Department of Mechanical Engineering

Climate and Health Impacts of Residential Wood Combustion in Finland

Mikko Savolahti

Aalto University

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Abstract

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Abstract

Elevated fine particle concentrations in ambient air cause significant negative impacts on public health. During the last decades, emissions of fine particle matter have been effectively reduced through legislation, especially in industry and transport. Emissions from residential wood combustion, however, have not been regulated, and wood burning has become the most significant source of particulate emissions in many countries. Wood burning has been viewed as carbon neutral, and thus climate policies have often aimed to increase use of wood, even if the negative health impacts of wood smoke have been acknowledged. In recent years, however, the climate impacts of biomass burning have also received increasing scientific interest, regarding both black carbon emissions and changes in global carbon stocks. It has been shown that wood burning has climate effects that can be of the same magnitude or larger than those of using fossil fuels.

This thesis examines the climate and health impacts of residential wood combustion in Finland. In this thesis, an approach for thorough estimation of emissions from Finnish residential wood combustion is presented. In addition, the work examines the effectiveness and costs of selected emission reduction measures. The thesis also presents a method for calculating the regional climate impact of emissions that affect the Earth's radiative forcing. The method is then applied to quantify the climate impact caused by residential wood combustion. Finally, the thesis presents an estimate of the negative health impacts caused by fine particle emissions from residential wood combustion in Finland, based on a chain of modeling steps.

The thesis demonstrates that wood combustion is the largest source of emissions of fine particles and black carbon in Finland. In relation to Finland's greenhouse gas emissions and measured particulate concentrations in ambient air, emissions from wood combustion are found to be significant in terms of both climate and health effects. On the other hand, the thesis also shows that it is possible to reduce emissions and their adverse effects by informative and administrative measures.

Keywords wood combustion, emissions, particles, climate change, air pollution

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Tiivistelmä

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Tiivistelmä

Kohonneet pienhiukkaspitoisuudet hengitysilmassa aiheuttavat merkittäviä kansanterveydellisiä haittoja. Viime vuosikymmeninä pienhiukkasten päästöjä on saatu tehokkaasti vähennettyä lainsäädännön avulla, erityisesti teollisuuden ja liikenteen pakokaasujen osalta. Puun pienpolton päästöjä ei kuitenkaan ole rajoitettu vastaavasti, ja pienpoltto onkin noussut monissa maissa merkittävimmäksi päästöjä aiheuttavaksi sektoriksi. Puun polttamisen on ajateltu olevan hiilineutraalia, jolloin ilmastopolitiikka on usein suosinut puun käytön lisäämistä, vaikka sen aiheuttamat ilmanlaatuongelmat olisikin tiedostettu. Viime vuosina kuitenkin myös biomassan polttamisen ilmastovaikutukset ovat saaneet paljon tieteellistä kiinnostusta, liittyen sekä mustan hiilen päästöihin että muutoksiin maapallon hiilivarastoissa. On osoitettu, että puun polttamisella on ilmastovaikutuksia, jotka voivat olla samaa suuruusluokkaa tai suurempia kuin fossiilisilla polttoaineilla.

Tässä väitöskirjassa tarkastellaan puun pienpolton aiheuttamia ilmasto- ja terveysvaikutuksia. Työssä esitetään perusteellinen laskentamenetelmä, jolla voidaan arvioida puun pienpolton aiheuttamia päästöjä Suomessa. Lisäksi työssä tutkitaan mahdollisten päästövähennyskeinojen vaikuttavuutta ja kustannuksia. Työssä esitetään myös menetelmä maapallon säteilypakotteeseen vaikuttavien, Suomen leveysasteilla tapahtuvien päästöjen ilmastovaikutuksen laskemiseksi, ja sovelletaan menetelmää käytännössä. Lopuksi työssä on esitetty mallintamalla tuotettu arvio pienpoltosta seuraavista terveyshaitoista Suomessa, sekä nykytilanteessa että erilaisissa skenaarioissa.

Väitöskirjassa osoitetaan, että puun pienpoltto on suurin pienhiukkasten ja mustan hiilen päästölähde Suomessa. Suhteessa Suomen kasvihuonekaasupäästöihin ja mitattuihin hengitysilman pienhiukkaspitoisuuksiin, puun pienpolton päästöjen todetaan olevan merkittäviä sekä ilmasto- että terveysvaikutusten osalta. Toisaalta väitöskirjassa osoitetaan myös, että päästöjä ja niiden haittavaikutuksia on mahdollista vähentää informatiivisilla ja hallinnollisilla keinoilla.

Avainsanat puunpoltto, päästöt, hiukkaset, ilmastonmuutos, ilmansaasteet

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Preface

The work for this thesis was carried out during the years 2010-2019, while working in the Centre for sustainable consumption and production of Finnish environment institute. I wish to thank my thesis advisor and head of our emission modeling team, Niko Karvosenoja, for providing invaluable guidance in all the work that led to this thesis. The team has provided a uniquely enjoyable working environment, for which a special thanks goes to all colleagues in the team. I also wish to thank my supervising professor Mika Järvinen for helping me structure the thesis.

Helsinki, January 31, 2020,

Mikko Savolahti

Contents

List of Publications

The following publications are included in the thesis. In the text they are referred to by their Roman numerals.

I
Mikko Savolahti, Niko Karvosenoja, Jarkko Tissari, Kaarle Kupiainen, Olli Sippula and Jorma Jokiniemi. 2016. Black carbon and fine particle emissions in Finnish residential wood combustion: Emission projections, reduction measures and the impact of combustion practices. Atmospheric Environment, ISSN: 1352-2310, Vol: 140, Page: 495-505, https://doi.org/10.1016/j.atmosenv.2016.06.023

II
Kaarle Kupiainen, Borgar Aamaas, Mikko Savolahti, Niko Karvosenoja, and Ville-Veikko Paunu. 2019. Climate Impact of Finnish Air Pollutants and Greenhouse Gases using Multiple Emission Metrics. Atmospheric Chemistry and Physics, 19, 7743–7757, 2019, https://doi.org/10.5194/acp-19-7743-2019

III
Mikko Savolahti, Niko Karvosenoja, Sampo Soimakallio, Kaarle Kupiainen, Jarkko Tissari and Ville-Veikko Paunu. 2019. Near-term climate impacts of Finnish residential wood combustion. Energy Policy, Volume 133, 2019, 110837, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2019.06.045

IV
Mikko Savolahti, Heli Lehtomäki, Niko Karvosenoja, Ville-Veikko Paunu, Antti Korhonen, Jaakko Kukkonen, Kaarle Kupiainen, Leena Kangas, Ari Karppinen and Otto Hänninen. 2019. Residential wood combustion in Finland: $PM_{2.5}$ emissions and health impacts with and without abatement measures. International Journal of Environmental Research and Public Health, 16(16), 2920, https://doi.org/10.3390/ijerph16162920

Author’s Contribution

Publication I: “Black carbon and fine particle emissions in Finnish residential wood combustion: Emission projections, reduction measures and the impact of combustion practices. Atmospheric Environment”

Savolahti is the lead author. Karvosenoja and Savolahti designed the improved emission calculation scheme. Savolahti carried out the update of the emission model, calculated the results and wrote the Publication. Karvosenoja provided valuable comments and guidance. Tissari wrote most of chapter 2.1. Kupiainen, Sippula and Jokiniemi helped to establish the emission factors and provided comments.

Publication II: “Climate Impact of Finnish Air Pollutants and Greenhouse Gases using Multiple Emission Metrics”

Kupiainen initiated the research and wrote a preliminary frame of the manuscript. Savolahti provided text to all main chapters and had major influence on the structure and the research questions of the Publication. The eventual design of the Publication was made in co-operation between Kupiainen and Savolahti. Aamaas provided the climate metrics that enabled the regional viewpoint. Aamaas also wrote chapter 2.2. and provided valuable insight to other chapters. Karvosenoja and Paunu provided comments.

