7	8.2E-7
CH_4	4.8E-5	6.9E-5
N_2O	1.5E-4	2.1E-4
NO_X	-1.7E-5	-1.9E-5
VOC	9.6E-6	1.6E-5
CO	4.1E-6	5.2E-6
BC	2.7E-3	2.2E-2
OC	-4.7E-4	-1.9E-3
SO_2	-2E-4	-8.5E-4

Mean temperature potential is a climate metric like GTP_{20} or GTP_{100}, but it takes into account the pathway of emission development during the studied time period. In our work, emissions of each year were multiplied by the mean(ARTP(1-25yrs)) metrics to estimate the cumulative climate impact of the changing emissions between 2015 and 2040. The ARTP metric presents the absolute temperature perturbation caused by a unit of each pollutant, instead of normalizing them to CO_2.

2.5. Warming impacts of biogenic CO_2 emissions and indirect impacts of forest harvesting

The dynamics related to changes in forest carbon stocks due to increased energy wood harvesting can be converted into climate impacts, for example through cumulative radiative forcing over a given time horizon (Pingoud et al., 2012), or further to the global temperature change at a given time horizon (Ericsson et al., 2013). No universally agreed method to estimate the climate impacts has been established, since the changes in the carbon balance between biomass, ground and atmosphere depend on a variety of factors, in addition to the studied time frame. Regardless, harvesting and combustion of biomass releases carbon into the atmosphere, and should be accounted for when comparing the climate impacts of different heating methods. This is especially relevant when studying a short-to-medium time frame of a few decades.

The impact wood combustion has on the net biogenic CO_2 emissions depends heavily on what happens to wood if not used for combustion, i.e. the reference system (Koponen et al., 2018). In Finland, increased harvest of wood has been assessed to reduce forest carbon sink over a 25-year time horizon by approximately twice as much as the amount of carbon harvested from the forest (Pingoud et al., 2016; Soimakallio et al., 2016). This is due to losses in carbon of harvested tree stock, sequestration in tree growth and in litter pool. This implies a twofold CO_2 emission factor, i.e. 224 g MJ^{-1} for wood combustion compared to the amount of CO_2 physically released in wood combustion, i.e. 112 g MJ^{-1} (Statistics Finland, 2019). However, increased harvesting of some wood compartments such as branches and cut-down small-diameter wood otherwise decaying in forest has significantly lower impact on the net biogenic CO_2 emissions, indicating CO_2 emission factor of less than 50 g MJ^{-1} over 25-year time horizon (Pingoud et al., 2016).In this paper, we used the direct end-of-pipe emission factor of 112 g MJ^{-1} for biogenic CO_2 emissions, as well as the mean(ARTP(1-25yrs)) for CO_2 presented in Table 2.

We have not calculated the impact of changes in forest albedo or the production of natural aerosols as a result of felling trees. These, as well as the impact of our chosen emission factor for biogenic CO_2, are discussed in chapter 4.

2.6. Finland's greenhouse gas emission projection for 2040 and emission factors for power and heat production

In chapter 3.2.1, emissions from RWC are compared to emissions from other sectors. No official GHG projection for Finland's total emissions exists up to the year 2040. The national Energy and climate strategy has a projection until 2030, including all GHG emissions as CO_2-equivalents using GWP_{100}. Using our chosen climate metrics would give a slightly different total impact if applied separately for different GHG emissions. However, as the comparison in chapter 3.2.1 is an order of magnitude estimate, we chose to use the available values from the Energy and climate strategy. As the projection ends in 2030, we extended it to 2040. Finland is committed to EU's goal to reduce GHG emissions by 80-95% from 1990 to 2050. In our projection, GHG emissions in 2040 were estimated using a linear path from the 2030 situation to the goal of 80% emission reduction in 2050.

