EMISSION SCENARIOS AND AIR QUALITY MODELLING FOR RESIDENTIAL WOOD COMBUSTION

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Scientific Report from DCE – Danish Centre for Environment and Energy No. 426 2021

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Abstract: In this project, the emission impacts for particulate matter (TSP, PM_{10} and $PM_{2.5}$) and black carbon (BC) of three scenarios for residential wood combustion have been estimated and the impacts of the concentrations of BC have been modelled over Denmark and the Arctic using the Danish Eulerian Hemispheric Model (DEHM). Additionally, the modelled concentrations have been compared to the measurement results. The overall greenhouse gas effect of residential wood burning in Denmark has been estimated considering the pollutants where the IPCC Fifth Assessment Report provides global warming potentials (CH_4, N_2O, NO_x, VOC and BC). The basic scenario have been compared to three scenarios which includes banning older wood stoves in areas with district heating, installing particle filters on stoves and boilers not being ecolabelled and requiring older stoves to be scrapped or replaced when a property is sold.

Keywords: Residential wood burning, emissions, air quality modelling, black carbon, air pollution, climate effects

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Preface

This project has been carried out as a supplementary project under the framework contract between Aarhus University and the Ministry of Environment.

The authors would like to thank the following for their assistance in various ways in discussing issues related to residential wood burning:

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- Henrik B. Jensen, Chimney sweeper
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Summary

In this project the emission impacts of three scenarios for residential wood combustion are estimated and the impacts of the concentrations of black carbon BC are modelled over Denmark and the Arctic using the Danish Eulerian Hemispheric Model (DEHM). Additionally, the modelled concentrations are compared to measurement results. The overall climate effect of residential wood burning in Denmark is estimated for pollutants where the IPCC Fifth Assessment Report provides global warming potentials.

Three reduction scenarios for residential wood burning

Three emission scenarios have been defined and the emission consequences for selected pollutants have been compared to a baseline scenario based on the latest official emission projections. The three scenarios are:

1. Ban on stoves that do not meet the requirements according to the Nordic Ecolabel in district heating areas
2. Particle filters on 20 % of the wood stoves and wood boilers that do not meet the requirements according to the Nordic Ecolabel
3. Phasing out of older stoves (2003 and before) in connection with transfer of house ownership

Impacts on particle emissions

The emission consequences for $PM_{2.5}$ (particles less than 2.5 micro meters in diameter) and black carbon were estimated showing that the effect in 2030 for scenario 1, 2 and 3 is a reduction of 382 tonnes, 337 tonnes and to 446 tonnes of $PM_{2.5}$, respectively, compared to the basic scenario emission in 2030. This corresponds to reductions of 8 %, 7 % and 10 %, respectively compared to 2030 emissions based on the latest emission projection (baseline scenario) from 2020 (2018 base year). For BC, the effect are an increase of 8 tonnes for scenario 1, corresponding 2 %, a decrease of 15 tonnes (3 %) for scenario 2 and an increase of 26 tonnes (6 %) for scenario 3. The increased BC emission observed for two of the three scenarios are caused by newer technologies having higher black BC emission factors.

Impacts on particle concentrations in Denmark and in the Arctic

The transport and transformation of Elemental Carbon (EC) and other air pollutants of the emissions scenarios have been determined by using the Danish Eulerian Hemispheric Model (DEHM). While BC is the term used in the emission inventory due to the definitions in the reporting requirements, the term EC is used in air quality measurements and modelling. In many cases, BC and EC is used interchangeably and EC is considered to be a good approximation for BC in most cases. The model runs made in this project are single year model runs, and the Danish emissions for year 2018 is used for the basic background model run with DEHM, which calculates the atmospheric concentrations and depositions of pollutants. The Danish emissions for year 2018 are the latest available. Four model runs have been made for 2030 for the scenarios basic, 1, 2 and 3. The results of the model runs show a decrease of the mean EC from 2018 to 2030 of 11.7 %. The largest decrease of the mean EC concentration in Denmark in 2030 compared to the basic scenario in 2030 is found for scenario 2 (0.16 percentage point), while scenario 1 and 3 results in minor increases compared to the basic scenario (0.08 percentage point and 0.28 percentage point, respectively). Further, the mean concentration and

deposition for the Arctic area has been modelled showing only minor changes for the three scenarios.

Comparison of model results and measurements in Denmark

The concentrations of EC modelled with DEHM has been compared to air quality measurements at three different sites; one rural, one suburban and one urban background site in Denmark. The comparison generally shows a good agreement between observed and modelled concentrations, with the best result for the rural measurement site. This is expected since the DEHM model will perform better for a rural area, where emissions from a larger area contributes to the concentrations, compared to the two other sites, where more local sources contribute significantly, e.g. residential wood burning and road transport. The model overestimates the concentration by about 11 % at the rural measurement site and captures the same trend as can be observed in the measurement.

Climate effects of residential wood burning in Denmark

Based on global warming potentials, the total climate effect of residential wood burning in Denmark has been estimated in CO_2 equivalents. In international reporting of national emission inventories, CO_2 emissions and removals due to the harvesting, combustion and growth of biomass are included in the carbon stock changes of the relevant land use category of the Land Use – Land Use Change and Forestry (LULUCF) sector for the country where the biomass originates. Therefore, CO_2 emissions from biomass burning is not included the Energy sector. However, that does not mean that CO_2 is not emitted when combusting wood in residential plants. For the purposes of this report, we have also included information on the CO_2 emissions associated with residential wood combustion to provide a more complete view of the overall climate impact. In fact, the scenario calculations show that by far the largest contribution to the total greenhouse gas emission from residential wood combustion expressed in CO_2 equivalents is from CO_2, which constitutes approximately 66 % of the total greenhouse gas emissions expressed in CO_2 equivalents. This emphasizes the importance of sustainable forestry. By using sustainably grown wood, CO_2 emissions are compensated by CO_2 uptake and thereby do not contribute to raising the CO_2 content in the atmosphere. The second most important pollutant contribution to the total greenhouse gas effect in the scenarios is black carbon (approximately 32 %) whereas the remaining pollutants considered (methane (CH_4), nitrous oxide (N_2O), non-methane volatile organic carbons (NMVOCs) and nitrogen oxides (NO_x)) contributes very little to the total greenhouse gas effect in the scenarios (2 %). There is very little difference between the baseline scenario and the three scenarios. In fact, the difference is at most 2 percentage point.

Sammenfatning

I dette projekt er der beregnet emissionskonsekvenser af tre scenarier for træfyring i husholdninger, og konsekvenserne for koncentrationen af black carbon (BC) er modelleret over Danmark og over Arktis ved brug af den Danske Euleriske Hemisfæriske Model (DEHM). De modellerede koncentrationer er sammenlignet med måleresultater. Den samlede klimaeffekt fra træfyring i husholdninger er opgjort i CO_2-ækvivalenter for de forureningskomponenter, hvor der er angivet et opvarmningspotentiale (GWP) i IPCCs femte hovedrapport.

Tre reduktionsscenarier for træfyring i husholdninger

Tre emissionsscenarier fokuseret på forskellige mulige tiltag og emissionskonsekvenserne for udvalgte forureningskomponenter er beregnet og sammenlignet med et basisscenarie baseret på den seneste officielle emissionsfremskrivning udarbejdet i 2020 (basisår 2018). De tre scenarier er:

1. Forbud mod brændeovne, der ikke lever op til Svanemærkets krav i fjernvarmeområder.
2. Partikelfiltre på 20 % af brændeovne og brændekedler, der ikke lever op til Svanemærkets krav.
3. Udfasning af gamle brændeovne (2003 og før) i forbindelse med ejerskifte af boliger.

Betydning for partikelemissionerne

Emissionskonsekvenserne for $PM_{2.5}$ (partikler med en aerodynamisk diameter mindre en 2,5 mikrometer) og BC er beregnet for 2030, og viser en reduktion i emissionen af fine partikler for scenarie 1, 2 og 3 på henholdsvis 382 tons, 337 tons og 446 tons. Dette svarer til yderligere reduktioner i forhold til den seneste fremskrivning i 2030 på henholdsvis 8 %, 7 % og 10 %. For BC er emissionskonsekvensen en stigning på 8 tons i scenarie 1 svarende til 2 %, et fald på 15 ton i scenarie 2 svarende til 3 % og en stigning på 26 tons i scenarie 3 svarende til 6 %. Den stigende BC emission, der kan observeres for to af scenarierne, skyldes, at nyere teknologier ikke har lavere emissionsfaktorer for BC i forhold til ældre teknologier.

Betydning for partikelkoncentrationen i Danmark og i Arktis

Transport og reaktioner i atmosfæren af elementært kulstof (EC) og andre forureningskomponenter i emissionsscenarierne er beregnet ved brug af DEHM. Mens BC er det udtryk, der anvendes i emissionsopgørelserne på grund af definitioner i retningslinjerne for rapportering, så anvendes EC i luftkvalitetsmålinger og modellering. I mange tilfælde bruges BC og EC i flæng og EC er i langt de flest tilfælde en god tilnærmelse til BC. De modelkørsler der er foretaget i dette projekt, er enkeltårskørsler og de danske emissioner for året 2018 er brugt i den grundlæggende basismodelkørsel, som beregner atmosfæriske koncentrationer og depositioner af forurenings-komponenter. De danske emissioner for 2018 er de senest tilgængelige. Fire yderligere modelkørsler er foretaget for 2030 for basisscenariet samt scenarie 1, 2 og 3 for træfyring i husholdninger. Resultaterne af model-kørslerne viser et fald i EC-gennemsnitskoncentrationen fra 2018 frem til 2030 på 11,7 %. Det største fald i EC-gennemsnitskoncentrationen i Danmark, i forhold til basisscenariet, ses for scenario 2 (0,16 %-point), mens scenarie 1 og 3 giver en lille stigning, sammenlignet med basisscenariet (henholdsvis 0,08 %-point og

0,28 %-point). Modelkørslerne for transport til Arktis viser, at betydningen for koncentrationer og deposition i Arktis er meget lille for alle de modellerede scenarier.

Sammenligning mellem modelresultater og målinger i Danmark

Koncentrationerne af EC modelleret med DEHM er blevet sammenlignet med måleresultater fra tre forskellige målestationer; en baggrundsmålestation, en forstadsmålestation og en vejmålestation. Sammenligningen viser generelt en god overensstemmelse mellem observerede og modellerede koncentrationer, med den bedste overensstemmelse for baggrundsmålestationen. Dette er som forventet, da DEHM vil være mest nøjagtig for landlige områder, hvor koncentrationen er baseret på et stort område uden store lokale kilder, i modsætning til mere bynære områder, hvor der er store lokale kilder, som f.eks. træfyring i husholdninger og vejtransport. Modellen overestimerer koncentrationen med ca. 11 % ved baggrundsmålestationen, men udviser den samme trend, som der kan ses i måleresultaterne.