Publication III: “Near-term climate impacts of Finnish residential wood combustion”

Savolahti is the lead author. Savolahti and Kupiainen developed the idea for the Publication. Savolahti designed the study, calculated the results and wrote the Publication. Tissari provided text to chapter 2.2 and comments to other chapters. Soimakallio provided comments and insight to the study design. Karvosenoja and Paunu provided comments.

Publication IV: “Residential wood combustion in Finland: $PM_{2.5}$ emissions and health impacts with and without abatement measures”

Savolahti is the lead author. The results were obtained from a three-year research project, which involved all of the authors. Savolahti wrote the Publication with the help of Lehtomäki, Karvosenoja and Paunu. Other authors provided comments.

1. Introduction

This chapter presents an overview to the research area, as well as the focus of this thesis. The scientific findings of the thesis have been reported in detail within the attached Publications.

1.1 Background and Motivation

Wood heating and use of sauna stoves have strong roots in Finnish culture, and the prevalence of installing stoves to new detached buildings has still increased during the last decades. Wood has been promoted as an environmentally friendly, domestic and renewable fuel. It is also a cheap or practically free source of energy, since it is common to have access to privately owned forests. Consumption of fuelwood has thus been steadily increasing since the 80s (Fig 1.1). Although evidence of the negative health impacts of the air pollutants in wood smoke has been mounting in scientific literature (e.g. Naeher et al. 2007, WHO 2013), the public opinion has not reflected this. Smell of wood smoke has been viewed as “natural” and “cosy”.

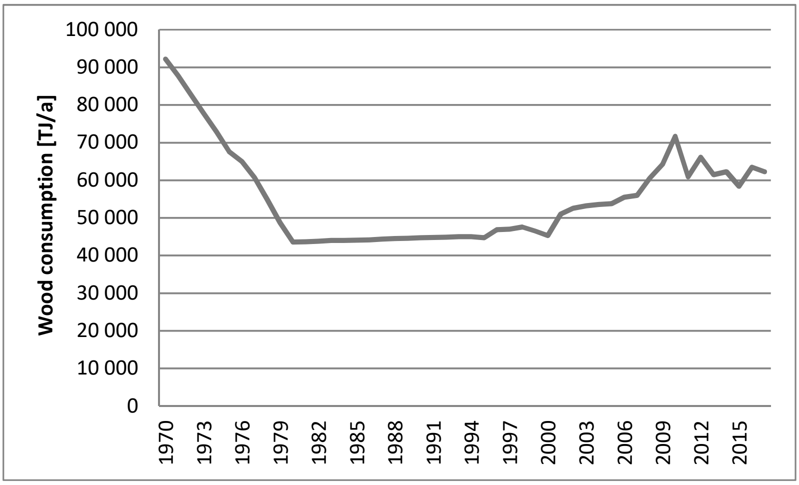


Figure 1.1. Consumption of fuelwood in Finnish residential stoves and boilers (Statistics Finland, 2018).

Compared to most other common fuels, wood has a relatively low net calorific heating value; 7 – 20 MJ/kg, depending on the moisture content (Alakangas, 2005). Typical moisture content in fuelwood is between 15 and 25 %. Wood has a high content of volatile matter (approx. 80 % of dry wood), the rest being fixed carbon and ash. Fig 1.2 shows the chemical composition of typical fuelwood.

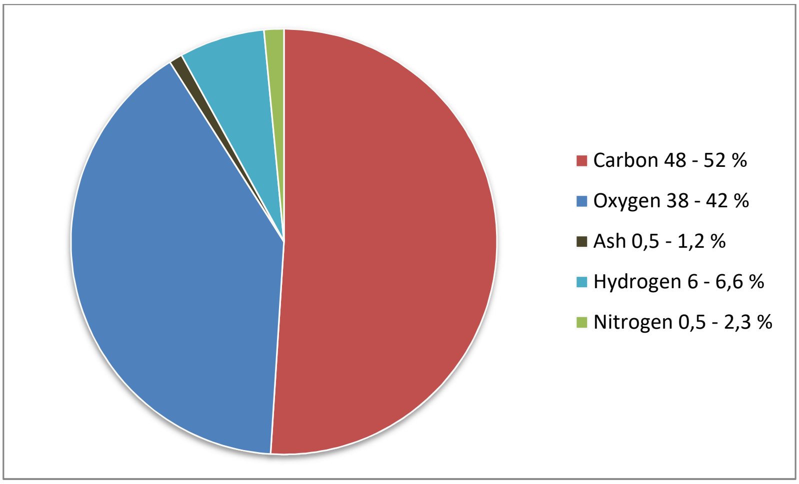


Figure 1.2. Elemental composition of wood. Ash contains mainly calcium, potassium, silicon, phosphorous, magnesium and iron (Alakangas, 2005)

During the last few years, awareness on the harmful health impacts of wood smoke has been notably increasing in Finland and other countries. This is likely due to increased scientific interest and media visibility of the topic, as well as upcoming EU regulation (Ecodesign requirements for local space heaters and solid fuel boilers: 2015/1185, 2015/189) and local awareness raising campaigns. With the understanding that wood heating causes negative impacts on public health, it has increasingly been viewed as a trade-off between climate and health benefits. However, wood combustion is a source of biogenic CO_2 and many Short-lived climate forcers (SLCF) like black carbon (BC) and organic carbon (OC). The scientific focus has been steadily moving from just harmful health or ecosystem impacts of air pollution to a more integrated approach, which includes the climate impact of e.g. particulate matter. At the same time, the climate impact of biogenic CO_2 has also been a contested topic (Koponen et al. 2018). Although the discussion related to biogenic CO_2 has mostly been about industrial-scale combustion of biomass, the same principles apply for wood that is harvested for residential combustion: The forest carbon sink is reduced when trees are harvested, and the reduction in the carbon sink is often greater than the amount of carbon received for energy (Pingoud et al., 2016).

Particulate emissions from most major sources like traffic, mobile machinery and combustion plants, have been regulated by law for decades. The legislation is updated as technology improves, thus continuously setting stricter limits for emissions. Emissions from wood combustion, however, have not been regulated thus far. For this reason, it is estimated that residential wood combustion (RWC) has become the biggest source of $PM_{2.5}$ (particles with a diameter of less than 2.5 µm) emissions in Finland (Fig 1.3) and many other countries. RWC includes all wood burning that occurs in residential-scale buildings and in their surrounding properties, but does not include district heating plants.

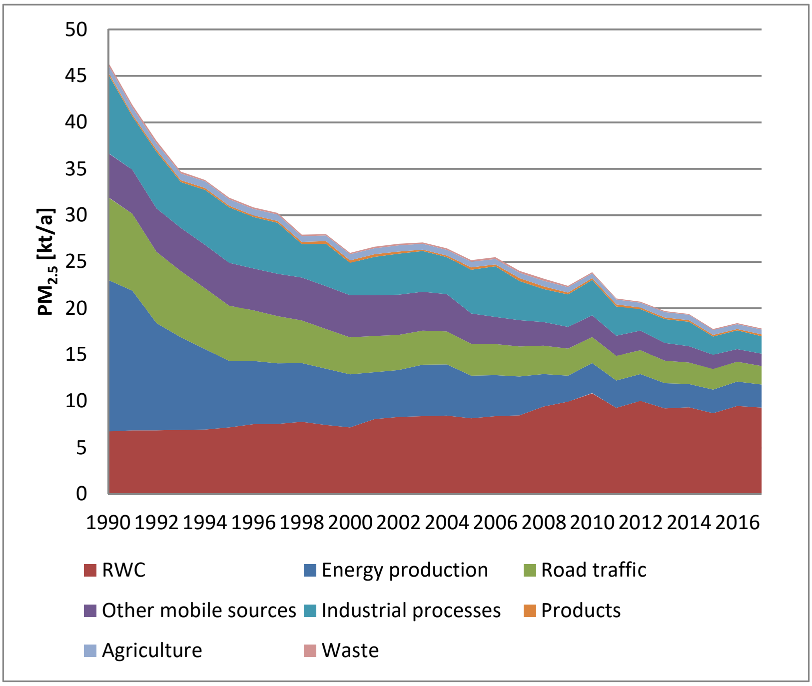


Figure 1.3. Development of $PM_{2.5}$ emissions from major sources in Finland (Finnish Environment Institute, 2018)

Even with increasing scientific interest in the environmental impacts of RWC, plenty of challenges remain in assessing those impacts. RWC appliances have a huge variance in build, combustion efficiency and optimal operation principles (Tissari 2008). Even with the same appliance, the combustion practices of the user often have a significant impact on the emissions produced (Tissari et al. 2008, Tissari et al. 2009). Thus estimating the total RWC emissions of a larger area, e.g. a country, is more complicated than for most major sources. Robust emission estimates are important for relevant assessment of dispersion and the various impacts of those emissions. The two latter parts of the modeling chain also include notable uncertainties. In recent years, Finnish and international scientific communities have been active in trying to close the knowledge caps in that modeling chain.