Annual averages for CO_2 emission factors in public heat and electricity production are given by Statistics Finland (2017). For 2015, they were 57 g_{CO2} MJ^{-1} for heat and 29 g_{CO2} MJ^{-1} for electricity. The major SLCF emissions from power plants are NO_x and SO_2. Emission factors for them were calculated using the annual emissions from Finland's national air pollutant inventory (Finnish Environment Institute, 2018) for public heat and power, as well as annually produced heat energy and electricity reported by Statistics Finland (2017). We used wood consumption along with the general efficiency of heat or electricity production to calculate the amount of heat and electricity produced by combusting biomass. We then used this value to calculate the CO_2 emission factors for heat and electricity, when including biogenic CO_2. Since no data is available for the changing of these emission factors between the years 2015 and 2040, we used the emission factors of 2015 for the whole study period. For calculating the annual emissions of the various heating methods, we used the following assumptions (as instructed in the National Building Code of Finland D5): For fuelwood, efficiency for generating net heat from primary energy was 0,6. For electricity and district heating, the amount of energy imported to the house was the same as net heat required. For geothermal heating, the ratio between electricity consumption and net heat production was 0,4. The distribution loss was 10% for district heating and 4% for electricity.

To represent an average coal fired power plant, emission factors of a typical 500MW plant were chosen from the FRES model. The emission factors used were 93 g MJ^{-1} for SO2 and 60 g MJ^{-1} for NOx in 2015. Due to legislation entering into force, they were assumed to decrease to 65 g MJ^{-1} and 54 g MJ^{-1} by 2040, respectively.

3. Results

3.1. Projected emissions from residential wood combustion

A baseline emission projection of the studied SLCFs is presented in Fig. 1 and in appendix (Table A2). Emissions of most pollutants decrease moderately, despite the slight increase in wood consumption. This is due to the increased share of combustion in modern and more efficient appliances. NO_x, SO_2 and CO_2 emission factors, however, are less dependent on combustion appliance efficiency, and thus increase along with the wood consumption in the projection. Biggest reductions are expected for particulate emissions $PM_{2.5}$, BC and OC. Improving the efficiency of combustion affects these emissions the most. One reason for the decrease is also the assumption that manually fed boilers without a heat accumulator tank have already started to phase out and that process will be complete by 2040. Those boilers are occasionally operated with deficit inlet air on purpose, resulting in poor combustion and high particulate emissions.

For some emissions, especially particulates, the emission factor is highly dependent on the combustion process. Thus the amount of wood consumption in an appliance type does not necessarily correlate with its relative share of total RWC emissions. Wood consumption and fine particle emissions, as well as the most significant warming (BC) and cooling (OC) pollutants by appliance type are shown in Fig. 2.

For OC, the connection between inefficient combustion and high emissions is typically seen. For BC, this relation is more complex. Emissions from sauna stoves are high for both of BC and OC. Although their wood consumption is only 15% of the sector in 2015, the relative shares of those emissions are over 40% of the total respective emissions in the sector. Open fireplaces are another appliance type with inefficient combustion. Their OC emissions are significant, but BC emissions are somewhat negligible due to low amount of wood consumption.

The biggest changes from 2015 to 2040 are the assumed phasing out of manually fed boilers without a heat accumulator tank, and the modernization of other manually fed boilers and masonry heaters. This modernization has been going on for more than a decade, especially with masonry heaters. The ecodesign directive is estimated to have limited impact on masonry heaters, but is expected to impact more on log boilers and iron stoves. Overall, BC emission decrease by almost 30% in the baseline projection, while OC emissions decrease by 20%.

We compared the calculated RWC emissions of BC and OC to those in the ECLIPSE V5a scenario of the GAINS model (Klimont et al., 2017). The results were very coherent, although ECLIPSE projected slightly bigger reductions by 2040. In ECLIPSE, BC emissions were estimated to be 3,8 kt in 2015 and 2,1 kt in 2040, and OC emissions to be 3,2 kt in 2015 and 1,8 kt in 2040. In addition to wood combustion, ECLIPSE numbers include a small amount of emissions from other fuels in the residential sector.

3.2. Climate impacts of RWC emissions

Using the mean(ARTP(1-25yrs)) emission metrics, we have calculated the climate impact of the baseline emissions from 2015 to 2040. The temperature response shows the absolute cumulative impact in 2040, caused by the studied emissions during this time span. The global