Drivhusgaseffekt af træfyring i husholdninger i Danmark

Den samlede klimaeffekt er opgjort i CO_2-ækvivalenter for træfyring i husholdninger baseret på globale opvarmningspotentialer. I forbindelse med internationale rapporteringer af emissionsopgørelser, så inkluderes CO_2-emissioner (og optag) i forbindelse med hugst, forbrænding og vækst af træ under ændringer i kulstoflager i den relevante arealanvendelsesklasse under LULUCF (Land Use – Land Use Change and Forestry) sektoren. CO_2-emissionen tilskrives i det land, hvor træet er fældet og ikke nødvendigvis der, hvor det forbrændes. Derfor inkluderes CO_2-emissioner fra forbrænding af biomasse ikke under Energisektoren i den nationale emissionsopgørelse. Dette betyder dog ikke, at der ikke udledes CO_2, når træ brændes i husholdninger. I forbindelse med denne rapport er det valgt at inkludere oplysninger om CO_2-emissionen fra forbrænding af træ i husholdninger for at give et mere dækkende billede af den samlede drivhusgasemissionseffekt. Faktisk viser de foretagne beregninger, at langt det største bidrag til den samlede drivhusgasudledning udtrykt i CO_2-ækvivalenter kommer fra CO_2, som udgør ca. 66 % af den samlede udledning i CO_2-ækvivalenter. Dette understreger vigtigheden af bæredygtig skovdrift. Ved at anvende bæredygtigt dyrket træ, sikrer man sig at CO_2-emissionen kompenseres af CO_2-optag og derved ikke bidrager til at hæve CO_2-indholdet i atmosfæren. Den næst vigtigste forureningskomponent er black carbon, som udgør ca. 32 %, hvorimod de resterende forureningskomponenter (metan (CH_4), lattergas (N_2O), andre flygtige organiske forbindelser end metan (NMVOC) og nitrogenoxider (NO_x) bidrager meget beskedent til den samlede emission udtrykt i CO_2-ækvivalenter. Effekten af de forskellige scenarier sammenlignet med basisscenariet er meget begrænset, og den største forskel er omkring 2 %.

1 Introduction

DCE (Danish Centre for Environment and Energy), Aarhus University is contracted by the Ministry of the Environment and the Ministry of Energy, Utilities and Climate to prepare emission inventories for Denmark. Department of Environmental Science, Aarhus University is responsible for calculation and reporting of the Danish national emission inventory to the EU (Monitoring Mechanism Regulation & Directive on reduction of national emissions of certain atmospheric pollutants) and the UNFCCC (United Nations Framework Convention on Climate Change) and UNECE CLRTAP (Convention on Long Range Transboundary Air Pollution) conventions.

The Danish national emission inventories covers all pollutants where there is a reporting requirement under the above mentioned international conventions or under EU obligations. These pollutants are both direct greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and air pollutants such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOC), ammonia (NH_3), carbon monoxide (CO), particulate matter (PM) and black carbon (BC). Some of the air pollutants also has a climate effect as indirect greenhouse gases or precursors. The latest emission inventories are published in Nielsen et al. (2020a & 2020b).

Residential wood combustion is an important source of air pollution in Denmark and therefore attracts great attention. In 2018 residential wood combustion contributed with 50 % of the national total $PM_{2.5}$ emission and 22 % of the national total BC emission.

In recent time, specific focus has been on emissions of BC. BC is part of the emission of particulate matter and in addition causing health effects; there is also a direct influence on global warming both related to radiative forcing but also affecting the albedo on ice-covered surfaces.

While BC is the term used in the emission inventory due to the definitions in the reporting requirements, the term elemental carbon (EC) is used in air quality measurements and modelling. In many cases, BC and EC is used interchangeably and EC is considered to be a good approximation for BC in most cases. The technical guidance for national emission inventories (EEA, 2016) generally uses a mix of EC and BC measurements as basis for the emission inventories and hence the inventory is in many cases based on emission factors expressed as EC. Therefore, it is considered appropriate to compare the BC inventory developed with measured and modelled concentrations of EC. In this report, the chapters referring to the emission inventories use the term BC, while the chapter on modelling uses EC. EC is measured by chemical analysis whereas BC is measured with light absorption.

The climate impact of residential wood burning is in many respects not considered, as the CO_2 emission is biogenic and therefore not considered in national reporting of greenhouse gas inventories where carbon stock changes in woody biomass is considered as a separate sector and therefore not part of the estimation of emissions from energy production.

In this project, the effect on emissions of three different scenarios was calculated. In addition, air quality modelling was done to model the transport of BC to the Arctic. Finally, for both the baseline scenario and the three scenarios developed in this project, the emission as expressed in CO_2 equivalents was calculated to give an indication of the emission impact.

2 Emission scenarios for residential wood combustion

Residential wood combustion (RWC) is an important source of air pollution in Denmark and therefore attracts great attention. There is however, large uncertainties associated with the emission inventory, as there are many parameters in the emission calculation, all of which have varying levels of uncertainty. This relates to the number of appliances per technology, the age distribution, the wood consumption and the emission factors. To create a time series, it is also necessary to have assumptions on the expected lifetime and replacement rates of stoves and boilers.

2.1 Methodology for residential wood combustion

The RWC model included in the Danish emission inventory system is used as basis for the scenario calculations. The RWC model covers both historical years and projection years. The scenarios focus on the effect in the projection year 2030.

As mentioned, the Danish RWC model is based on a number of parameters, including the number of appliances per technology, the age distribution, the wood consumption, the emission factors, and expected lifetime and replacement rates of stoves and boilers. The RWC model went through a comprehensive update, which were finalised and applied in the 2020 submission to the EU and the UN. The parameters in the updated RWC model are described in the following chapters. A detailed description of the model update is available in Nielsen et al. (2021a).

2.1.1 Technologies

The wood burning appliances are categorised in the model according to appliance type and age. The categories further distinguish between appliances that are ecolabelled or have similar emission factors.

Table 2.1 Type of wood burning appliances considered.

Appliance type	Further information
Stove (-1989)	
Stove (1990-2007)	Stove with Danish Standard mark
Stove (2008-2014)	Stove conforming with Danish legislation (2008)
Stove (2015-2016)	Stove conforming with Danish legislation (2015)
Stove (2017-)	Stove conforming with Danish legislation (2017)
Ecolabelled stove/new advanced stove (-2014)	
Ecolabelled stove/new advanced stove (2015-2016)	
Ecolabelled stove/new advanced stove (2017-)	
Open fireplaces and similar	
Masonry stoves and similar	
Boilers with accumulation tank (-1979)	
Boilers without accumulation tank (-1979)	
Boilers with accumulation tank (1980-)	
Boilers without accumulation tank (1980-)	
Pellet boilers/stoves	

2.1.2 Wood burning appliances

The number of wood burning appliances have been updated as part of the comprehensive review of the RWC model. A data set from the Danish chimney sweeper association from 2017 is the most accurate and up to date data set for small wood burning appliances. This data set cover the major part of Denmark. Data from the Danish building and dwelling register (BBR) from 2017 is used for the areas not covered by the chimney sweeper data.

Building and dwelling register data (BBR)

The BBR data include information of primary heating source, heating fuel, and supplementary heating source. Wood stoves and wood boilers are identified in the BBR based on the combination of the three heating categories. It is only possible to register one value for each category for each address in the BBR, which causes an underestimation of appliances in case more appliances occur at a single address. The fact that the house owners are responsible for updating the heating information the BBR increases the uncertainty of the data set, as this is often neglected by the house owners. Case studies have shown large differences between the occurrence of wood stoves and the registration in the BBR.

Heating appliances categorised as stoves or boilers, used as primary or supplementary heating, and using wood as fuel are included in the analysis. The appliances in BBR are categorised based on primary heating, fuel and supplementary heating. A description of the methodology is included in Nielsen & Plejdrup (2018).

Generally, the number of wood stoves are known to be underestimated in the BBR register. A comparison of data from the BBR and the SFL for 2017 showed that the number of stoves was underestimated by around 37 % in the BBR. As the BBR data are used for only smaller areas, this large uncertainty does not affect the resulting total appliance number much.

Chimney sweeper data (SFL)

The chimney sweeper association has provided data for 2017 including number and location of small wood burning appliances. The data set has been processed and analysed by DCE, as described in Nielsen & Plejdrup (2018). The SFL data are considered the most accurate data set available even though the coverage is not complete. SLF data are missing for a few areas (~10 % of the land area), and to complete the coverage, data from the Danish building and dwelling register (BBR), the BBR2017 data set, have been supplemented for these areas. The supplement data make up around 5 % of the total number of appliances (Table 2.2). The data set made up of the SFL2017 data and the supplement data from the BBR2017 is in the following referred to as SFL2017sup.

Table 2.2 Number of appliances identified in the SFL2017 data set.

Data set	Stoves	Other appliances	Boilers
SFL2017	635 141	46 283	62 457
Supplement from BBR2017	34 205	2 020	5 614
SFL2017sup	669 346	48 303	68 071

2.1.3 Time series

The RWC model cover the years from 1990 and onwards, and therefore it is necessary to prepare time-series for the number of appliances by technology.

The time-series are based on annual sales, assumptions of expected lifetime and replacement rates, and average unit consumptions.

Annual sales

The annual sales figures are not publically available, but a time-series has been constructed based on information from the industry (Kristensen, 2019) together with DCE assumptions (Table 2.3).

Table 2.3 Annual sales of wood stoves.

Year	-1996	1997-2000	2001-2005	2006-2010	2011-2018
Annual sale	20000	25000	31000	22400	20500

The specific number varies between the years, but for the purpose of the model, approximate averages have been calculated and used in the model.

For the other technologies there is no information on the annual sales. For boilers there is a fixed assumption on a replacement rate of 3.3 % per annum, corresponding to a lifetime of 30 years.

Replacement rates

Since detailed data are not available on annual scrapping of old stoves, construction of new stoves and replacement of existing stoves, the population of stoves has been modelled using a replacement curve (Figure 2.1). The curve has been constructed with input from the industry, chimney sweepers, the Danish EPA and the Ministry of Environment.

The constructed curve assumes that the first stove is replaced / scrapped 15 years after being sold with the last stove being replaced / scrapped 50 years after being sold. The majority of stoves are being replaced / scrapped between the ages of 20 and 40.

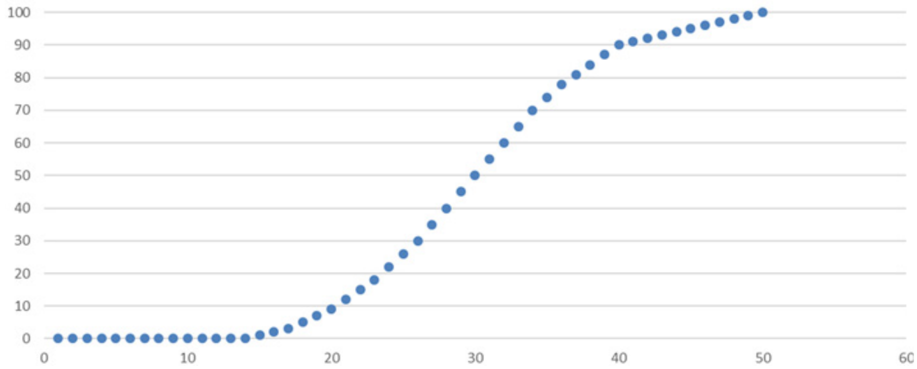

Figure 2.1 Replacement curve for wood burning stoves.

For other technologies, there is either no age dependent technology split (wood pellet appliances, fireplaces and similar, and masonry stoves and similar) or there is assumed a fixed rate replacement (wood boilers).

The resulting time-series for the numbers of stoves and boilers are shown in Figure 2.2 and Figure 2.3.

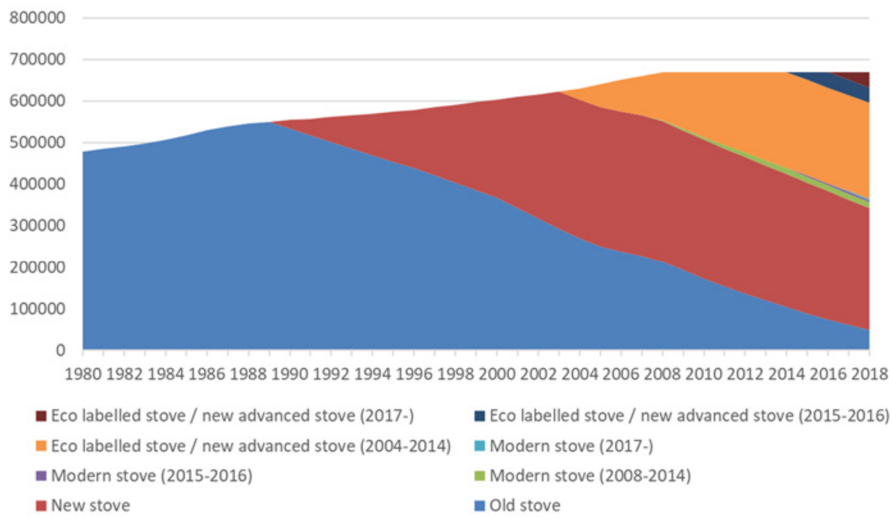

Figure 2.2 Time-series for stoves (excluding Other appliances (fireplaces, masonry etc.)).