1.2 Residential Wood Combustion Appliances in Finland

Estimates on wood consumption and the prevalence of various combustion appliances in Finland are based on questionnaire surveys. The most recent extensive survey was carried out in 2018 by Natural Resources Institute Finland. Wood use in residential boilers and stoves in 2017 was estimated to be 63 PJ, with the total heating energy used in the residential sector being 330 PJ (Statistics Finland, 2018). The shares of main appliance types are shown in Fig 1.4.

Figure 1.4. Share of wood consumption by major appliance types in 2015. Other stoves include open fireplaces, kitchen ranges and iron stoves.

1.2.1 Masonry heaters

The most common wood combustion appliance in Finland is a masonry heater (Fig 1.5) or oven. They have a large mass of heat-storing material that surrounds the combustion chamber, and releases the heat slowly into the room in a period of 10 hours to two days (Tissari et al. 2008). Masonry heaters have advantages in combustion efficiency due to several reasons, e.g. secondary combustion chamber, hot and closed surfaces of the firebox, inlets for secondary air (in modern appliances) and the ability to store heat. This results in relatively low emissions, compared to other types of stoves.

Figure 1.5. Operating principle of a masonry heater (Tissari et al. 2005)

Masonry heaters are mostly used for supplementary heating in detached houses. They can be used to save electricity or to provide extra heating during the coldest periods in winter. Masonry ovens can be used for slow cooking in addition to heating the house. Majority of detached houses and nearly half of summer cottages in Finland have a masonry heater or oven. Almost all new detached houses include one, and especially in sparsely populated areas, it is viewed as a necessary back up heating system in case of power failures or other distribution problems.

1.2.2 Sauna stoves

Sauna stoves (Fig 1.6) are very common in Finland, and most detached houses and summer cottages have one (or more). In a sauna room the heating need is temporarily very high, so the stoves operate with a high combustion rate. This results in a high gasification rate of the fuel, and typically the air supply is insufficient. During the last decade, Finnish manufacturers have improved the structures of their sauna stoves and added e.g. secondary air inlets (Tissari et al. 2019). Still, most sold sauna stoves are cheap and easily installed appliances, and this requires a relatively simple structure. Although emissions in modern sauna stoves are lower than in older ones, and the variance is high, generally emissions from sauna stoves are considerably higher than from masonry ovens.

Figure 1.6. Sauna stove with a hot water tank (Tykkyläinen, 2019).

1.2.3 Residential wood boilers

Wood boilers are used as primary heating devises, mostly in rural areas. Logs and wood chips are most commonly used as fuel in central heating boilers, while the popularity of pellet boilers has remained low. Wood chips are mostly used in agricultural and commercial buildings in rural areas, while logs are used to heat detached residential houses. Log boilers are typically used with a storage tank where water is heated. Sometimes they are operated without a heat storage tank, by purposely restricting the combustion rate to lower the thermal output. This causes smouldering combustion and very high emissions. On the other hand, automatically fed pellet and wood chip boilers, as well as the best modern log boilers have the lowest emissions of all RWC appliances. The structures of log boilers differ, and this affects the emissions. Typically Finnish boilers have been updraught boilers, which have higher emissions than downdraught boilers (Fig 1.7). Overall, emission factors of different types of boilers have great variance, and particulate emissions in the most inefficient boilers can be more than 40 times as high as in the best ones.

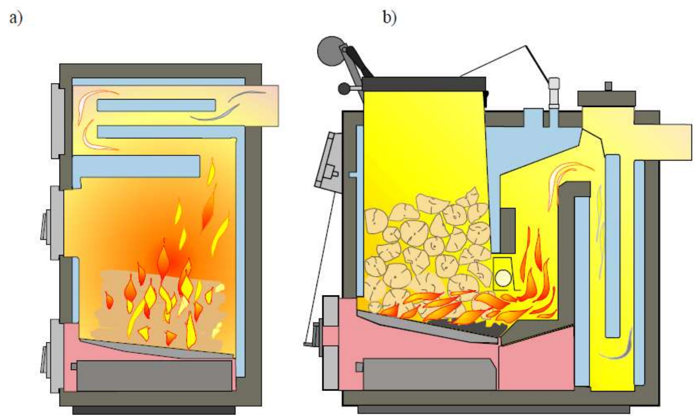


Figure 1.7. Schematics of a) updraught and b) downdraught boilers (Tissari et al. 2005).

1.2.4 Other stoves and fireplaces

In addition to masonry heaters and sauna stoves, a large range of various other stoves are used in Finnish residential houses and summer cottages. Open fireplaces are common in older buildings, but are not used much. Wood ranges are still used in cooking to some extent, and light, easy to install wood stoves made of iron (called iron stoves in this thesis) are common in buildings were heating need is not constant. Examples of these are shown in Fig 1.8. In addition to stoves, various outdoor grills and tubs are popular in rural areas and summer cottages.

a)

b)

Figure 1.8. a) Wood range (Silvo, 2019) and b) traditional Finnish iron stove (Tykkyläinen, 2019)

1.3 Formation and Dispersion of Emissions

Air pollutants, such as particulate matter (PM), CO, VOC, SO_2 and NOx, as well as greenhouse gases (GHGs) CO_2, CH_4 and N_2O are produced in wood combustion (Tissari 2008). PM emissions include varying amounts of carbonaceous particles, such as black carbon (BC) and organic carbon (OC), depending on the combustion conditions. The combustion process in RWC appliances is more challenging to control than in industrial-size boilers. This leads to increased amount of incomplete combustion and the formation of soot particles (EC = elemental carbon, often interpreted as BC), as well as many other particulate and gaseous emissions. Wood also contains sulfur, nitrogen and various volatile mineral compounds, which produce sulfur dioxide and nitrogen oxides in combustion, as well as so called fly ash. Particulate emissions from RWC consist of coarse particles (> 2.5 μm) and fine particles (< 2.5 μm). The former is mostly fly ash and unburnt char particles, and the latter soot, particle organic matter (POM) and fine fly ash.

Once emitted, the pollutants disperse and chemically transform in the ambient air. Organic gases condense to particulates (SOA = Secondary Organic Aerosol) as the combustion aerosol is cooled and diluted in the chimney and atmosphere, or they can form new particles by nucleation (Pleijel 2007). Secondary inorganic PM is also formed from SO_2, NO_x and NH_3 in the atmosphere. The extent of the dispersion depends on the type of pollutant, height of the emission source and meteorological conditions. The residence times of particulate emissions in the atmosphere are typically less than a week, whereas its ~10 years for CH_4 and > 100 years for CO_2 and N_2O (IPCC 2013). Especially for primary particulates, the biggest impact on ambient concentrations occurs close to the emission source. This is even more pronounced if the emission height is low and the emissions have not had the time to dilute in the air. Typically people are exposed to fine particle concentrations that are combinations formed of international, national, local and natural emissions (Fig 1.9). Concentrations on a street level comprise of regional background, urban background and emissions from nearby sources, such as traffic, RWC, construction sites etc. (Fig 1.10).