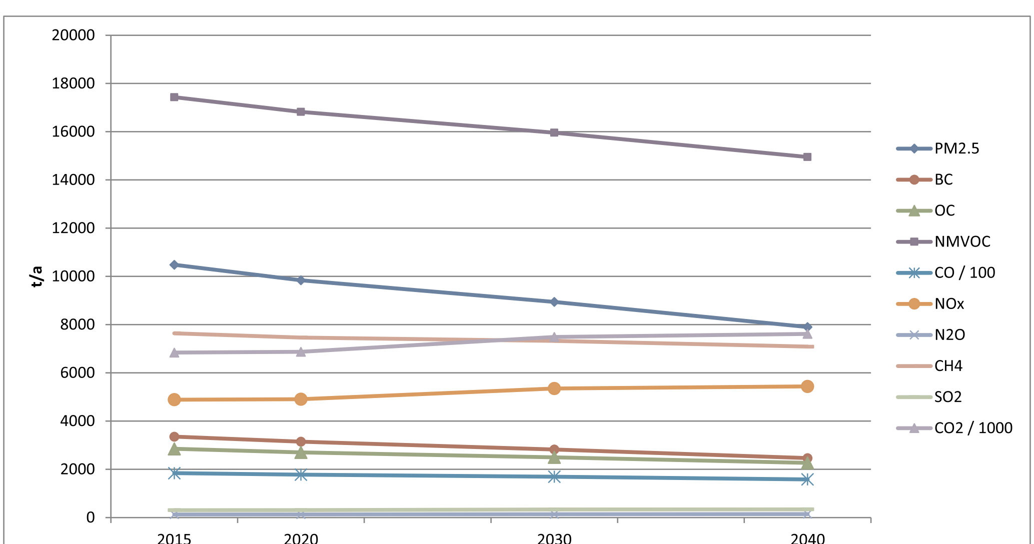

Fig. 1. Total projected emissions from Finnish RWC in the baseline scenario. CO_2 presented as direct emissions.

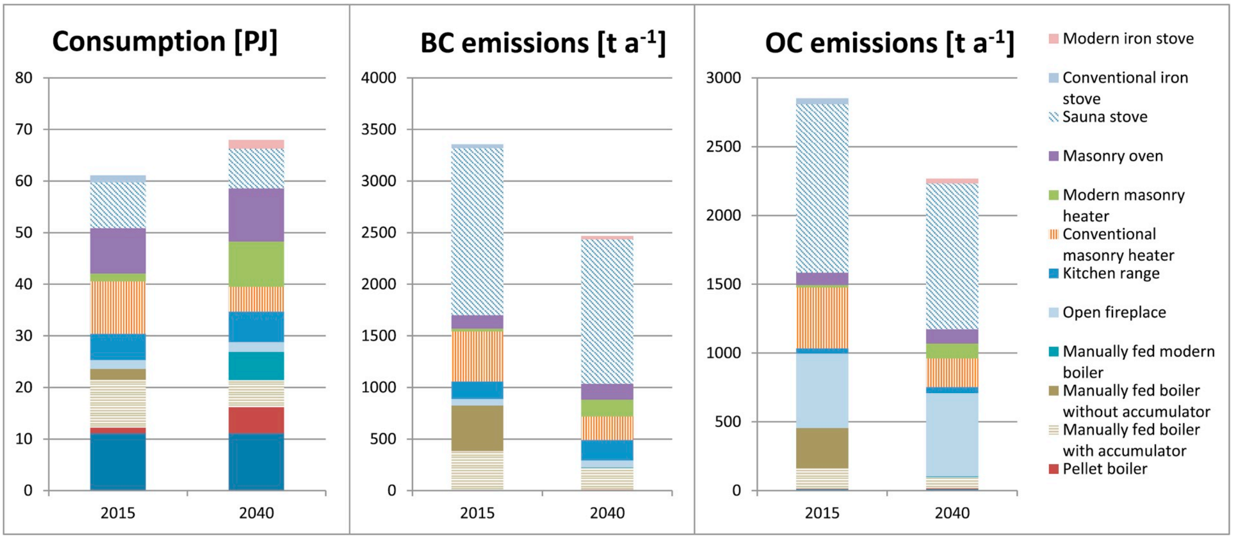

Fig. 2. Wood consumption and most significant warming (BC) and cooling (OC) SLCF emissions by appliance type.

Table 3
Temperature response of the cumulative RWC emissions between 2015 and 2040.