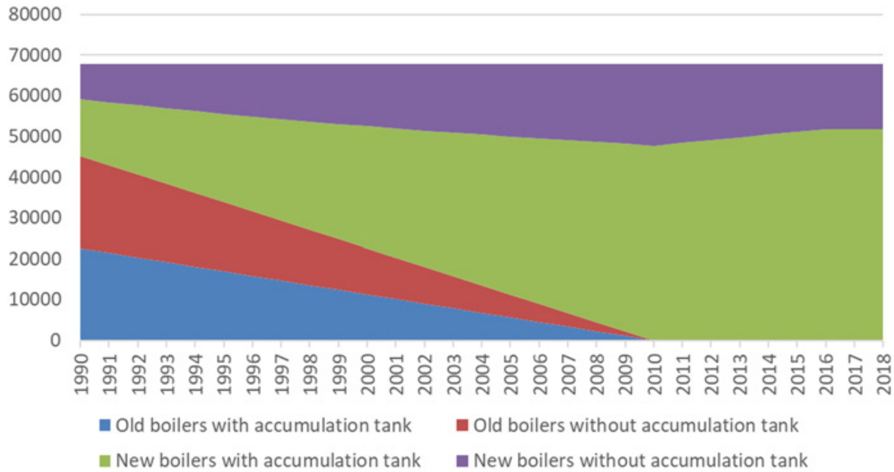

Figure 2.3 Time-series for boilers.

Unit consumption

For the different appliances, a unit consumption is used to estimate the total wood consumption for one year. The unit consumption for all regular stoves are considered equal and the same is the case for the boilers. The data for unit consumption is referenced to Ea Energianalyse (2016) and the values are shown in Table 2.4. The unit consumptions are weighted between permanent residences and summerhouses. The study conducted by Ea Energianalyse (2016) did not show a significant difference in unit consumption based on the age of the appliance.

Table 2.4 Unit consumption of firewood depending on appliance type.

Appliance type	GJ/appliance/year
Stoves	23.4
Open fireplaces and similar	11.8
Masonry stoves and similar	42.1
Boilers	121.2

When calculating the wood consumption based on the number of appliances and the unit consumption, the total does not match the registered consumption in the Danish energy statistics (DEA, 2019). Since the inventory should be based on the official energy statistics, the wood consumption calculated bottom-up is scaled with the official wood consumption in the energy statistics. The scaling is done across all technologies of appliances using firewood, i.e. all technologies except wood pellet stoves/boilers. This assumption is made since no other information is available. The scaling factors are shown in Table 2.5.

Table 2.5 Scaling factors for wood consumption to match the energy statistics.

Year	1990	2000	2005	2010	2015	2018
Scaling factor	2.5	1.8	1.2	1.0	1.0	1.0

The correlation between the bottom-up estimated wood consumption and the statistics are much better in the last part of the time series compared to the first part. This is partly connected to the fact that in later years the biennial surveys have been utilised both in the energy statistics and in the emission inventory. The poor correlation in the beginning of the time series can possibly be attributed to a change in the energy statistics. The first survey on residential wood combustion was carried out for the year 2005 and showed a markedly higher wood consumption than previously considered in the statistics. A revision was made for 2000 to 2005 but not further back in time. As a result, the consumption of firewood shows a very large increase over these years as illustrated in Figure 2.4.

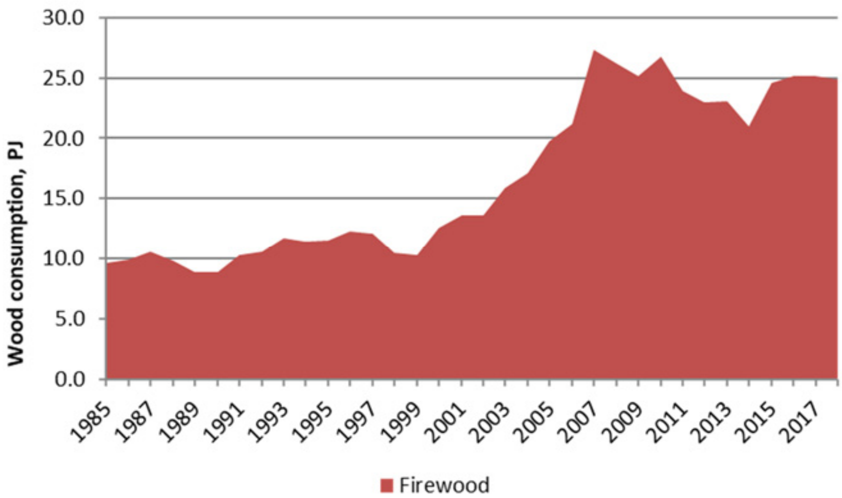

Figure 2.4 Firewood consumption in the energy statistics (DEA, 2019).

2.1.4 Emission factors

Emission factors in the RWC model are based on measurements when available or refer to the international guidelines for emission inventories provided in the EMEP/EEA Guidebook (2016). The emission factors were updated in the comprehensive review of the RWC model and results from several Danish measurement programs have been included and supplemented with the outcome from a large literature study (Nielsen et al. 2021a). The emission factors for TSP, PM_{10}, $PM_{2.5}$ and BC are shown in Table 2.6. Further details and results from the review and update of the emission factors, including emission factors for other pollutants included in the national emission inventory, are provided in Nielsen et al. (2020a).

Table 2.6 Emission factors for TSP, PM_{10}, $PM_{2.5}$ and BC.

Technology	TSP, g/GJ	PM_{10}, g/GJ	$PM_{2.5}$, g/GJ	BC, g/GJ
Stoves (-1989)	1000	950	930	18
Stoves (1990-2007)	500	475	465	17
Stoves (2008-2014)	389	370	362	23
Stoves (2015-2016)	317	301	295	44
Stoves (2017-)	253	240	235	44
Ecolabelled stoves/new advanced stoves (-2014)	253	240	235	31
Ecolabelled stoves/new advanced stoves (2015-2016)	190	181	177	31
Ecolabelled stoves/new advanced stoves (2017-)	127	121	118	31
Open fireplaces and similar	882	838	820	34
Masonry heat accumulating stoves and similar	63	60	59	18
Boilers with accumulation tank (-1979)	588	559	547	24
Boilers without accumulation tank (-1979)	736	699	684	24
Boilers with accumulation tank (1980-)	64	61	60	6
Boilers without accumulation tank (1980-)	335	318	312	6
Pellet boilers/pellet stoves	51	48	47	7

Comparison of BC emission factors between technology groups applied in the Danish emission inventory might not be accurate as the emission factors refer to different references and different measurements. The emission measurement programs do include all technology groups and the relation between BC emission and $PM_{2.5}$ emission is not simple. BC emission is also dependent on other factors than the PM emission and the sensitivity to wood species, temperature and misuse conditions are different for PM and BC. Therefore the $PM_{2.5}$/BC ratio might be different for the individual technologies.

Emission factors for residential wood combustion show great variability depending on numerous parameters. Studies have shown that the emission from a specific appliance varies with the load of the appliance, the quality of the wood (e.g. moisture content and wood species), the firing technique and the measurement methods. This report will not go into detail describing the impact of the uncertainty associated with these parameters, but as an example, Table 2.7 indicates the intervals of emission factors, which are assessed in relation to the update of the residential wood combustion model (Nielsen et al. 2021a).

Table 2.7 Span on emission factors included in the review for the update.

Technology	TSP EF g/GJ		BC EF g/GJ		PM2.5 EF g/GJ	
	min	max	min	max	min	max
Stoves (-1989)	557	5 253	18	19	434	557
Stoves (1990-2007)	119	1 195	10	118	96	330
Stoves (2008-2014)	84	634	10	76	39	423
Stoves (2015-2016)		317		no data		no data
Stoves (2017-)		253		44		188
Eco labelled stoves / new advanced stoves	103	271	19	41	103	271
Open fireplaces and similar	105	977	22	171	18	820
Masonry heat accumulating stoves and similar	63	76	7	110	59	285
Boilers with/without accumulation tank	539	1 410	23	31	318	1 162
Boilers with accumulation tank (1980-)	13	96	0.1	8	16	227
Boilers without accumulation tank (1980-)	48	1 162	6	31	61	1 162
Pellet boilers/pellet stoves	3	416	0.1	10	3	416

2.1.5 Emissions

The largest $PM_{2.5}$ emission source in Denmark in 2018 is residential plants, which contributes 58 % to the national total $PM_{2.5}$ emission in 2018 (Figure 2.5). The national total $PM_{2.5}$ emission decreased by 34 % from 1990 to 2018 as the increasing wood consumption in the residential sector has been counterbalanced by decreasing emissions for the remaining sectors, the most important being the transport sector.

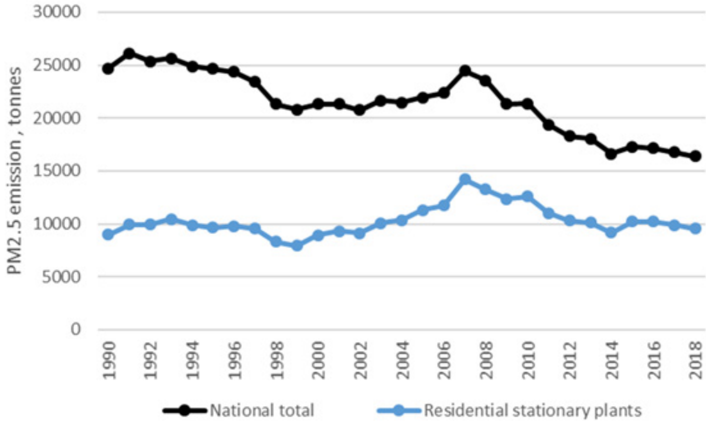

Figure 2.5 National total $PM_{2.5}$ emissions and $PM_{2.5}$ emissions from residential plants in the years 1990-2018.

Emissions from residential plants increased by 58 % from 1990 to 2007, followed by a decrease of 33 % from 2007 to 2018 (Figure 2.6). The increase was caused by increasing wood consumption while the decrease has been caused by a slightly lower wood consumption combined with legislative demands on new wood stoves and boilers since 2008. Changes of stoves and boilers to newer and improved technologies contribute to reduction of the emissions for the entire time series. As the older technologies are phased out, the wood consumption are moved to newer technologies with lower $PM_{2.5}$ emission factors. In 1990, the emissions mainly came from old stoves (pre-1990), while the emissions in 2018 mainly came from the technology stoves (1990-2007).

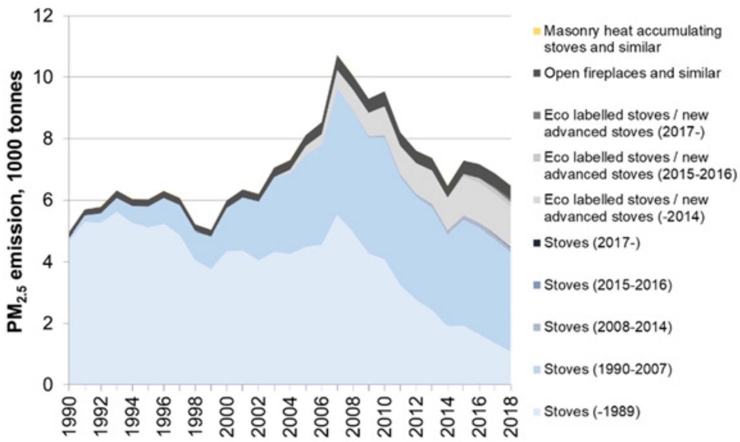

Figure 2.6 $PM_{2.5}$ emissions from wood fired residential plants in the years 1990-2018.