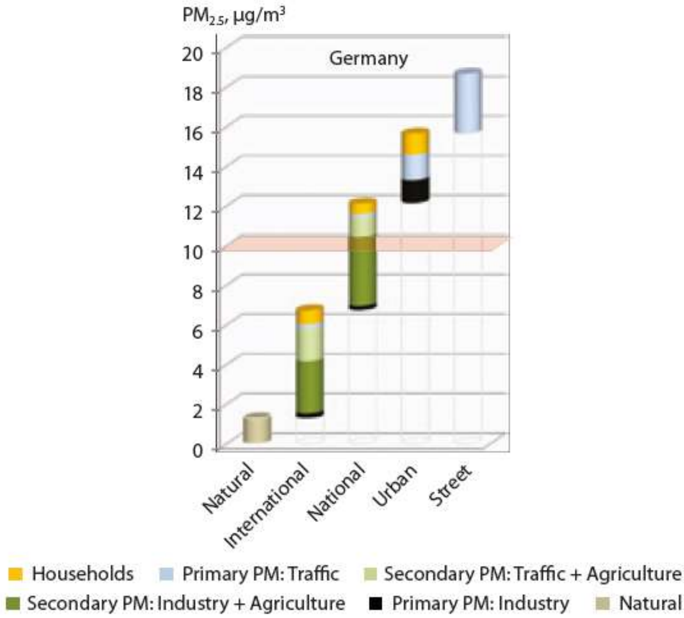


Figure 1.9. Average origin of fine particles at streel level in several German cities (Maas & Grennfelt, 2016 Towards cleaner air)

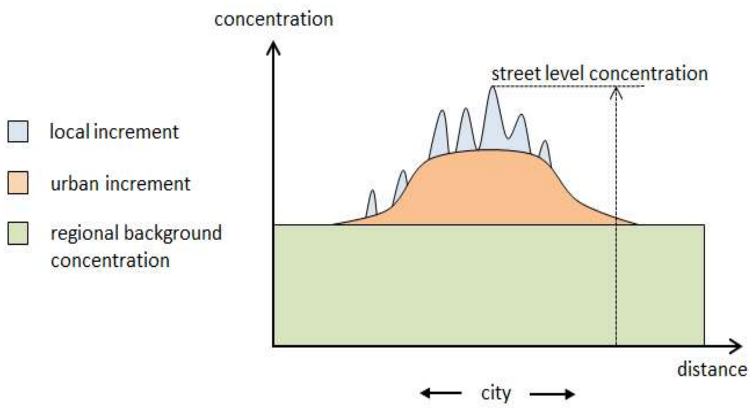


Figure 1.10. Local and distant sources contribute to fine particle concentrations on a city street.

1.4 Environmental Impacts of Emissions

Air emissions have a wide range of impacts on the environment. During the last decade, climate change, caused mostly by greenhouse gases, has been the most featured impact in public discussion. Recently also the hazardous impacts of air pollution on human health have received a renewed scientific and public attention (Lancet 2018, Lelieveld et al. 2019). In the 70's, acidification and the degradation of ecosystems was the motivation for intergovernmental regulation on air pollution (Maas

& Grennfelt 2016) Impacts of common gaseous and particulate emissions are presented in Table 1.1.

Table 1.1. Toxic properties and effect on climate change of different gases and particle types (Pleijel 2009)

Compound	Toxic properties	Climate change properties
CO_2	Acidification of sea waters, affects photosynthesis	Greenhouse gas
N_2O	Destruction of the stratospheric ozone layer	Greenhouse gas
CH_4	Precursor of ground-level ozone	Greenhouse gas
O_3	Adverse effects on health and vegetation	Greenhouse gas
SO_2	Acidification, health effects	Sulfate particles suppress global warming
PM, BC, OC	Health effects	Black particles increase and reflecting particles suppress global warming
NO_x	Precursor of ground-level ozone, acidification, eutrophication, health effects	Nitrate particles may suppress global warming

1.4.1 Impacts on Human Health

Globally air pollution is estimated to cause 7 – 8.8 mil. premature deaths every year (Lancet 2018, Lelieveld et al. 2019). It is the largest environmental cause of disease and premature deaths. In Finland, air pollution has been estimated to cause 2000 – 4000 annual premature deaths (Lehtomäki et al. 2018, Lelieveld et al. 2019). The social cost of air pollution is significant. In the EU, health-related costs due to air pollution were estimated to be EUR 330 – 940 billion in 2010 (EC 2013).

Most of the health impacts of air pollution are due to increased fine particle concentrations in ambient air. Inhaled fine particles can get deep into the lungs or even bloodstream, and cause a variety of problems, ranging from increased respiratory symptoms to chronic illness and premature death. Long-term exposure is the most harmful, since it can increase chronic inflammation and lead to various diseases. RWC is a major contributor to fine particle concentrations in European cities and towns. During the heating season in Helsinki, $PM_{2.5}$ concentrations attributable to RWC were estimated to be 18 – 29 % in urban sites and 31 – 66% in suburban sites (Saarnio et al. 2012). Similar numbers are typical for estimates made in other European cities. Chafe et al. (2015) estimated that 61 000 annual premature deaths in Europe are caused by household space heating with solid fuels (mostly wood, but including coal).

1.4.2 Impacts on Climate

Black carbon is the most potent compound of the SLCF emissions that affect climate change. It impacts Earth's radiative forcing in three ways, as presented in Table 1.2. All of these effects are estimated to have a warming impact in total, although some of the cloud effects can also have a cooling impact (Bond et al. 2013). Uncertainties in all climate impact estimates of BC are high. In wood combustion, BC is always produced simultaneously with many co-emitted SLCFs, which have both warming and cooling impacts on climate. Warming species include CH_4, VOC and CO, while OC, NO_x, SO_2 and NH_3 form light reflecting particles in the atmosphere that reduce radiative forcing. Bond et al. (2013) estimate that globally the total climate forcing of biofuel heating and cooking is only slightly warming, due to strong cooling impact of co-emitted species. RWC is also a major source of CO_2, although wood being a renewable fuel, these emissions are often neglected in climate assessments.

Table 1.2. Mechanisms of BC effects on radiative forcing.

Direct effect	Dark particles in the atmosphere absorb sunlight and emit heat radiation to their surroundings. This reduces the amount of sunlight that would reach the surface and be reflected back to space.
Indirect and semi-indirect effects	Particulates in the atmosphere affect the formation and chemical properties of clouds, which in term affect the radiative forcing of Earth. Heat absorbing particles also alter the atmospheric temperature structure and cloud distribution.
Snow and ice effects	Deposition of particles on ice or snow decreases the albedo of the surface, thus increasing the amount of sunlight it absorbs.

1.5 Objectives and Scope of the Thesis

The objective of this thesis was to get an overview of the environmental impacts of RWC in Finland. This included projections of future development as well as possible mitigation measures. For this purpose, new calculation methods were needed to create an improved integrated assessment modeling system. In Publication I, a detailed calculation scheme of the RWC emissions in Finland is created. BC and $PM_{2.5}$ emissions are calculated in three scenarios up to 2030, and options to reduce emissions are also explored. Publication II shows how the climate impact of Finnish SLCF emissions can be evaluated using various climate metrics. It also presents specific metric values that were created to be used with Finnish SLCFs in scenario assessments. In Publication III, the climate impact of RWC emissions in Finland is calculated using the emission calculation scheme of Publication I and the metrics of Publication II. Publication IV includes an assessment of the health impact of RWC emissions in Finland. Both Publication III and Publication IV present the impacts in a baseline scenario, as well as with mitigation measures.

2. Materials and methods

This chapter explains the principles of emission calculation and modeling used in this research. Specific methods are explained in more detail in the accompanying Publications.

2.1 Appliances, Wood Consumption and Emission Factors

We used Finnish Regional Emission Scenarios (FRES) model (Karvosenoja 2008) to calculate the emissions from RWC appliances. In Publication I, the model was improved to include five boiler categories and nine stove categories. These categories were selected so that they cover the main types of heaters used in Finland, and so that emission factor and wood consumption data was available for them. The basic equation for calculating the emissions of a RWC appliance category is

$$EM_{i,t,p} = A_{i,t} EF_{i,p} (1 - \eta) \tag{2.1}$$

where $A_{i,t}$ is the activity or fuel use of a given appliance category in a given year, $EF_{i,p}$ is the emission factor of that appliance for a given pollutant, and η is the removal efficiency of a possible flue gas cleaning device, if one is used.