	Global response [μK]	Arctic response [μK]
CO_2	110	160
CH_4	9.2	13
N_2O	0.53	0.75
NOX	-2.3	-2.6
VOC	4	6.7
CO	1.8	23
BC	210	1700
OC	-31	-130
SO_2	-1.7	-7.2
Total without GHGs	180	1600
Total	300	1800

climate response by pollutant is shown in Table 3, and by aggregated appliance groups in Table 4. We have also included the climate response specifically in the Arctic area in Table 3. This is to show that all of the pollutants, including CO_2, have an increased impact in the Arctic area. This amplification is especially strong for BC emissions. For a Northern country like Finland, that is located between latitudes 60°N and 70°N, this is a factor to consider in climate assessments.

Of the total RWC sector, the biggest warming impact comes from BC (62% globally, 89% in the Arctic). When using the direct emission factor for CO_2, it has the second biggest warming impact (33% in global response, 8% in Arctic response). OC has by far the biggest cooling impact (89% in global response, 93% in Arctic response). Although total emissions of BC and OC are quite comparable in the baseline, their combined climate impact is strongly warming.

The temperature response of different appliance groups varies considerably (Table 4). Sauna stoves and masonry heaters have the biggest warming impact, both when excluding and including CO_2 emissions. Masonry heaters also have the biggest wood consumption, but in the case of sauna stoves, high emission factor for BC is the main reason for the warming impact. Pellet and wood chip boilers show a cooling response when excluding CO_2 emissions. This is because emissions of BC are very low in these appliances, due to efficient combustion, but they still emit cooling pollutants like NO_x and SO_2 as much as other appliances. However, when CO_2 emissions are included, the total climate impact of all appliances is clearly warming.

3.2.1. Putting the climate impact of RWC into perspective

Table 5 shows the 2040 climate response of the cumulative emissions of RWC and Finland's total GHGs from 2015 to 2040. The impact of RWC is shown with and without GHGs. A complete comparison can't be made since Finland's projected GHGs don't include SLCFs, other than CH_4. However, the clear majority of Finland's BC emissions come from RWC, and thus most of the SLCFs' warming impact from other sectors is due to CH_4 (Kupiainen et al., 2019).

If Finland's projected GHG emissions would also include the SLCFs from RWC presented in this paper, the warming impact of the emissions would increase notably in 2040. Using our selected metrics, the inclusion of SLCF emissions from RWC would add to the warming impact of Finland's projected GHG emissions by 28% in global temperature response and by 170% in the Arctic response. Accounting for biogenic CO_2 would roughly double the warming impact of both RWC emissions and total GHGs from all sectors in global temperature response.

We also made a theoretical comparison between the climate impact of RWC and coal-fired district heating plants (Table 5). Using the same amount of primary energy as RWC uses in the baseline, typical coal fired power plants would produce a considerably lower warming impact in a 25 year time span. If biogenic CO_2 is excluded, the warming impact of RWC would be three times the impact of coal power. Including biogenic CO_2, the impact of RWC would be almost five times more warming. District heating plants also have higher heat production efficiency, so they would produce more net heat out of the same amount of primary energy, which would further increase the inferiority

Table 4
Temperature response [μK] of the cumulative emissions between 2015 and 2040, by aggregated RWC appliance groups.

	Wood use in 2015 [PJ]	Wood use in 2040 [PJ]	Global response without CO_2	Global response
Automatic fed boilers, wood chips & pellets	12	16	-0.3	24
Manually fed boilers	11	11	36	54
Masonry heaters and ovens	20	24	37	74
Sauna stoves	8.9	7.7	99	110
Open fireplaces, conventional wood stoves and kitchen range	8.1	9.5	13	28

Table 5
Cumulative temperature impacts of emissions of RWC and all sectors between 2015 and 2040.

	Global response [μK]	Arctic response [μK]
RWC total, without CO_2, CH_4 and N_2O	180	1600
RWC total, without CO_2	190	1600
RWC total, including CO_2,CH_4 and N_2O	300	1800
Finland's projected GHGs from all sectors, without biogenic CO_2	650	930
Finland's projected GHGs from all sectors, including biogenic CO_2	1300	1900
Coal-fired district heating plant	64	76
Coal-fired district heating plant, SLCFs only	-27	-55

of RWC when calculated per produced net heat. One reason for the big difference in climate impact is the different composition of SLCF emissions. Coal plants only produce large amounts of NO_x and SO_2, both of which are cooling pollutants (in the studied time frame at least). This partly offsets the warming impact of their CO_2 emissions (both NOx and SO_2 have other harmful environmental impacts however). Again, a direct comparison between RWC and coal fired power plants is not completely expedient, since fuelwood in residential appliances is used for a variety of purposes other than just heating a house.