The main source to the national total black carbon (BC) emission is residential plants contributing 36 % in 2018 (Figure 2.7). From 1990 to 2018, the total BC emission decreased by 63 %. Decreasing emissions are seen for most sectors, mainly for transport. BC emissions from residential plants increase by 16 % from 1990 to 2018.

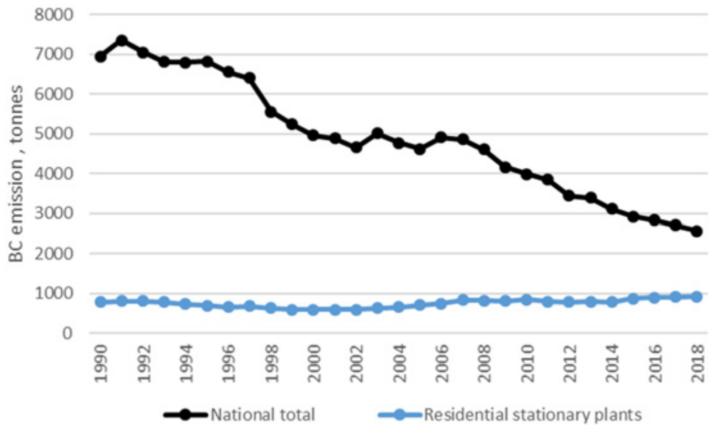

Figure 2.7 National total BC emissions and BC emissions from residential plants in the years 1990-2018.

The trend for BC emissions from wood fired residential plants is controlled by the trend for the wood combustion and by the technology composition of the wood fired appliances (Figure 2.8). Where the PM emission factors are lower for the newer technologies, the BC emission factors does not follow the same pattern. As BC emission factors are relatively higher for newer technologies, the emission pattern are more dominated by newer technologies than old stoves.

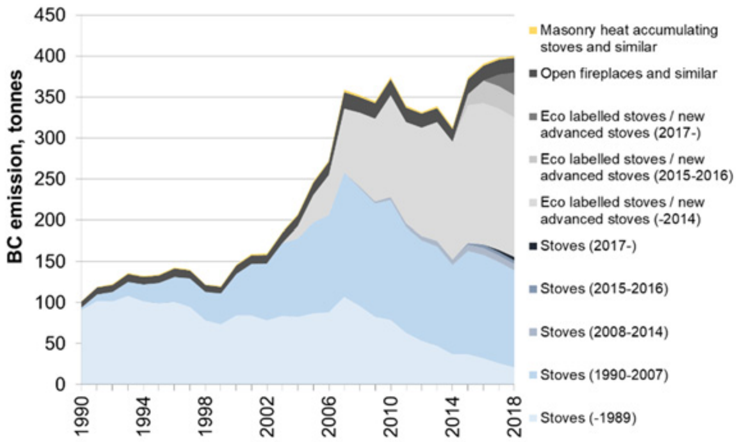

Figure 2.8 BC emissions from wood fired residential plants in the years 1990-2018.

2.2 Scenarios

Three scenarios have been set up in cooperation with the Danish Environmental Protection Agency to evaluate the effect of measures focusing on reducing emissions from residential wood combustion. The three scenarios are:

1. Ban on stoves that do not meet the requirements according to the Nordic Ecolabel in district heating areas
2. Particle filters on 20 % of the wood stoves and wood boilers that do not meet the requirements according to the Nordic Ecolabel
3. Phasing out of older stoves (2003 and before) in connection with transfer of house ownership.

In December 2020, the Danish Parliament passed a new law corresponding to scenario 3. The law is planned to enter into force 1 April 2021. It requires additional legislation to make the measures evaluated in scenario 1 and 2 enter into force.

The impact on the emissions in 2030 will be estimated for each of the three scenarios and compared to the latest emission projection as the basic scenario (Nielsen et al. 2021b).

2.2.1 Scenario 1 – Ban on non-Ecolabel stoves in district heating areas

Scenario 1 describes the impact of introducing a ban on wood stoves that do not meet the requirements according to the Nordic Ecolabel (the Swan label) in district heating areas. Scenario 1 takes as its starting point that the measure is introduced and fully implemented in 2030. If the measure was introduced earlier and implemented over years, the outcome would be slightly different, as some of the stoves without the Nordic Ecolabel would have been replaced by newer technologies before 2030 as part of the general replacement rate. This might lessen the effect of scenario 1, as a slightly smaller number of stoves would be affected by the ban. Stoves that would have been replaced in the years 2018-2029 to new stoves without the Nordic Ecolabel would still need to be replaced in scenario 1, which decrease the influence of assuming the full introduction of the ban in 2030.

Introducing a ban on selected stoves causes house owners either to replace the stove with a new stove, which fulfil the Nordic Ecolabel requirements or to completely close down the fireplace. When replacing wood stoves, it is assumed that 90 % will be replaced with a new time-corresponding wood stove while 10 % are expected to completely close down their fireplace. This is an estimate with great uncertainty, and is based on data from MST and the Chimney Sweepers' Association and experiences with a scrapping scheme in 2015-16 (Milfeldt, 2020). Scenario 1 build on the assumption that 90 % replace the stove and the remaining 10 % close the fireplace.

It is assumed that all stoves being replaced in scenario 1 are replaced by stoves of the newest technology with the Nordic Ecolabel, corresponding to the technology category “Ecolabelled stove / new advanced stove (2017-)” in the RWC model.

Methodology

The data from the chimney sweeper association for 2017 are the base for scenario 1, together with a map of the supply areas from PlanDanmark, including district heating areas (Figure 2.9). The data sets are analysed in a geographical information system (GIS), to identify stoves located in district heating areas. In 2017 there were 224 350 stoves located in district heating areas, corresponding to 34 % of the total number of stoves in Denmark.

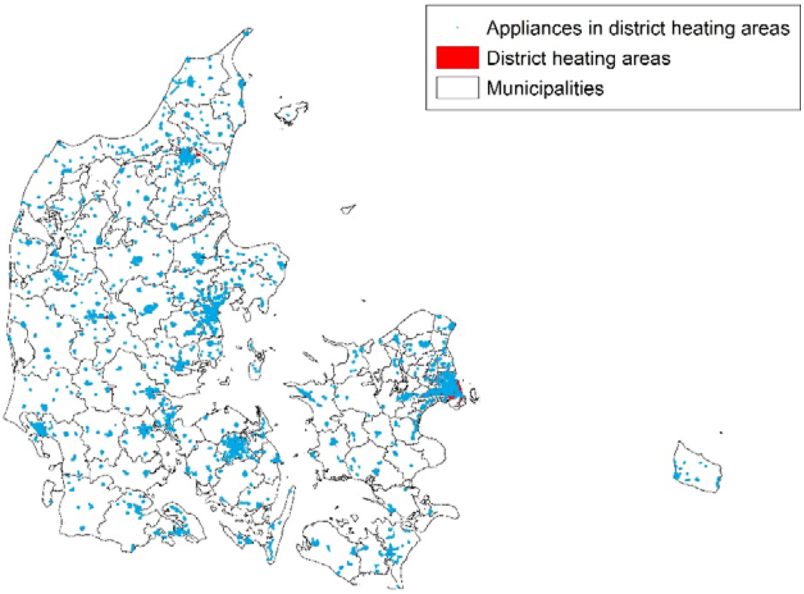

Figure 2.9 Small wood fired appliances (blue dots) in district heating areas (read areas).

The chimney sweeper data include information about the type of appliance, but no information about the age or technology. Therefore, it is necessary to assume that the distribution by technology categories are evenly distributed nationwide.

The number of stoves in district heating areas in 2017 are scaled to 2030, based on data from the latest projection prepared by DCE (Nielsen et al., 2021b). It is assumed that the share of stoves located in district heating areas is constant over the time period, as no other information is available. Further, it is assumed that the share of stoves without the Nordic Ecolabel is evenly distributed nationwide. The analysis result in 224 477 stoves in district heating areas in 2030, hereof 59 793 stoves without the Nordic Ecolabel. This give rise to replacement of 53 814 stoves and closure of 5979 fireplaces.

The RWC model includes a bottom-up calculation of fuel consumption based on number of appliances and unit consumptions by technology category. The estimated total fuel consumption is subsequently scaled to the total wood consumption as given in the official energy statistics by the Danish Energy Agency (DEA). The number of appliances are reduced through the measure reflected in scenario 1, and following the estimated total wood consumption based on unit consumptions and appliance numbers is reduced compared to the base scenario. This is taken into account by reducing the wood consumption from the DEA energy statistics similarly percentage-wise. The reduced number of appliances in scenario 1 cause a decrease of the wood consumption by 0.4 %, and the DEA wood consumption is following reduced from 22.03 PJ to 21.94 PJ.

Emission calculations are based on the projected number of appliances adjusted by the effect of the measure for district heating areas, and the unit consumption and emission factors included in the RWC model, and the reduced DEA wood consumption.

Spatial distribution

The measures in scenario 1 focus only on district heating areas, which entail a change to the spatial distribution of emissions from wood stoves. The Danish model for spatial distribution of the national emission inventory (the SPREAD model) makes use of spatial distribution keys (GeoKeys) on sectoral level (Plejdrup et al., 2018). Emissions from wood stoves are distributed using the GeoKey "_Key_0202_Solid". Output from the SPREAD model is used as input to air quality models. For projection years SPREAD uses the GeoKeys from the latest historical year. However, an updated GeoKey is prepared for scenario 1 and included in the SPREAD model to prepare data for air quality modelling for scenario 1.

Results

A ban on wood stoves without the Nordic EcoLabel in district heating areas will cause the closure of 5979 fire places and replacement of 53 814 stoves to new stoves with the Nordic EcoLabel.

The year of implementing the measure influences the effect of the measure. As an example, calculations of the effect of implementing the measure in scenario 1 in 2022 instead of in 2030 has been made. If the measure was introduced and fully implemented in 2022, it would cause the closure of 9860 fire places and replacement of 88 743 stoves.

Introducing and implementing the measure in 2030 will entail a reduction of the number of stoves in district heating areas from 224 477 stoves to 218 498 stoves, corresponding 2.7 % (Table 2.8). The unit consumption is assumed equal for all stove types except for the two categories "Open fireplaces and similar" and "Masonry stoves and similar", which make up approximately 4 % of the wood consumption for stoves. The estimated wood consumption for wood stoves in district heating areas is reduced by 2.7 % from 5.26 PJ to 5.12 PJ.

The total number of wood stoves in Denmark in 2030 is reduced from 669 726 to 663 747, corresponding a reduction of the number of stoves of 0.9 %. The total estimated wood consumption for stoves in 2030 is reduced from 14.66 PJ to 14.56 PJ, corresponding 0.7%.

The total wood consumption for residential wood fired appliances (stoves, boilers and pellet appliances) is reduced from 33.04 PJ to 32.95 PJ, corresponding 0.3 %.

Table 2.8 Number of stoves in 2017 in the basic scenario and in 2022 and 2030 in scenario 1.