Total wood consumption for the base years 2010 and 2015 was obtained from Statistics Finland (2018). The statistics are based on questionnaire surveys, in our case one that was conducted by the former Finnish Forest Research Institute, Metla (Torvelainen, 2009). This survey was also the basis for our estimation of the amount of wood fuels combusted in each appliance category. 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 Publications I - IV. However, they are well in line with the wood consumption assumptions we have used. Between the surveys, wood consumption statistics for each year vary, depending on temperature and other factors. Our estimations of the wood use development in each appliance is based on various sources of information and expert opinions. Wood consumption estimates for future years are taken from national Energy and climate strategies. The projection of fuelwood consumption in the latest strategy (Huttunen, 2017) is based on the expected development of the building stock and the prevalence of wood stoves and boilers in new and renovated buildings. Energy and climate strategies are updated and published every few years.

The emission factors for our studied pollutants, $PM_{2.5}$, BC, OC, CH_4, NMVOC, CO, SO_2, NO_x, and N_2O are mostly based on national measurements, as explained in Publications I and III. RWC emissions have been measured from diluted flue gases to account for the condensable particulate matter forming in the chimney or in ambient air immediately after the emission occurs. In Publication III, we also used an emission factor for biogenic CO_2, and discussed variables related to calculating it. In addition to Equation 2.1, we also try to take into account the varying skills of stove users and how they affect the emissions. For each pollutant related to each stove category, we have two emission factors, one for *normal* combustion and one for *smouldering* combustion. *Normal* combustion means proper use of the stove and *smouldering* combustion occurs with poor user practices. Emission factors for smouldering combustion are typically 1.5 to 6 times higher than for *normal* combustion. In Publication I, we explain our method of dividing stove users to three skill categories, based on the feedback received from chimney sweeps. We have then estimated the prevalence of *normal* and *smouldering* combustion in each skill group. Having emission factors for both *normal* and *smouldering* combustion, we have used emission factors that are combinations of the two, and take into account the assumed share of *smouldering* combustion. If the share of *smouldering* combustion is assumed to be zero, the emission factors used are those of *normal* combustion.

2.2 Dispersion Modeling

To be able to model the fine particle concentrations resulting from various activities, the emission sources must first be placed on the map as accurately as possible. In the case of RWC, this is especially challenging, since no register exists for the appliances that are being used. Neither is there data for wood consumption in a given household or building. In Publication IV, we have spatially distributed total annual emissions from RWC into a 250 m x 250 m grid, using several proxies. The national building and dwelling register was used to identify building locations and primary heating methods. The emissions were distributed into detached and semidetached houses, based on their estimated average wood consumption obtained from questionnaires. The wood consumption of a given house depended on: 1) Main heating method, 2) residential area type and 3) heating degree day (describes the demand for energy needed to heat buildings) (Paunu et al. 2013). Distribution of recreational building's emissions was based on floor space and heating degree day. Consumption in boilers is distributed only to buildings where wood heating has been reported as the primary heating method. For supplementary heating (use of stoves), only detached and semidetached houses were assumed to have consumption. In other building types, i.e. row and apartment houses, wood burning appliances are rare (<2% of the consumption in residential buildings) (Statistics Finland, 2018). Houses in urban areas of mild-weathered Southern Finland, with district heating as their primary heating method, are supposed to use the least wood for supplementary heating. Total wood consumption in different types of stoves are estimated separately for residential and recreational houses, but each house within those groups are assumed to have the same appliance stock.

In Publication IV, the dispersion of emissions and resulting fine particle concentrations were estimated using source-receptor matrices (SRMs) in a 250 x 250 m resolution. SRMs were based on the urban dispersion modeling system UDM-FMI, developed at the Finnish Meteorological Institute (Karppinen et al. 2000). The system includes a Gaussian dispersion model and meteorological conditions for ten separate parts of Finland, calculated on six-year average. In the system, the release height for residential combustion emissions was assumed to be 7.5 m. For sources with such a low release height, the size of the SRMs is 40 km x 40 km, with the emission source in the middle of this area. A major part of the concentration occurs close to the emission source, and no dispersion from that source is modeled beyond the area.

2.3 Assessing the Impacts on Climate and Health

On a global scale, Finnish emissions and their climate responses are relatively small. Therefore, it is challenging to use climate models to study the climate effect of national policies and to analyze the role of each pollutant and sector. Using emission metrics can overcome this challenge, as well as being less labor and hardware intensive. In Publication II, we have compared various metrics that can be used to estimate climate impacts of emissions. However, no climate metrics specifically suited for use with Finnish emissions were found in literature. The assumption was that due to e.g. the snow albedo effect of BC, global climate metrics for SLCFs would not represent the Finnish case with acceptable accuracy. Thus, we created a metric using the ARTP (Absolute Regional Temperature Potential) approach, where the temperature response was scaled to represent emissions coming from Finland's latitudes. We have presented metric values that can be used to calculate the cumulative climate impact of a 25-year emission pathway. In Publication III, we have used those metric values to calculate an estimate of the climate impacts of RWC emissions in Finland.

The health impacts of $PM_{2.5}$ are assessed by comparing population maps to concentration maps in the same respective grid size. Thus the modeling chain goes from changes in emissions and resulting concentrations to changes in population exposure and resulting health impacts. In literature, response functions are usually presented as a relative increase in the incidence of a given disease, when e.g. $PM_{2.5}$ concentration in ambient air is increased (WHO 2013). This relative risk increase is added to the specific background risk of the disease. We have used such response functions with a log-linear shape in Publication IV, to assess the negative heath impacts of RWC in Finland.

3. Summaries of the Publications

The four Publications included in this thesis constitute a general view on the Finnish residential wood combustion (RWC) emissions and an estimation of their climate and health impacts. The main scientific contribution of this thesis lies within the Publications, of which summaries are given below.

3.1 Publication I

The goal of this Publication was to notably improve the earlier estimates of black carbon (BC) and fine particle ($PM_{2.5}$) emissions resulting from RWC in Finland. Other goals were to create plausible emission projections for the future, estimate the development of the wood combustion appliance stock and to study measures for emission reduction. The foundation of the work was to update new appliance-specific emission factors to the calculation scheme of the used emission model. This included emission factors for *normal* combustion, as well as *smouldering* combustion, that results from typical mistakes made in operating a stove. These were implemented in a novel method to estimate the impact of stove using practices on total emissions from RWC. Three different scenarios for wood consumption were studied, as well as four measures to reduce the emissions by 2030. The measures were 1) Ecodesign directive that applies to solid fuel fired room heaters and boilers, 2) A national legislation that would set emission limits on sauna stoves, 3) Informational campaigns for stove users on cleaner combustion practices and 4) Reducing emissions from boilers by installing heat accumulator tanks or electrostatic precipitators (ESPs) designed for small-scale combustion. In addition, the cost-efficiency of each measure was studied.

Results from the updated emission calculating scheme supported the earlier finding, that RWC is the single biggest source of both $PM_{2.5}$ and BC emissions in Finland (Fig 3.1.a). Emission estimates for both pollutants increased from earlier estimations. The increase was especially notable for BC, as the emissions from Finnish RWC appliances had been shown to be relatively rich in BC. The relative share of estimated emissions from different appliances also changed significantly. Sauna stoves were found to cause the biggest emissions, accounting for 35 % of $PM_{2.5}$ and 45 % of BC emissions from RWC in 2010. The impact of user behavior on country-level emissions was estimated to be relatively modest, compared to other factors like the amount of wood consumption and state of the appliance stock.