3.2.2. A comparison of popular heating methods in Finnish detached houses

In Finland, the most common heating methods in new detached houses are geothermal, electric, district and wood heating. Wood heating can also be supplementary to, or supplemented by other heating methods. In this chapter, we compare the climate impact of two wood heating methods to other common alternatives. To simplify the comparison for this example, we assume that all the heating methods are used as the sole source of space heating in the house.

The cumulative global temperature responses after heating a house for 25 years by various heating methods are shown in Table 6. When excluding the impact of biogenic CO_2, using a masonry heater for warming a house caused the biggest warming impact, while using a pellet boiler caused a cooling impact. When biogenic CO_2 emissions were included, both masonry heater and pellet boiler had a considerably stronger warming impact than the other heating methods. One reason for this is that residential appliances have a lower net heating efficiency than district and electric heating. The direct CO_2 emission factor of biomass is also higher than in most other fuels used in power plants, due to its lower heating value. Also a major portion of electricity (70% in 2015) is produced by other renewable or nuclear energy. In addition, emissions of SO_2 are notably bigger from district heat and power production, and they partly offset the warming impact.

3.3. Mitigation potential of climate impacts from RWC

The emission reduction potentials of the five scenarios are shown in Table 7. Setting stricter emission limits for new sauna stoves was the most efficient measure for reducing BC emissions (a 36% reduction from the baseline). Combustion ban in the biggest population centres was the only measure that notably reduced CO_2 emissions (by 11% from the baseline). When combining all the measures (MFR), reduction of BC emissions was 56%.

The temperature response of the emission reduction scenarios in 2040 is shown in Table 8. Banning of wood combustion in the biggest population centres had the biggest reduction on the warming impact of RWC (17% from the baseline). Although setting new emission limits for sauna stoves decreased the baseline emissions of BC by 36% in 2040, the reduction in temperature response was only 9%. This is due to the time it takes to convert the existing appliance stock into modern sauna stoves. The share of cleaner sauna stoves in the appliance stock was estimated to be 0% in 2020, 70% in 2030 and 99% in 2040. The other measures were assumed to produce full results by 2020. Thus the climate impact cumulates over a longer period of time, although their annual emissions in 2040 are higher. This highlights the importance of immediate action. In the MFR scenario, reduction in temperature response was 32% from the baseline. As the Arctic amplification of climate impacts is the strongest for BC, assessing Arctic temperature response would favor BC reductions considerably more than CO_2 reductions.

4. Discussion

All presented climate impacts in this paper should be considered as indicative estimates. The climate impacts studied in this paper only address one time frame, 25 years, and only use one set of emission metrics; mean(ARTP(1-25yrs)). A larger set of metrics would give valuable information on the uncertainties. However, few comparable metrics were available. Many models don't include the albedo effect of BC on snow or ice, which is an important factor with emissions near the Arctic. Kupiainen et al. (2019) used a combination of two sets of metrics, Aamaas et al. (2017) and Sand et al. (2016), to scale the climate response of SLCF emissions to be representative for the latitudes of Nordic countries. These were considered to be the most accurate metrics for Finnish SLCF impacts. However, no quantitative uncertainty analysis was given for the metrics presented in Kupiainen et al. (2019).

Table 6
Cumulative global temperature response [pK] at the end of a 25 period, due to the emissions produced by heating a detached house, depending on the heating method.

	Pellet boiler	Modern masonry heater	District heating	Electric heating	Geotermal heating
Primary energy [GJ a^{-1}]	18.5	18.5	11.4	11.2	4.44
Emission					
CO_2, fossil	0.0	0.0	9.3	4.6	1.8
CO_2, including biogenic	30	30	16	6.8	2.7
CH_4	0.07	1.3	0.0	0.0	0.0
N_2O	0.13	0.17	0.0	0.0	0.0
NOx	-0.63	-0.63	-0.63	-0.18	-0.07
NMVOC	0.01	0.62	0.0	0.0	0.0
CO	0.24	2.3	0.0	0.0	0.0
BC	0.79	23	0.0	0.0	0.0
OC	-0.17	-2.6	0.0	0.0	0.0
SO_2	-0.46	-0.46	-4.4	-1.3	-0.51
Total, without biogenic CO_2	-1.6	15	4.2	3.1	1.3
Total, including biogenic CO_2	29	51	11	5.3	2.1

Table 7
Emissions of the studied pollutants in the baseline and reduction scenarios [kt a[-1]].