	2017	2022	2030
Stoves in district heating areas (number)	224 350	224 350	224 477
Share of stoves in district heating areas (share)	0.34	0.34	0.34
Stoves without the Nordic Eco Label (number)	383 596	294 183	178 393
Stoves without the Nordic Eco Label in district heating areas (number)	128 573	98 604	59 793
Share being closed (share)		0.1	0.1
Stoves being closed (number)		9 860	5 979
Stoves being replaced (number)		88 743	53 814

The wood consumption in stoves (excl. open fireplaces and masonry stoves) used for emission calculation in scenario 1 is reduced by 0.7 % in 2030 compared to the basic scenario. The emission in scenario 1 are reduced compared to the basic scenario by TSP: 412 tonnes, PM_{10}: 391 tonnes and $PM_{2.5}$: 383 tonnes, while the emission of BC is increased by 8 tonnes (Table 2.9).

Table 2.9 Wood consumption and emissions for stoves (excl. open fireplaces and masonry stoves) for the basic scenario and scenario 1 for selected years.

		2020	2030	Reduction 2020-2030
Wood consumption (stoves), basic scenario	PJ	16.67	14.66	2.01 PJ (12 %)
Wood consumption (stoves), scenario 1	GJ		14.56	2 PJ (13 %)
Scenario 1 / basic scenario (wood consumption)	%		99.3	
TSP (stoves), basic scenario	tonnes	6 445	3 984	2461 tonnes (38 %)
TSP (stoves), scenario 1	tonnes		3 572	2874 tonnes (45 %)
Scenario 1 / basic scenario (TPS)	%		89.7	
PM_{10} (stoves), basic scenario	tonnes	6 122	3 786	2337 tonnes (38 %)
PM_{10} (stoves), scenario 1	tonnes		3 394	2728 tonnes (45 %)
Scenario 1 / basic scenario (PM10)	%		89.67	
$PM_{2.5}$ (stoves), basic scenario	tonnes	5 993	3 703	2289 tonnes (38 %)
$PM_{2.5}$ (stoves), scenario 1	tonnes		3 320	2673 tonnes (45 %)
Scenario 1 / basic scenario (PM2.5)	%		89.6	
BC (stoves), basic scenario	tonnes	417	422	-5 tonnes (-1 %)
BC (stoves), scenario 1	tonnes		430	-13 tonnes (-3 %)
Scenario 1 / basic scenario (BC)	%		101.8	

The impact on emissions are summarised for all three scenarios in Chapter 2.3.

2.2.2 Scenario 2 – retrofitting of particle filters

Scenario 2 describes the impact of installation of electrostatic precipitators (ESP) on 20 % of the wood stoves and boilers in 2030, which do not have the Nordic Ecolabel. Scenario 2 takes as its starting point that the measure is introduced and fully implemented in 2030. If the measure was introduced earlier and implemented over years, the outcome would be slightly different, as some of the stoves without the Nordic Ecolabel would have been replaced by newer technologies before 2030 as part of the general replacement rate. This might lessen the effect of scenario 2, as the number of wood stoves and wood boilers without the Nordic Ecolabel would be slightly lower. Stoves that would have been replaced in the years 2018-2029 to new stoves without the Nordic Ecolabel would still be included in scenario 2, which decrease the influence of assuming the full introduction of the measure in 2030.

Efficiency of electrostatic precipitators (ESP)

A literature study has been conducted to assess the efficiency of electrostatic precipitators (ESP). A large number of references including information about measurements of ESP efficiency have been reviewed. The references included in the literature study is listed in Annex 1. Results from type testing measurements are neglected or given less influence on the decision of efficiencies, as they often represent optimal circumstances rather than real-life conditions. Summary of the literature study shows that there is great variation in the efficiency of ESPs. For the most part, there is relatively high efficiency, while for single filter types and in some measurement situations there are very low or negative efficiency.

Most information has been found on the efficiency in relation to TSP, and based on the literature study it is estimated that a general assumption can be made of 70 % efficiency for electrostatic precipitators for TSP.

There are few measurements of the efficiency for PM_{10} and $PM_{2.5}$, while there are slightly more studies for PM_1. The tendency is that the filters have higher efficiency for the smaller particle fractions than for TSP. Insufficient data have been found for PM_{10} and $PM_{2.5}$ to make an assessment of the efficiency, and due to the large variation for different types of ESPs, stoves / boilers, fuels and firing conditions, it is uncertain to base the efficiency for different particle fractions on different measuring arrays. The literature review indicates an overall efficiency for PM_1 around 80 %. Also for PM_1 there are large variations in the measured efficiency, but the differences are smaller than for TSP. No examples of negative efficiency have been found for PM_1. Based on the few data for PM_{10} and $PM_{2.5}$, it is estimated that the efficiency of these fractions is more similar to PM_1 than to TSP.

In several studies, measurements for TSP show a negative efficiency. The reason is that particles are formed when the flue gas condenses after the electrostatic precipitator. This may be due to the filter being placed too close to the stove, where the flue gas is very hot (Danish Environmental Protection Agency, 2015), which is supported by the fact that measurements on a Nordic Ecolabelled stove made by the Danish Technological Institute have shown that no particles are formed after the filter, which was placed either on top of the chimney or in the flue gas pipe (Danish Environmental Protection Agency, 2015). Previous measurements showing the formation of particles after the filter had been installed on an older non-Nordic Ecolabelled stove. In the assessment of the overall efficiency of ESPs, measurement campaigns that include measurements with negative efficiency are excluded.

Measurements of filter efficiency are available for both stoves, wood boilers and pellet boilers. For TSP, no general difference was observed. For the other particle fractions, there are too few measurements to be able to assess whether there is a difference between stoves and boilers. Therefore, the same efficiency is assumed for stoves and boilers.

Based on the available data, it is estimated that the following efficiency for ESP can be used in scenario 2:

- TSP: 70 %
- PM_{10}: 80 %
- $PM_{2.5}$: 80 %
- BC: 80 % (A reduction of BC has been tentatively recognized, assuming that the efficiency for BC is the same as for $PM_{2.5}$. Only few references have been found to support this assumption. Bäfver et al. (2012) generally find high efficiency for reduction of elemental carbon (89 % -95 %), while Nussbaumer et al. (2010) find 16 % for soot.

A summary of the efficiency of ESP from the literature study is shown in Table 2.10. The results are grouped for appliance types and particle fractions. For the appliance types "Stoves and boilers", "Stoves" and "Boilers, all", averages have been made both for all results from the literature study and for selected results. Measurements performed on pellet fired boilers and references where measurements have shown negative efficiency are disregarded here, as this may be due to errors in the measurement setup. In addition, there are measurements, where particle filters are combined with a smoke extractor and additional air.

Table 2.10 Summary of efficiency of ESP found in the literature study.

		TSP	PM_{10}	$PM_{2.5}$	PM_1
Stoves and boilers	All	67.7	88.0	58.0	76.4
	Selected	69.8	88.0	87.0	78.7
	n	58	1	2	11
Stoves	All	64.3	88.0	43.5	89.3
	Selected	70.2	88.0	87.0	89.3
	n	21	1	1	3
Boilers, all	All	70.1		87.0	74.2
	Selected	69.6		87.0	74.8
	n	37		1	8
Boilers, ex. pellet fired boilers	Selected	68.4		87.0	74.8
	N	28		1	8
Boiler, wood fired	Selected	63.9		87.0	79.0
	n	12		1	4
Boiler, pellet fired	Selected	73.2			
	n	10			

The references used for the data contained in Table 2.10 are included as Annex 1.

Methodology

Scenario 2 builds on the appliance number, the unit consumption and the total wood consumption in the RWC model.

The wood consumption is estimated for the appliances in 2030 and scaled to the DEA wood consumption. The emissions are calculated using the emission factors in the RWC model. For 20 % of the wood stoves and wood boilers that are not Nordic Ecolabelled, the emission factors for TSP, PM_{10} and $PM_{2.5}$ is reduced according to the ESP efficiency from the literature study (TSP: 70 %, PM_{10}: 80 %, $PM_{2.5}$: 80 % and BC: 80 %).

Results

Scenario 2 reflects the emission reduction due to installation of ESP on 20 % of the wood stoves and wood boilers, which do not have the Nordic Ecolabel. The wood consumption for non-Nordic Ecolabelled appliances are 5.49 PJ in 2030 corresponding to 25 % of the total wood consumption.

Table 2.11 Wood consumption and emissions in 2030 for scenario 2, and emission reductions compared to the basic scenario.

	FC PJ	TSP tonnes	PM_{10} tonnes	$PM_{2.5}$ tonnes	BC tonnes
Non-Nordic Ecolabelled stoves	3.75	1 442	1 338	1 310	71
Non-Nordic Ecolabelled boilers	1.74	503	466	457	9
All stoves and boilers	22.0	4 612	4 340	4 249	451
Share (non-ecolabelled/all)	25 %	42 %	42 %	42 %	18 %

The wood consumption in stoves and boilers (excl. pellet fired appliances) used for emission calculation in scenario 2 is unchanged compared to the basic scenario, as only the measure affects the emission factors. The impact of installation of electrostatic precipitators (ESP) on 20 % of the wood stoves and boilers in 2030, which do not have the Nordic Ecolabel, assuming the efficiency as of the literature study result in a reduction of the emissions as follows. The emissions in scenario 2 are reduced compared to the basic scenario by TSP: 317 tonnes, PM_{10}: 344 tonnes, $PM_{2.5}$: 337 tonnes and BC: 15 tonnes (Table 2.12).

Table 2.12 Wood consumption and emissions for stoves and boilers (excl. pellet fired appliances) for the basic scenario and scenario 2 for selected years.

		2020	2030	Reduction 2020-2030
Wood consumption, basic scenario	PJ	41.58	33.04	8.53 PJ (21 %)
Wood consumption, scenario 2	GJ		33.04	8.53 PJ (21 %)
Scenario 2 / basic scenario (wood consumption)	%		100	
TSP, basic scenario	tonnes	7 520	4 928	2591 tonnes (34 %)
TSP, scenario 2	tonnes		4 612	2908 tonnes (38.7 %)
Scenario 2 / basic scenario (TPS)	%		93.6	
PM_{10}, basic scenario	tonnes	7 144	4 683	2460 tonnes (34 %)
PM_{10}, scenario 2	tonnes		4 340	2804 tonnes (39.3 %)
Scenario 2 / basic scenario (PM10)	%		92.66	
$PM_{2.5}$, basic scenario	tonnes	6 996	4 585	2411 tonnes (34 %)
$PM_{2.5}$, scenario 2	tonnes		4 249	2747 tonnes (39.3 %)
Scenario 2 / basic scenario (PM2.5)	%		92.7	
BC, basic scenario	tonnes	468	466	1 tonnes (0.3 %)
BC, scenario 2	tonnes		451	16 tonnes (3.5 %)
Scenario 2 / basic scenario (BC)	%		96.8	

2.2.3 Scenario 3 – phase out of older stove at transfer of house ownership

Scenario 3 describes the impact of introducing a requirement that all wood stoves from before 2003 have to be removed in case of transfer of house ownership. Older stoves in scenario 3 are defined as the numbers of pre-2003 stoves which is estimated via the appliance numbers and the exchange curve in the RWC model, and takes as its starting point that the measure is introduced from 2021, so the first impact due to the measure occurs in 2021. The calculations for scenario 3 cover the years 2020-2030.

Methodology

Scenario 3 is based on a number of assumptions, which are all in line with the scenario prepared by the Ministry of the Environment (Milfeldt, 2020). The assumptions are described in the following paragraphs.

As the measure is related to sales of residences, the assumption is, that a residence changes ownership every 14^{th} year. In connection with sales of residences, it is assumed that 1/3 of the stoves are replaced in baseline as a result of current behaviour in the event of a transfer of house ownership. The remaining 2/3 are assumed to be additional replacements as a result of the measure in scenario 3.

Introducing the measure concerning ownership causes house owners either to replace the stove with a new stove or to completely close the fireplace. Scenario 3 builds on the assumption that 90 % replace the stove and the remaining 10 % close the fireplace, which corresponds to the assumption used in scenario 1.