Projected PM emissions varied significantly between the scenarios. Assumption for wood consumption had a bigger impact on emissions in 2030 than the implementation of reduction measures (Fig 3.1.b). Still, significant emission reductions could be achieved with the studied measures. Implementing all studied abatement measures was estimated to reduce annual emissions by almost 45 % in 2030. The only measure that's currently agreed to be implemented, the Ecodesign, was found to be relative ineffective by 2030. Setting emissions limits for new sauna stoves was estimated to be the most effective method in reducing both $PM_{2.5}$ and BC emissions. Assessing the impact of an informational campaign has major uncertainties, but when successful, it was estimated to have bigger emission reduction potential than implementing the Ecodesign directive. Installing ESPs and accumulator tanks to boilers was effective in reducing emissions, but was evaluated to be the most challenging to implement.

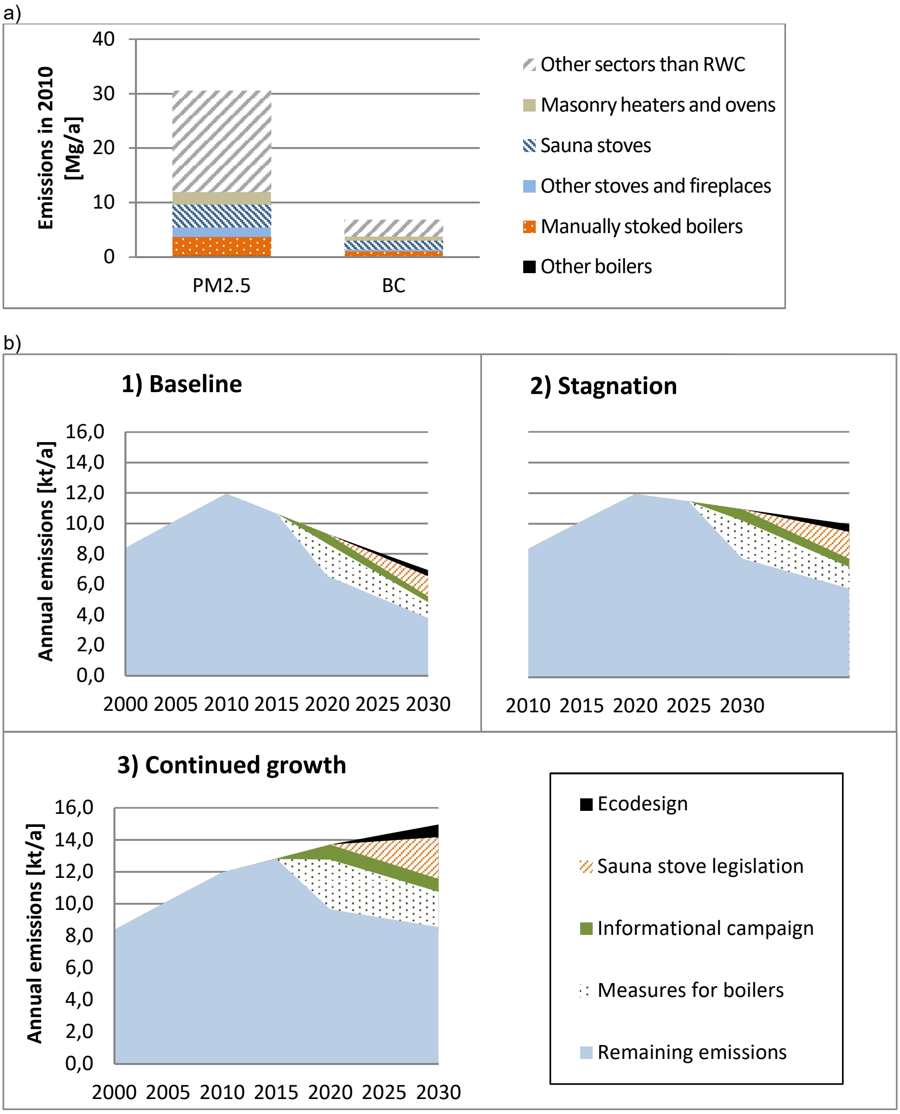


Figure 3.1. a) Finnish emissions from RWC and other sectors (Finnish Environment Institute 2015) in 2010

b) Annual emission reduction potentials for the studied measures, when implemented cumulatively. Initial emissions depend on the assumed wood consumption.

The most cost-efficient measure was the informational campaign, even if the impact was assumed to be minimal (Table 3.1). The most costly measure was installing ESPs to boilers. The principles of the calculation scheme laid out the foundation for the impact estimations of the later Publications.

Table 3.1. Emission reduction costs in 2030. Annual cost is annuity of all costs included in implementing the measure. With the exeption of Informational campaigns, all measures are implemented through the whole stock of the given appliances. Unit cost includes the emission reduction efficiency of the measure.

Measure	Annual cost [M€/a]	Unit cost of emission reduction [k€/Mg]	
		$PM_{2.5}$	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

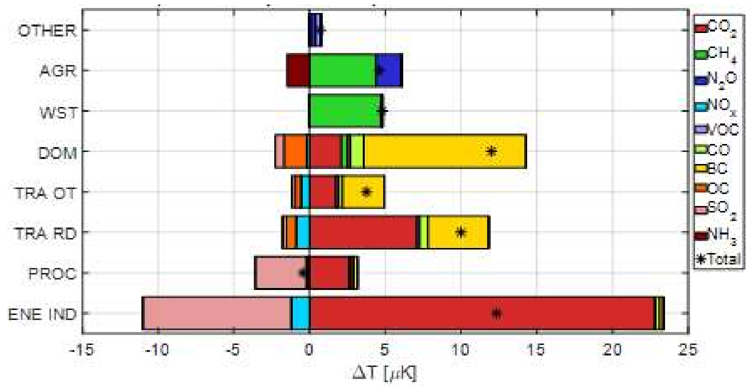
3.2 Publication II

In this Publication, we explored ways to use various metrics for estimating the climate impact of Finnish short-lived climate forcer (SLCF) and greenhouse gas (GHG) emissions. Metrics are a useful way to estimate the climate impact of a small amount of emissions, and thus suitable for comparing mitigation measures in a small country. We calculated an emission projection from 2000 to 2030 for all climate-relevant pollutants from all anthropogenic sources in Finland. The goal was to compare the utility of the available metrics, and to use the most suitable ones to assess the climate impacts of those emissions.

Fig 3.2a shows the warming/cooling impacts of the studied emissions from each sector, as well as the overall impact of the given sector. The shown impact represents the annual temperature response in a 25-year time span after a single emission pulse. Overall, the largest warming impacts were caused by three sectors: domestic combustion, traffic and industrial-scale combustion plants. Temperature response from traffic was estimated to be considerably smaller in 2030 than in 2000. In the case of industrial-scale combustion plants, the amount of SO_2 emissions impacted heavily on the temperature response. Due to reduction of SO_2, total emissions from that sector were estimated to have larger warming impact in 2030 than in 2000. Domestic combustion appeared to remain a key sector in the future. Our analysis across climate metrics, time horizons, pollutants and Finnish emission pathways demonstrated that CO_2 emissions have the largest climate response even in the near-term perspective of 10 to 20 years, and its relative importance is further increased with a longer time span. Hence, mitigation of carbon dioxide is crucial for reducing the climate impact of Finnish emissions. In the near or medium term, i.e. 25-year perspective, especially CH_4 and BC have relatively significant warming impacts additional to those of CO_2. For all of the species, the temperature response of Finnish emissions is generally stronger in the Arctic than globally, but most significantly so in the case of BC and SO_2 (Fig 3.2b). For those two pollutants, a notable difference in temperature response was also found between winter time and summer time emissions. The snow albedo effect of the Finnish BC emissions is found to be significant and thus emissions in winter or early spring have the largest warming impact. This phenomenon should be adequately included in the analyses regarding the climate impacts of BC.