		Baseline	Info Campaign	Sauna Legislation	ESP Installations	Combustion Bans	MFR
	2015	**2040**	**2040**	**2040**	**2040**	**2040**	**2040**
CO_2	6800	7600	7600	7400	7600	6800	6600
CH_4	7.6	7.1	6.4	5	7.1	5.9	4.1
N_2O	0.13	0.14	0.14	0.14	0.14	0.13	0.13
NOX	4.9	5.4	5.4	5.3	5.4	4.9	4.7
VOC	17	15	13	8.9	15	12	6.5
CO	180	160	150	120	160	130	94
BC	3.4	2.5	2.4	1.6	2.2	2	1.1
OC	2.9	2.3	2	1.6	2.2	1.8	1.1
SO_2	0.31	0.34	0.34	0.33	0.34	0.3	0.3

Table 8
Cumulative global temperature response of the emissions between 2015 and 2040 in the emission reduction scenarios [μK].

	Baseline	Info Campaign	Sauna Legislation	ESP Installations	Combustion Bans	MFR
CO_2	110	110	110	110	97	96
CH_4	9.2	8.3	7.9	9.2	7.9	6.4
N_2O	0.53	0.53	0.53	0.53	0.48	0.48
NOX	-2.3	-2.3	-2.3	-2.3	-2.1	-2.1
VOC	4	3.6	3.3	4	3.3	2.5
CO	1.8	1.7	1.6	1.8	1.6	1.3
BC	210	200	180	180	170	120
OC	-31	-28	-27	-29	-27	-19
SO_2	-1.7	-1.7	-1.7	-1.7	-1.5	-1.5
Total	301	292	272	273	250	204

A relatively short time frame, like the 25 years in this study, will show a bigger impact for SLCFs in relation to GHGs than the commonly used 100 years would. This then results in an increased impact from the emissions of BC-rich sectors like RWC. Typically metrics like GWP and GTP are used to estimate the future impact of an emission pulse (e.g. annual emissions in 2015). However, for understanding the cumulative climate impact of emissions up to a certain end point, emissions of each year in the studied time frame should be accounted for. This will underline the importance of the timing of any action, when planning measures to reach a selected climate goal. Using emission metrics such as these is not as time or resource consuming than actual climate modelling. They can also be used with any amount of emissions, even when they would be too low to show impacts in a climate model. The accuracy of the results will depend on the quality of the metrics, as well as their suitability for the emission data.

Climate policy has focused mainly on greenhouse gas (GHG) emissions. However, the role of carbon sinks is rising as the Paris agreement aims to achieve balance between anthropogenic emissions and sinks in the second half of this century (UNFCCC, 2015). Holding the increase in the global average temperature to less than 2°C above pre-industrial levels is likely not possible without significantly enhancing carbon sinks (Rockström et al., 2017). Besides technical measures under development to remove CO_2 from the atmosphere, forests and soil as natural carbon sinks are cost-efficient and technically available (Minx et al., 2018) and more powerfully included in the climate policy regime in the EU from 2021 onwards compared to the Kyoto Protocol up to 2020.

A number of studies have concluded that increased wood harvesting results in lowered forest carbon stocks or reduced sink for decades (Matthews et al., 2014). For example, taking a 25 year time-horizon, increased harvesting of branches and stumps in Finland results in carbon stock loss corresponding 40% and 80% of the CO_2 emissions from coal combustion per equivalent energy content of the fuels (Repo et al., 2012). If increased amount of energy wood is derived from living trees, forest carbon stocks are lowered more significantly, corresponding to CO_2 emissions even twice those of the same energy content of coal combustion over 25 year time-horizon (Pingoud et al., 2016), as explained in chapter 2.5. No universal method exists to account for the net biogenic CO_2 emissions, as their assessment depends on the reference system, time horizon and metrics considered (Koponen et al., 2018). Stemwood is usually used as a fuel in RWC. Removing stemwood from a forest results in a bigger depletion of its carbon storage than removing residues or saplings. The element of indirect emissions (i.e. the resulting changes in the forest carbon stocks) is missing in our comparison in chapter 3.2.2.