It is assumed that all stoves being replaced in scenario 3 are replaced by stoves of the newest age-category (2017-). It is assumed that 50 % is replaced by a stove that fulfil the legal environmental requirements (4 g/kg) and 50 % is replaced by a Nordic Ecolabelled stove (2 g/kg). This corresponds to the following categories in the RWC model: "Modern stove (2017-)" and "Eco-labelled stove/new advanced stove (2017-)".

Results

The number of stoves pre-2003 in the RWC model for 2017 and the projection years is the basis for the scenario 3. In 2017, there are 260 576 pre-2003 stoves.

Based on the RWC projection and the assumptions described, an additional replacement around 12 500 stoves will occur only in the first year. As the number of old stoves decrease rather fast in scenario 3, the number of stoves targeted by the measure will decrease over the time series. In 2030 the number of additional replacements compared to the basic scenario is 38 653, and the remaining number of stoves pre-2003 is 53 618 (Table 2.13).

Table 2.13 Stock data used in scenario 3 for selected years.

	2020	2021	2025	2030
Stoves pre-2003	260 576	241 101	167 916	92 271
Traded residences with pre-2003 stoves		18 613	10 699	4 636
Total number additional replacements		12 408	39 344	38 653
Residual stock pre-2003 stoves	260 576	228 693	128 572	53 618

The distribution of stoves on technology categories in 2017 and in the projection years is used to distribute the adjusted number of stoves due to the measure in scenario 3 (Table 2.14). Figure 2.10 illustrates that the technology categories "Old stove" and "New stove" are phased out faster in scenario 3 than in the basic scenario, and also that the number of stoves of the newest technology (2017-) increases faster.

Table 2.14 Number of stoves per technology category used in scenario 3 for selected years.

	2020	2021	2025	2030
Old stove	29 486	20 308	0	0
New stove	272 377	249 406	159 948	61 089
Modern stove (2008-2014)	14 920	14 920	14 786	13 765
Modern stove (2015-2016)	4 100	4 100	4 100	4 080
Modern stove (2017-)	8 200	15 834	40 140	60 542
Ecolabelled stove/new advanced stove (2004-2014)	229 563	228 803	220 912	196 318
Ecolabelled stove/new advanced stove (2015-2016)	36 900	36 900	36 900	36 716
Ecolabelled stove/new advanced stove (2017-)	73 800	97 834	187 740	290 142
Total (stoves)	669 346	668 105	664 526	662 650

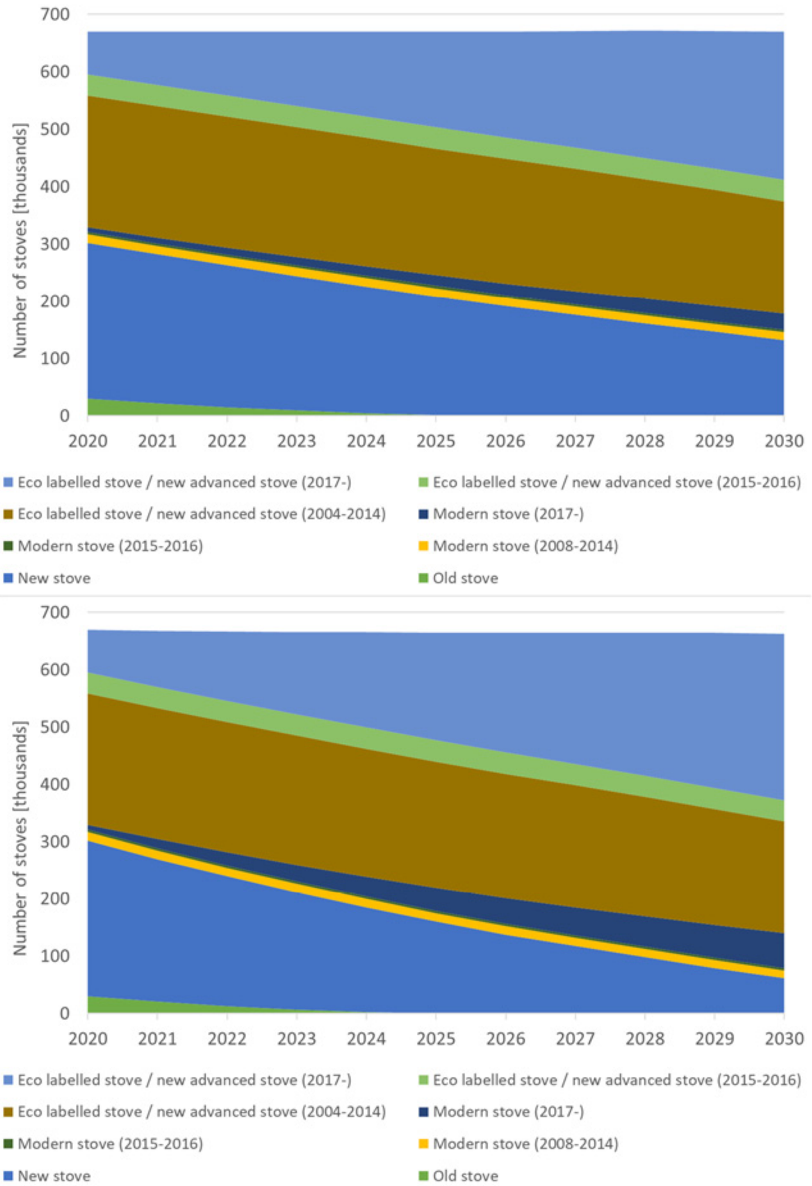

Figure 2.10 Stoves by technology category used in the basic scenario (a) and in scenario 3 (b).

The additional replacement of pre-2003 stoves in scenario 3 leads to a small decrease of the total number of stoves due to the fact that 10 % choose to close their fireplace in connection with change of ownership due to residence sales. The remaining 90 % replace the stove with a stove of the newest technology that either fulfil the legal environmental requirements (4 g/kg) or has the Nordic Ecolabel. This result in a change of the technology distribution compared to the basic scenario. The emission factors for particles decrease with improved technology, while the BC emission factors are lower for the older technology categories "Old stoves", "New stoves" and "Modern stove (2008-2015)"(Table 2.15). This causes the particle emissions are reduced in scenario 3 compared to the basic scenario, while the BC emission increase.

Table 2.15 Emission factors (g/GJ) used in both the basic scenario and scenario 3.

	TSP	PM_{10}	$PM_{2.5}$	BC
Old stove	1000	950	930	18
New stove	500	475	465	17
Modern stove (2008-2015)	389	370	362	23
Modern stove (2015-2017)	317	301	295	44
Modern stove (2017-)	253	240	235	44
Ecolabelled stove/new advanced stove (2004-2014)	253	240	235	31
Ecolabelled stove/new advanced stove (2015-2016)	190	181	177	31
Ecolabelled stove/new advanced stove (2017-)	127	121	118	31

As the measure in scenario 3 is introduced in 2021, the input data for 2020 are taken directly from the RWC model. The additional closure of fireplaces in scenario 3 reduces the wood consumption. In the RWC model, the estimated wood consumption based on the number of appliances and unit consumptions is scaled to the total residential wood consumption given in the DEA energy statistics (DEA, 2020b) and projection (DEA, 2020a). In order to account for the additional decrease of the number of appliances, the DEA residential wood consumption is adjusted correspondingly. In 2021, the DEA residential wood consumption is adjusted by -0.1 %. The corresponding value for 2030 is -0.5 %.

The wood consumption in stoves (excl. open fireplaces and masonry stoves) used for emission calculation in scenario 3 is reduced by 0.8 % in 2030 compared to the basic scenario. The emission in scenario 3 are reduced compared to the basic scenario by TSP: 482 tonnes, PM_{10}: 458 tonnes and $PM_{2.5}$: 448 tonnes, while the emission of BC is increased by 26 tonnes (see Table 2.16 and Figure 2.11).

Table 2.16 Wood consumption and emissions for stoves (excl. open fireplaces and masonry stoves) for the basic scenario and scenario 3 for selected years.

		2020	2021	2025	2030	Reduction 2020-2030
Wood consumption (stoves), basic scenario	PJ	16.67	16.48	15.75	14.66	2.01 PJ (12 %)
Wood consumption (stoves), scenario 3	GJ		16.46	15.66	14.54	2 PJ (13 %)
Scenario 3 / basic scenario (wood consumption)	%		99.9	99.5	99.2	
TSP (stoves), basic scenario	tonnes	6 445	6 108	4 990	3 984	2461 tonnes (38 %)
TSP (stoves), scenario 3	tonnes		6 002	4 621	3 502	2943 tonnes (46 %)
Scenario 3 / basic scenario (TPS)	%		98.3	92.6	87.9	
PM_{10} (stoves), basic scenario	tonnes	6 122	5 803	4 740	3 786	2337 tonnes (38 %)
PM_{10} (stoves), scenario 3	tonnes		5 701	4 390	3 328	2794 tonnes (46 %)
Scenario 3 / basic scenario (PM_{10})	%		98.25	92.60	87.91	
$PM_{2.5}$ (stoves), basic scenario	tonnes	5 993	5 679	4 639	3 703	2289 tonnes (38 %)
$PM_{2.5}$ (stoves), scenario 3	tonnes		5 580	4 295	3 255	2737 tonnes (46 %)
Scenario 3 / basic scenario ($PM_{2.5}$)	%		98.3	92.6	87.9	
BC (stoves), basic scenario	tonnes	417	420	426	422	-5 tonnes (-1 %)
BC (stoves), scenario 3	tonnes		425	445	448	-31 tonnes (-7.4 %)
Scenario 3 / basic scenario (BC)	%		101.2	104.4	106.1	