Since the atmospheric lifetime of SLCFs is relatively short, their climate impact is more dependent on the emission region than with GHGs. Our study of the Finnish case demonstrated that climate assessments and further development of the metrics should aim to use the precise geographical location of the source as the emission region, in order to provide more accurate temperature estimates. A key product of this Publication was a set of climate metrics for each relevant pollutant and suitable for Finnish conditions, that can be used to estimate the climate impact of a 25-year emission projection. We evaluated mean(ARTP(1-25yrs)) to be the most useful metric for policy relevant scenario work.

a)



b)

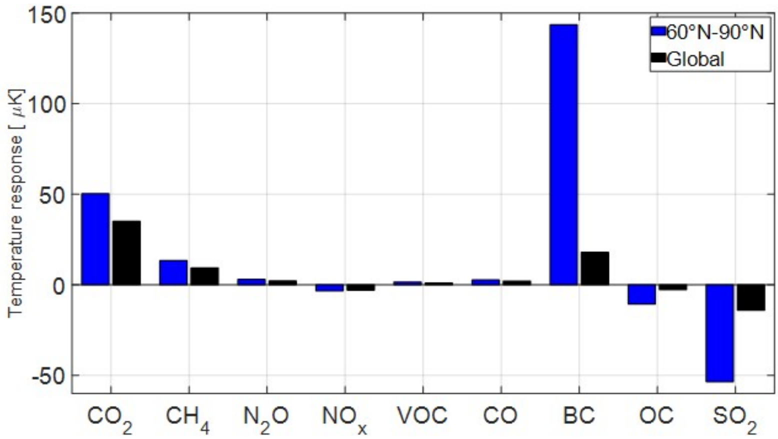


Figure 3.2. Annual temperature responses (μK) in the following 25 years after a pulse of emissions. The size of the pulse is the total Finnish emissions of the given sector and/or pollutant in 2010. The climate metric applied is the mean(ARTP(1-25 yrs))

a) Temperature response by sector and pollutant. Sectors: Energy and industry (ENE IND), industrial processes (PROC), transport road (TRA RD), off-road transport and machinery (TRA OT), domestic (DOM), waste (WST), agriculture (AGR), and other (OTHER). Global and Arctic (60-90° N) temperature responses by pollutant.

b) Global and Arctic temperature responses for total emissions of each pollutant.

3.3 Publication III

In this Publication, methods created in the first two Publications were used to assess the climate impact of RWC emissions in Finland. We calculated a projection for all relevant climate-impacting emissions from RWC up to the year 2040. We included emissions of biogenic CO_2 from RWC and other sources, as well as discussion on how those emissions should be viewed in climate assessments. We then used the metric mean(ARTP(1-25yrs)), created in Publication II, to assess the climate impact of various emissions projections from 2015 to 2040. A comparison was also made between typical Finnish methods to heat detached houses, in order to assess their climate impacts. The main goal of the Publication was to estimate the relevancy of SLCF emissions from RWC in the context of climate change caused by emissions from Finland, and to evaluate whether wood heating can be claimed as climate-friendly. We also studied the climate impact of a set of mitigation measures designed to reduce population exposure to fine particles.

The emissions of most pollutants were estimated to decrease slightly from 2015 to 2040. Using our selected climate metric for 25 years, BC was estimated to be by far the most significant climate-impacting pollutant from RWC. Global temperature response for BC emissions was twice as large as for biogenic CO_2, which had the second biggest warming impact. Arctic temperature response for BC emissions was 10 times larger than for biogenic CO_2. The impact of cooling species was considerably smaller, and did not noticeably compensate for the warming impact. In total, SLCF emissions from RWC added to the warming impact of Finland's projected GHG emissions by 28% in global temperature response and by 170% in Arctic temperature response (Table 3.3). Of the appliance categories, the biggest warming impact was caused by sauna stoves, followed by masonry heaters. In the case of pellet boilers, the impact of SLCFs only was slightly cooling. However, the overall impact that included biogenic CO_2 was clearly warming.

Fig 3.3 shows the estimated temperature response, when the energy needed to heat a house is produced by various methods. The response is divided by pollutants, of which some are warming and some are cooling. The resulting temperature response represents the cumulative effect of annual emissions during a 25-year time span. CO_2 (both fossil and biogenic) and BC were the pollutants that most impacted the temperature. When compared with other common heating methods in Finnish detached houses, using a masonry heater was the least climate-friendly option, i.e, it produced the largest warming impact. Taking biogenic emissions into account further highlighted this finding, and showed pellet boiler to be the second worst option in terms of climate response. Low heating value of wood, as well as low net heating efficiency of wood heaters were the main reasons for comparably high CO_2 emissions, as we used the direct end-of-pipe emission factor.

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. The conclusion of this Publication was that climate policies that include biomass combustion must include both SLFC and biogenic CO_2 emissions in the assessments. Even with large uncertainties in our study, it seems evident that wood heating is likely the least climate-friendly option of the common heating methods in Finland, when all relevant emissions are taken into account.

Table 3.3. 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, CH4 and N2O	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

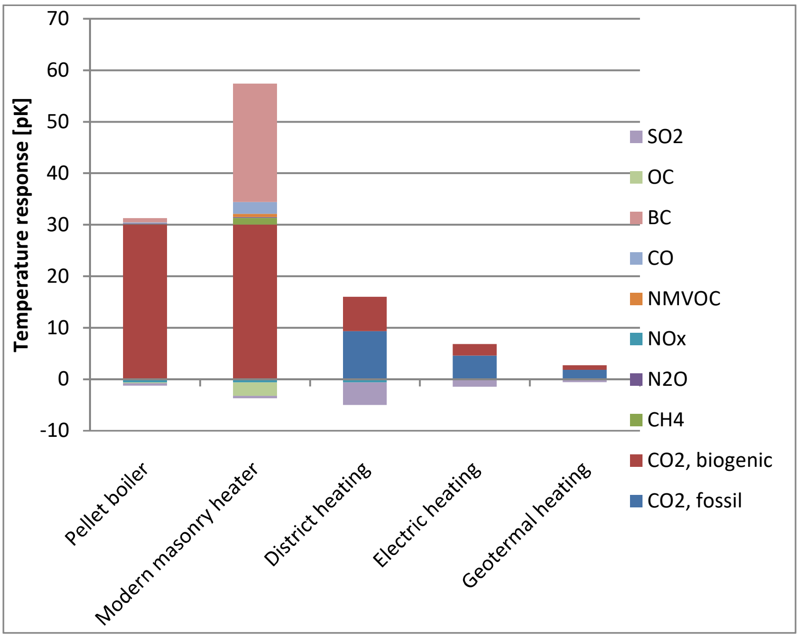


Figure 3.3. Cumulative global temperature response [pK] at the end of a 25 period, due to the emissions produced by heating a detached house, depending on the heating method.

3.4 Publication IV

In this Publication, emission calculation methods created in the first Publication were used to assess a new projection of $PM_{2.5}$ emissions from RWC. A baseline scenario and a set of mitigation measures were calculated up to 2030. In each scenario, emissions were spatially distributed into a 250 m x 250 m grid. The concentrations in ambient air resulting from these emissions were then modelled, using source-receptor matrices based on a Gaussian dispersion model UDM-FMI. In the same grid, these concentrations were compared to population data, to estimate the population exposure to $PM_{2.5}$, and ultimately the effects on health. The goals of the Publication were to assess the extent of harmful health impacts attributable to RWC in Finland, and to point out feasible mitigation measures to be implemented in air quality policies.

Without measures, the annual average concentrations resulting from RWC were between 0.5 and 2 $\mu g/m^3$ in the proximity of most towns. Disease burden attributable to RWC was 3420 DALY and 205 premature deaths in 2015 (Table 3.4). DALY was dominated by mortality. The disease burden due to RWC accounted for 13% of that caused by total $PM_{2.5}$ concentrations in Finland. Most of the harmful heath impacts were caused by supplementary heating in residential houses, i.e. the use of stoves. In the Baseline scenario for 2030, DALY and premature deaths decreased by 8%, whereas the decrease was 66% in the MFR scenario. The most effective measures were urban combustion bans and implementing a legislation that sets emission limits for sauna stoves. Informational campaigns targeted to urban areas were shown to be very efficient in terms or reduced DALY per reduced unit of emissions.