An important notion considering the comparison of heating methods in chapter 3.2.2 is that we have used constant emission factors per produced heat and electricity for CO_2, SO_2 and NO_x, as they were in 2015. In reality, all of those emission factors will probably decrease considerably by 2040. Because the net climate impact for heat and electricity production is clearly warming, decreasing the emission of all those pollutants will also most likely decrease the warming climate impact, even though they also include cooling pollutants like SO_2. On the other hand, if a masonry heater or a pellet boiler is installed in 2015, their emission factors will likely be the same in 2040. Taking this into account would further highlight the inferiority of RWC as a measure to mitigate the climate impacts of residential heating.

There is an uncertainty considering the emission factors of current sauna stoves that is worth noting. The emission factors in our model, which are remarkably high compared to other appliances, are based on relatively few measurements. Also, according to manufacturers, the design of sauna stoves has changed since the measurements were carried out, due to EU requirements for CE certificate, which entered into force in 2013. These factors might lead to overestimation of emissions, especially in the future, when a larger part of the appliance stock has been renewed. However, sauna stoves still have relatively simple structure and short, intensive combustion process. This typically results in higher BC emissions than in most other appliances. Thus, the uncertainty in the emission factors does not undermine the conclusion that emissions from sauna stoves cause a relatively large climate impact and that controlling their emissions is relevant.

Forests and forest industry have also other types of climate impacts than the ones assessed in this paper. Forests produce natural aerosols that have an impact on cloud formation and thus affect the radiative forcing of atmospheric components. Spracklen et al. (2008) estimate that the organic vapors from a boreal forest double the regional cloud condensation nuclei. This would produce negative radiative forcing, i.e. a cooling impact. On the other hand, the albedo of a forest area is lower than that of a plain (Lukeš et al., 2013). Harvesting a forest can therefore increase the albedo of the area, and thus partly offset its negative climate impact. However, no sufficient data was found on the impact of removing individual trees from a forest, as is often the case with harvesting fuelwood for RWC. For this reason we have not estimated the climate impact of RWC due to changes in canopy albedo or organic vapors.

5. Conclusions and policy implications

This study shows that emissions from residential wood combustion have a significant warming impact on climate, when compared with Finland's reported and projected greenhouse gas emissions. In 2040, Finland's total projected GHG emissions from 2015 onwards are estimated to cause a warming temperature response of 650 μK globally and 930 μK in the Arctic area. This projection does not include emissions of SLCFs from RWC (except CH_4). Including the other SLCFs than CH_4 from RWC would increase the warming impact of Finland's emissions by 28% in global response and 170% in Arctic response. Accounting for the biogenic CO_2 would further greatly increase the warming responses of the projected GHG emissions.

Wood combustion has been advocated as a climate-friendly heating method in Finland. However, this study shows that BC emissions from stoves cause a warming impact, which can be multiple times larger than that of district or electric heating, in a 25 year time span. As an exception, SLCF emissions from wood pellet boilers were not shown to have a warming impact, due to relatively efficient combustion and therefore low emissions of unburnt carbonaceous particles. However, biogenic CO_2 emissions and changes in carbon storages have to be accounted for as well, to be able to estimate the climate impacts of biomass combustion. The examples in this study show that the calculation method has a decisive influence on how climate-friendly each heating method appears to be. Using a direct emission factor for biogenic CO_2 will significantly increase the warming impact of wood combustion, relative to other methods. This is due to low net heating efficiency of residential heaters and low heat value of wood. Taking the indirect emissions – such as the changes in forest carbon stock – into account would further highlight the warming impacts caused by burning logs. Depending on how the impact of wood harvesting is allocated between stemwood and residues, using the indirect emissions might show a somewhat reduced impact for pellets and wood chips.

In recent years, emissions from RWC have been in focus in many countries, including Finland, due to their harmful health impacts. This has been recognized as a problem in densely populated areas, such as suburbs, whereas wood combustion in rural areas has been considered less problematic. From climate impacts point of view, however, emissions from RWC are equally effective in sparsely populated areas.