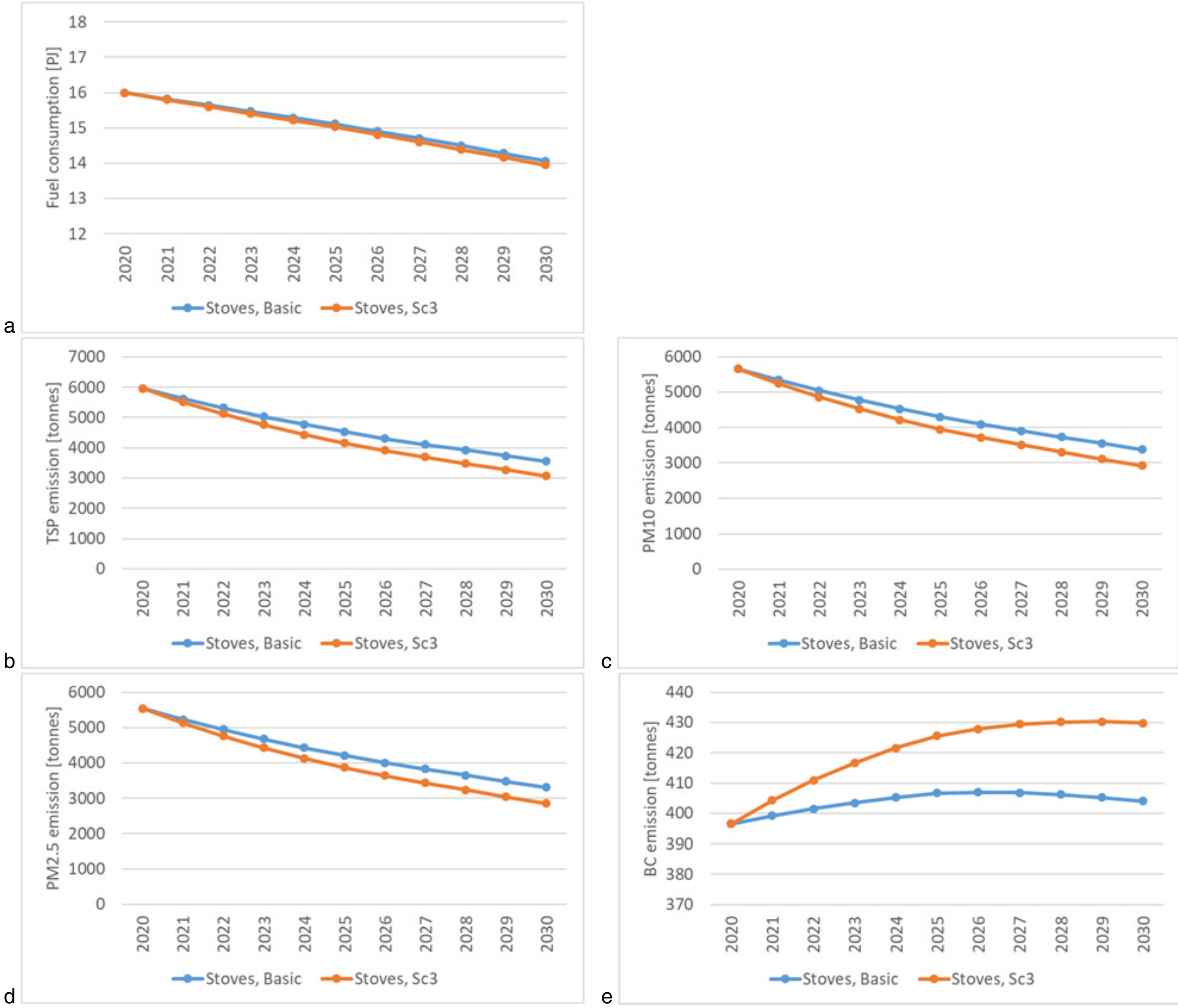

Figure 2.11 Wood consumption (a) and emissions (b-e) for basic scenario and scenario 3 for the years 2020-2030.

2.3 Summary of results for all three scenarios

Three scenarios have been set up to evaluate the effect of measures focusing on reducing emissions from residential wood combustion. The three scenarios are:

- Ban on stoves that do not meet the requirements according to the Nordic Ecolabel in district heating areas
- Particle filters on 20 % of the wood stoves and wood boilers that do not meet the requirements according to the Nordic Ecolabel
- Phasing out of older stoves in connection with transfer of house ownership

The impact of the measures on the emissions in 2030 have been estimated for each of the three scenarios and compared to latest emission projection as the basic scenario (Nielsen et al., 2021b).

The measure in scenario 1 impacts the number of stoves, the technology distribution, the spatial distribution and the resulting emissions.

The measure in scenario 2 impacts the emission factors for part of the stoves and boilers and the resulting emissions.

The measure in scenario 3 impacts the number of stoves, the technology distribution and the resulting emissions.

The impact on the number of appliances and the technology distribution is shown in Table 2.17. Both scenario 1 and 3 cause a shift from older to new stoves combined with a small reduction of the total number of stoves, due to the assumption that 10% of the stoves covered by the scenario measures will be completely closed down. Scenario 1 result in a reduction of stoves that do not meet the requirements according to the Nordic Ecolabel (non-ecolabelled stoves). Part of these stoves are newer technologies, e.g. 10 987 stove from 2015 or later, which have significantly lower PM emission factors than older stoves. The measures in scenario 3 only apply to stoves from 2003 or older, which have relatively high particle emissions compared to the newer technologies. Further, scenario 3 cover a larger number of stoves than scenario 2 (70 759 stoves and 59 794 stoves, respectively).

Table 2.17 Reduction of stoves in 2030 compared to the basic scenario [number].

	Scenario 1 Ban on non-eco-labelled stoves in district heating areas	Scenario 2 Particle filter on 20 % of the non-ecolabelled stoves	Scenario 3 Phase-out of older stoves with transfer of house ownership
Old stove	0	0	0
New stove	44 193	0	70 759
Modern stove (2008-2015)	4 614	0	0
Modern stove (2015-2017)	1 367	0	0
Modern stove (2017-)	9 620	0	-31 842
Ecolabelled stove/new advanced stove (2004-2014)	0	0	0
Ecolabelled stove/new advanced stove (2015-2016)	0	0	0
Ecolabelled stove/new advanced stove (2017-)	-53 814	0	-31 842
SUM	5 979	0	7 076

The impact on the emissions is shown in Table 2.18 and illustrated in Figure 2.12 for particles and BC. As scenario 3 result in a larger number of stoves being replaced and closed, and as the stoves are all pre-2003 with higher PM emission factors, the emission reduction for scenario 3 is larger than for scenario 1 (Table 2.18). The same pattern are seen for NMVOC, NH_3 and CO as the emission factors for these pollutants also decrease for newer technologies. Emissions of NO_x are lowest for the stove technologies "old" and "new" and highest for the "Modern stove"-technologies, and following, scenario 1 and 3 result in an increase of the NO_x emissions.

Table 2.18 Reduction of emission in 2030 [tonnes] compared to the basic scenario.

	Scenario 1 Ban on non-ecolabelled stoves in district heating areas	Scenario 2 Particle filter on 20 % of the non-eco-labelled stoves	Scenario 3 Phase-out of older stoves with transfer of house ownership
SO_2	1	0	1
NO_x	-15	0	-33
NMVOC	464	0	530
NH_3	34	0	53
TSP	410	317	480
PM_{10}	390	344	456
$PM_{2.5}$	382	337	446
BC	-8	15	-26
CO	2108	0	3312

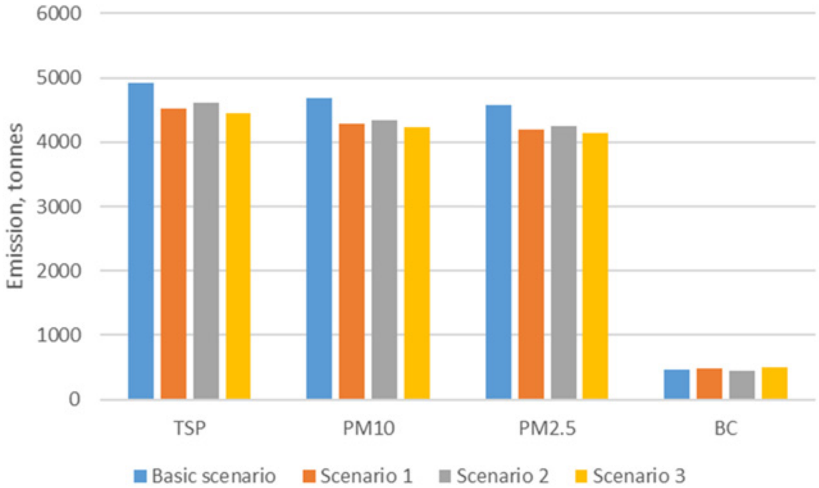

Figure 2.12 Emission (tonnes) in 2030 for residential wood fired appliances ex pellet appliances.

Scenario 2 does not affect the number of stoves or the distribution per technology, but only the PM emission factors applied for 20% of the non-eco-labelled wood stoves and wood boilers. The main part of the emission reduction is seen for the technology "new stoves", which contribute 61 % of the total $PM_{2.5}$ emission reduction in scenario 2 (Table 2.19). Wood boilers contribute 26 % to the $PM_{2.5}$ emission reduction in scenario 2.

Table 2.19 Reduction of emission in scenario 2 per technology in 2030 [tonnes] compared to the basic scenario.

	Basic scenario, 2030, $PM_{2.5}$ [tonnes]	Scenario 2, 2030, $PM_{2.5}$ [tonnes]	Reduction [tonnes]	[%]
Old stove	0	0	0	0
New stove	1288	1082	206	16
Modern stove (2008-2015)	105	88	17	16
Modern stove (2015-2017)	25	21	4	16
Modern stove (2017-)	142	119	23	16
Ecolabelled stove / new advanced stove (-2014)	969	969	0	0
Ecolabelled stove / new advanced stove (2015-2016)	137	137	0	0
Ecolabelled stove / new advanced stove (2017-)	640	640	0	0
Other stove, High emission, e.g. fireplaces	391	391	0	0
Other stove, Low emission, e.g. masonry stoves	7	7	0	0
Old boiler, with accumulation tank	0	0	0	0
Old boiler, without accumulation tank	0	0	0	0
New boiler, with accumulation tank	338	338	0	0
New boiler, without accumulation tank	544	457	87	16
Pellet boilers/stoves	518	518	0	0
Total	5103	4766	337	7

3 Modelling concentrations

The transport and transformation of EC and other air pollutants of the different emissions scenarios in the project have been determined using the Danish Eulerian Hemispheric Model (DEHM), see e.g. Christensen (1997) and Brandt et al. (2012). DEHM has been widely used to describe the transport of pollutants from national scale over Denmark within the National Air Quality Monitoring Program – NOVANA (Ellermann et al., 2021) up to hemispheric scale in order to describe the transport of pollution to the Arctic (Christensen, 1997; Christensen et al., 2004; Skov et al., 2006; Hole et al., 2009; Winther et al., 2014; Massling et al., 2015; Eckhardt et al., 2015; Skov et al., 2020). DEHM has also been used in many assessments in the Arctic Monitoring and Assessment Programme (AMAP 2006, 2011, 2015 and 2021). DEHM is a 3D chemical transport model and in this study the model has been set up with four nested domains with a horizontal resolution of 5.6 km resolution for Denmark, 16.7 km for Northern Europe, 50 km for Europe and up to 150 km at the 60^{th} parallel north for the Northern Hemisphere. The Model has 29 irregular vertical levels, where the lowest 15 levels are below 2,000 m above the surface. The lowest model level is 12 m thick and the top of the model domain is at 100 hPa i.e. the whole troposphere and very lowest part of the stratosphere. DEHM includes a SO_x-NO_x-VOC-ozone chemistry scheme with 71 components including secondary organic aerosols (SOA), where volatility basis set (VBS) mechanism are used, and nine particulates including hydrophobic and hydroscopic EC, primary organic aerosols, primary anthropogenic dust, $PM_{2.5}$ fraction and coarse fraction of PM_{10} of sea salt and lead (Pb). The model is driven by meteorological data from a numerical weather prediction model from the WRF model (Skamarock et al., 2008), version 4.1, with 1-hour resolution. The WRF model system is driven by nudging of the global reanalysis data from the ERA5 made by ECMWF (European Centre for Medium-Range Weather Forecasts).

All the model runs made in this project are single year model runs using meteorological data for 2018.

The basic background model run with DEHM calculates the atmospheric concentrations and depositions of pollutants based on the anthropogenic emissions for the latest historical year 2018 for Denmark, European emissions from EMEP for the year 2018, global emissions based on the Eclipse version 6b for the year 2015, and global ship emissions based on the STEAM model (Johansson et al., 2017). Furthermore emissions from biomass burning from the CAMS Global Fire Assimilation System (GFAS) have been used (https://www.ecmwf.int/en/forecasts/dataset/global-fire-assimilation-system).

In Figure 3.1, the annual mean concentrations for the surface layer of the total EC are shown. The highest concentrations are observed for areas south of Denmark with a south-north gradient indicating the importance of transport of EC from source areas south of Denmark. The contribution of Danish sources to the total EC in Denmark is approximately 30 % according to the model. For Denmark the highest concentration are over the city centre of Copenhagen.