The conclusions of this study were that health hazards due to exposure to $PM_{2.5}$ from RWC are relevant in national scale, and that possibilities for mitigation exist. Two measures were found feasible and were included in the National Air Pollution Control Programme 2030: Implementing informational campaigns to increase the awareness and skill of stove users, as well as figuring out a way to replace most polluting sauna stoves with cleaner models. Another conclusion was that a major share of the health impacts occurs in relatively small municipalities (Fig 3.4), whereas public and authoritative attention has mainly focused on air quality problems in larger towns. Most of the previous informational campaigns in Finland have been arranged by Helsinki Regional Environmental Services Authority HSY, and the focus area has been mainly been Helsinki capital area and some other major towns.

Table 3.4. Estimates for population exposure and disease burden attributable to RWC in the studied scenarios

Scenario	$PM_{2.5}$ [kt/a]	PWC [µg/m³]	DALY	Premature Deaths
2015	10.5	0.70	3420	210
2030 Baseline	9.1	0.64	3140	190
1. Infocampaign				
a Cities	9.0	0.62	3010	180
b All areas	8.5	0.59	2880	170
2. Sauna legislation	7.0	0.49	2370	140
3. ESP installations	5.5	0.44	2150	130
4. Urban combustion bans	4.8	0.24	1150	69

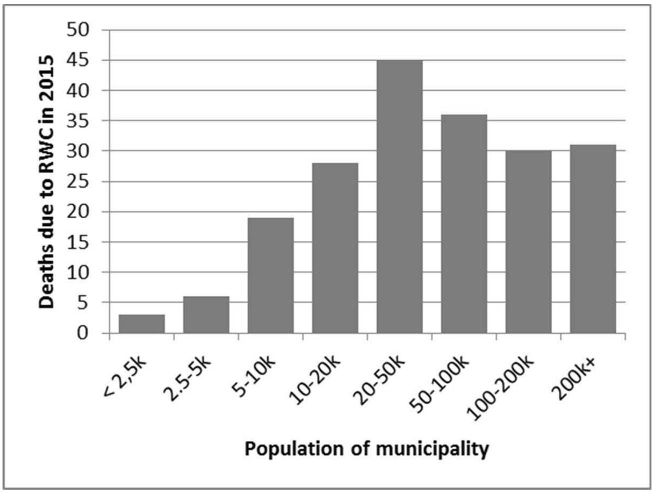


Figure 3.4. Deaths attributable to RWC, classified by population size in a municipality.

4. Conclusion

4.1 Summary and Scientific Contributions

The objective of this thesis was to create a calculation scheme for the accurate estimation of all relevant air emissions from RWC in Finland, and then to quantify the most important environmental impacts they cause. The thesis was motivated by a clear need for scientific results to support policy making that aims to mitigate the harmful impacts of emissions from RWC. In recent years, emissions from RWC and resulting health hazards have received notable scientific and public attention. Fine particle emissions from RWC have attained a key role in many national and intergovernmental air quality strategies and policies. At the same time, increased focus has been put on the climate impact of black carbon emissions, especially in the Arctic area, and RWC has been recognized as one of the important sources of BC emissions. However, estimating the emissions from the widely varying appliance stock of a given country has proved to be challenging. Being able to estimate the current and projected emissions, as well as the environmental impacts they cause, enables the creation of policies that focus on the most relevant mitigation measures.

In Publication I, we presented our method of calculating emissions from RWC in Finland. The method is the first to include a transparent calculation scheme for estimating the impact of user behavior on the emissions from stoves. This is an important policy support tool in itself, as intergovernmental treaties, such as EU's NEC directive (2016/2284), require the reporting and reduction of air pollutant emissions. However, all air quality policies are ultimately designed to reduce environmental impacts, instead of just emissions. In Publication II, we explored the usefulness of various climate metrics in assessing the climate impact of Finnish SLCF and GHG emissions, without having to use laborious climate models. We ended up creating a new metric, especially designed to be used with Finnish emissions in scenario work that supports policy making. In Publications III and IV, we quantified the most significant environmental impacts of emissions from RWC, namely impacts on global warming and human health. In both Publications, projected impacts in the near future were also estimated, and measures for mitigating these impacts were explored.

In this thesis, the calculation scheme for many of the air pollutants from RWC in Finland was presented for the first time, and the environmental impacts of those emissions were quantified. It supports the previous finding that RWC is the major source for both $PM_{2.5}$ and BC emissions in Finland. The thesis produced the following scientifically significant findings: 1) Emissions from RWC appliances in Finland were shown to be rich in BC, when compared to values in international literature, making the sector a larger source of BC emissions than previously estimated, 2) Sauna stoves were identified as an appliance group with high emissions and having potential for reduction, 3) Climate warming emissions from RWC are of notable scale, when compared to national GHG emissions, 4) Wood heating was found to be the least climate-friendly method to heat a house, compared to other common options, 5) $PM_{2.5}$ emissions from Finnish RWC were estimated to cause 200 attributable deaths in 2015 6) Feasible abatement measures exist and should be implemented in air quality policies.

4.2 Limitations of the Approach

There are limitations in each step of the modeling chain used in this thesis that should be acknowledged. All emissions factors in use represent averages that have been attained from a limited set of measurements. In reality, it is impossible to take into account all the factors that affect the formation of emissions, such as the enormous quantity of various combustion appliances, skill level of the users, quality of fuel etc.

The climate impacts of RWC emissions in Publication III were calculated using a single metric, which focuses on a time span of 25 years only. This relatively short time frame highlights the impact of SLCFs over more long-lived GHGs, as discussed in Publication II. No climate metric or time span has emerged as the most scientifically sound and/or applicable in general impact assessments. In addition, regardless of the chosen metric, they all include the inherent uncertainties of climate models that were used to create them. Metrics add yet another layer of uncertainty, as they are based on simplified functions. While not as sophisticated tools as climate models, metrics have their advantages, as they are more accessible and can be conveniently used in scenario work where the amount of emissions is small in global perspective.

Accurate modeling of air pollutant concentrations in ambient air is key in health impact estimates. Our emission dispersion modeling in Publication IV is done on a relatively coarse scale and does not take into account the impact of local topography or infrastructure (e.g. street canyons) on the dispersion of emissions or accumulation of concentrations. However, when compared to most previous assessment on a national level, the resolution is high. Modeling of $PM_{2.5}$ concentrations also deals with primary particles only, and excludes e.g. the poorly understood formation of secondary organic aerosols (SOA). Finally, there is a need for better understanding of the specific heath impacts of $PM_{2.5}$, depending on the chemical composition of the particles, concentration levels and length of exposure.

The estimates for uncertainties, in so far as they have been assessed, are presented in the Publications. Overall, even with the large uncertainties, it seems a robust conclusion that RWC has a notable impact in terms of both global warming and population exposure to air pollution, when compared to other sources of emissions in Finland. The methods presented in this thesis are relatively straightforward and feasible as a tool to support policy making processes on any level nationally.

4.3 Policy Implications of the Results and a View on the Role of Residential Wood Combustion

Since wood combustion has such a prevalent position in Finnish culture and is so commonly used to heat houses, legislation that prohibits it is not currently seen as a practical or politically feasible option. For a sizable part of the population, access to fuelwood is free, making it the cheapest source of energy. In addition, making firewood, going to sauna and the recreational value of fire are associated with benefits on health and quality of life. Having a wood heater is also a matter of energy security in the events of power failure etc. However, even if houses are equipped with wood heaters in the case of emergency, other means can be used for regular heating. Despite a strong body of scientific evidence on the negative climate impacts of wood combustion, it has been viewed as a climate neutral fuel in domestic and international climate policies. This message appears to be well received by the public in Finland and has arguably impacted peoples' choices of heating methods. Thus, increasing awareness of the harmful environmental impacts of RWC could be a starting point to help reduce wood consumption. In addition to reduction of redundant use, local and temporary wood burning prohibitions in certain problem areas could be used as regulatory ways to mitigate harmful impacts. However, ultimately policy measures should lead to a situation where people are provided with easy and affordable access to more environmentally friendly ways to produce heating energy. If wood combustion is the only convenient method in a given situation, up-to-date appliances should be used and attention paid to proper combustion practices.

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