Currently SLCF emissions are typically not accounted for, when assessing the climate impact of various heating methods. Biogenic CO_2 emissions are also often neglected in comparisons. Still, climate policies usually deal with time frames in which both of them are very relevant. Although the metrics used in this study involve large uncertainties, the conclusion appears evident: Wood heating is likely the least climate-friendly option of the common heating methods in Finland, when all relevant emissions are taken into account. There are other factors that favor wood heating, such as security of supply and price, but it should not be promoted as beneficial for the environment.

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Appendix

Table A1
Emission factors for RWC used in the FRES model [mg MJ^{-1}].

	$PM_{2.5}$	BC	OC	NMVOC	CO	NOx	N_2O	CH_4	SO_2	CO_2
Boilers										
Wood chip boiler	15.5	0.5	1	3	233	80	1.8	3	5	112000
Pellet boiler	19.6	0.6	0.8	3	127	80	1.8	3	5	112000
Manually fed boiler with accumulator	135	40.6	16	49	2770	80	2	150	5	112000
Manually fed boiler without accumulator	700	210	140	402	2770	80	2	150	5	112000
Manually fed modern boiler	16.5	0.5	1	49	233	80	2	150	5	112000
Stoves										
Open fireplace	638	36.8	7.6	92	2150	80	3	24	5	112000
Kitchen range	52.5	33.7	43.4	209	2660	80	3	89	5	112000
Conventional masonry heater	136	47.3	12.1	139	1230	80	3	59	5	112000
Modern masonry heater	48.3	18.7	10.1	92	1860	80	3	39	5	112000
Masonry oven	48	14.7	138	1270	8430	80	1	434	5	112000
Conventional sauna stove	470	182	68.9	633	4220	80	1	217	5	112000
Modern sauna stove	235	91.1	33.1	398	3290	80	3	89	5	112000
Conventional iron stove	113	27.7	21	82	1670	80	3	59	5	112000
Modern iron stove	72	17.6	1	3	233	80	1.8	3	5	112000

Table A2
Emissions of SLCFs by appliance type [kt a^{-1}].

	$PM_{2.5}$		BC		OC		NMVOC		CO		NO_x		N_2O		CH_4		SO_2		CO_2	
	2015	2040	2015	2040	2015	2040	2015	2040	2015	2040	2015	2040	2015	2040	2015	2040	2015	2040	2015	2040
Boilers																				
Wood chip boiler	170	170	5.6	5.6	11	11	33	33	2600	2600	890	890	20	20	33	33	56	56	1240627	1241384
Pellet boiler	22	100	0.66	3.1	0.88	4.1	3.3	15	140	650	88	410	2	9.2	3.3	15	5.5	26	123200	571200
Manually fed boiler with accumulator	1300	700	380	210	150	83	460	250	26000	14000	740	420	20	11	1400	780	47	26	1041600	582400
Manually fed boiler without accumulator	1500	0	440	0	290	0	840	0	5800	0	170	0	4.6	0	320	0	11	0	235200	0
Manually fed modern boiler	0	91	0	2.8	0	5.5	0	270	0	1300	0	440	0	12	0	830	0	28	0	616000
Stoves																				
Open fireplace	1100	1200	63	70	540	600	690	770	14000	16000	140	150	3.4	3.8	450	500	8.5	9.5	190400	212800
Kitchen range	270	310	170	200	39	45	470	540	11000	13000	410	470	13	15	120	140	26	30	571200	660800
Conventional masonry heater	1400	650	480	230	440	210	2100	1000	27000	13000	820	380	26	12	910	430	51	24	1142400	537600
Modern masonry heater	72	420	28	160	18	110	210	1200	1900	11000	120	700	3.8	22	89	520	7.5	44	168000	985600
Masonry oven	420	490	130	150	89	100	810	950	16000	19000	700	820	22	26	350	410	44	52	985600	1153600
Conventional sauna stove	4200	3600	1600	1400	1200	1100	11000	9800	75000	65000	710	620	9.8	8.5	3900	3300	45	39	996800	862400
Conventional iron stove	150	0	36	0	43	0	520	0	4300	0	100	0	3.3	0	120	0	6.5	0	145600	0
Modern iron stove	0	120	0	30	0	36	0	140	0	2800	0	140	0	4.3	0	100	0	8.5	0	190400
Total	10000	7900	3400	2500	2900	2300	17000	15000	180k	160k	4900	5400	130	140	7600	7100	310	340	6696560	7452800

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