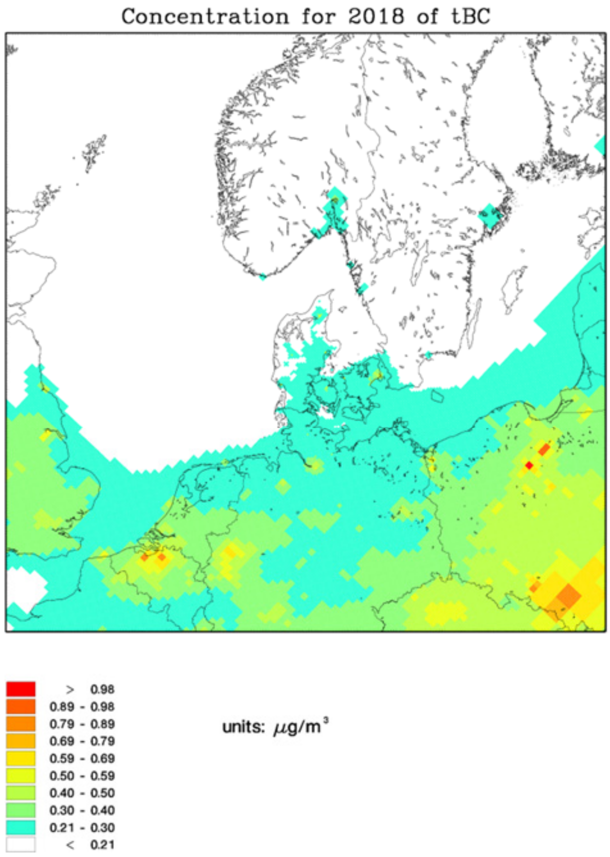

Figure 3.1 Annual mean concentration of the total EC for the surface layer for the year 2018 of the basic 2018 emissions run. tBC is total BC.

There have been made four model runs with the DEHM model for 2030:

1. A model run where the basic 2018 emissions for Denmark have been replaced with the basic 2030 emissions (the latest emission projection 2030).
2. A model run where the basic 2018 emissions for Denmark have been replaced with the 2030 scenario 1 emissions.
3. A model run where the basic 2018 emissions for Denmark have been replaced with the 2030 scenario 2 emissions.
4. A model run where the basic 2018 emissions for Denmark have been replaced with the 2030 scenario 3 emissions.

Figure 3.2 shows the changes in EC concentrations due to basic 2030 emissions scenario compared to the basic 2018 emission inventory. In the large urban areas as Copenhagen, Aarhus and Aalborg the changes are up to 50 % but declines to less than 10 % in the rural areas, and decreases furthermore outside Denmark.

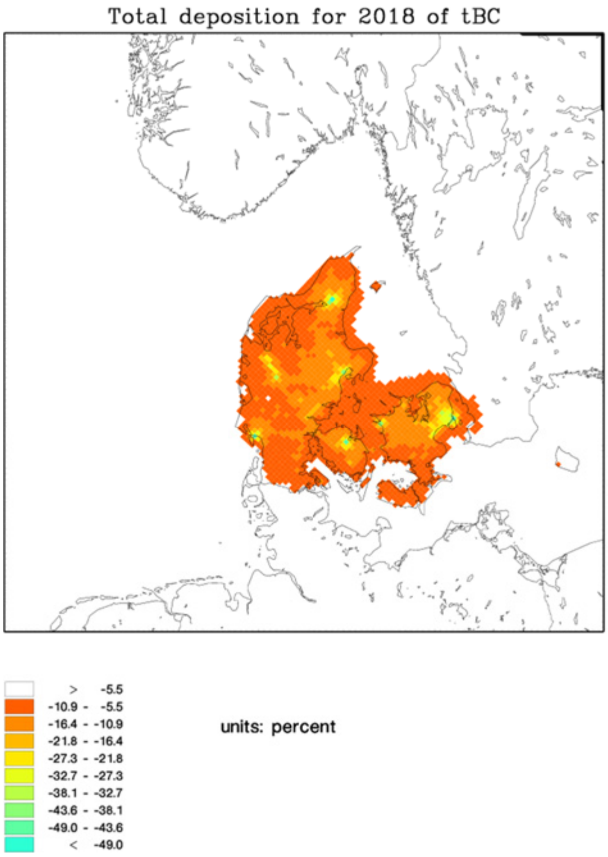

Figure 3.2 Changes in percent of the total EC concentration between basic 2030 emissions scenario and 2018 basic emissions inventory. tBC is total BC.

Table 3.1 shows the average changes for the different regions due to the four different emission scenarios for 2030 compared to the 2018 emission inventory for EC. Totally for Denmark the Basic 2030 emissions decrease the mean concentrations with 11.7 % EC. Compared to the 2030 basic emissions the 2030 scenario 1 gives an additional minor increase with 0.08 percentage point, 2030 scenario 2 an additional minor decrease of 0.16 percentage point and 2030 scenario 3 gives an additional minor increase of 0.28 percentage point. Overall conclusion are that the 2030 scenario 2 emissions results in the largest reduction of EC over Denmark while the three additional scenarios for 2030 only results in a minor change compared to the 2030 scenario 2 scenario.

Table 3.1 Mean concentrations of EC for different regions in Denmark and whole Denmark and the changes in percent due to the different emission scenarios compared to the 2018 emission inventory.

Region	2018	2030basic	2030scen1	2030scen2	2030scen3
Nordjylland	0.20 µg/m3	-12.14 %	-12.07 %	-12.32 %	-11.83 %
Midtjylland	0.21 µg/m3	-12.19 %	-12.10 %	-12.37 %	-11.88 %
Syddanmark	0.22 µg/m3	-10.53 %	-10.46 %	-10.68 %	-10.29 %
Hovedstaden	0.27 µg/m3	-15.54 %	-15.44 %	-15.69 %	-15.28 %
Sjælland	0.24 µg/m3	-10.60 %	-10.51 %	-10.75 %	-10.33 %
Danmark	0.22 µg/m3	-11.66 %	-11.58 %	-11.82 %	-11.38 %

Mean concentrations and depositions for the northern mid-latitudes and Arctic for the model run with 2018 emissions inventory and the changes in percent for the model run with 2030 basic emissions inventory compared to 2018 emissions inventory are shown in figure 3.3. The summary of the mean concentrations and depositions in the Arctic area north of Arctic Circle (66.56°N) and the changes in percent due to the different emission scenarios compared to the 2018 emissions inventory are shown in

Table 3.2. The changes in concentrations and depositions due to the 2030 basic emissions scenario are about -0.1 %, while 2030 scenario 1 gives an additional minor increase with +0.0016 percentage point for concentrations and +0.0011 percentage point for deposition. The similar values for 2030 scenario 2 are -0.0026 and -0.0016 percentage point and for 2030 scenario 3 the values are +0.0045 and +0.0032 percentage point.

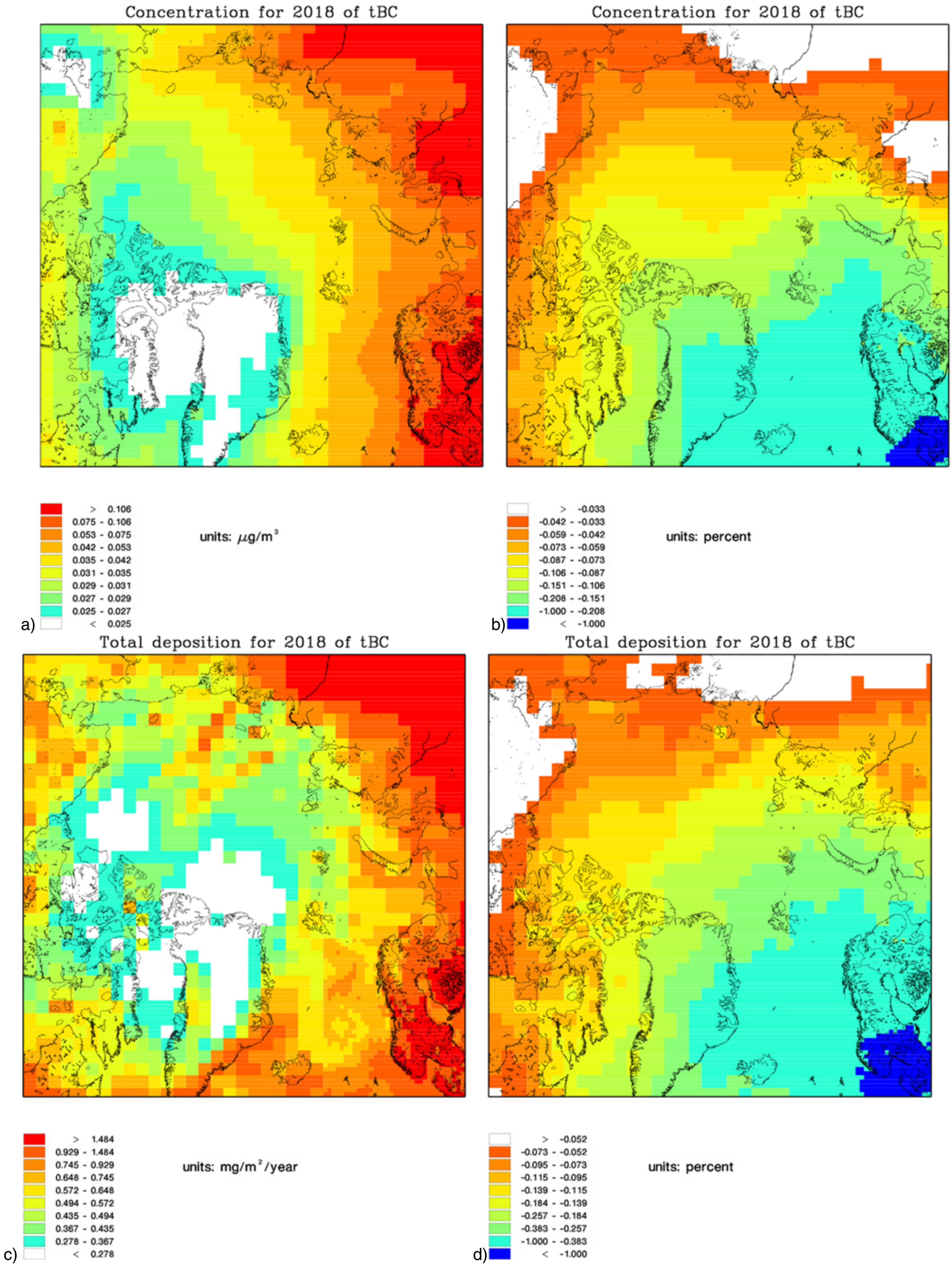

Figure 3.3 Mean concentrations (a: [µg/m^3] and b) [%]) and depositions (c: [mg//m^3/year] and d) [%]) for the northen mid-latitudes and the Arctic area in 2018. tBC is total BC.

Table 3.2 Mean concentrations and depositions for the Arctic area north of Arctic Circle (66.56°N) and the changes in percent due to the different emission scenarios compared to the 2018 emissions inventory.

Arctic >66.56°N	2018	2030basic	2030scen1	2030scen2	2030scen3
Concentration	44.0 ng/m3	-0.110 %	-0.1085 %	-0.1125 %	-0.1054 %
Deposition	5.5 mg/m2/year	-0.095 %	-0.0941 %	-0.0968 %	-0.0920 %

3.1 Validation of modelled concentrations of EC

The concentrations of EC calculated by DEHM for the period 2010-2019 have been compared with measurements of EC for Denmark for three different locations, Risø (rural), Hvidovre (suburban) and H.C. Ørsted Instituttet (urban background) by ENVS-DCE-AU (Ellermann et al., 2021). In Figure 3.4 the annual mean concentrations of both measured and calculated EC are shown for these three locations. Generally, there is good agreement between the model calculations and measurements. The figure shows that the DEHM model are able to describe the observed temporal variations at the rural site, Risø. The model overestimates Risø concentration with 11 %, overestimates Hvidovre with 17 %, and underestimate HCØ with 33 %. It is expected that the model will perform better for a rural area, where emissions from a larger area contributes to the concentrations compared to the two urban sites, where more local sources contribute. The model calculates higher concentrations for the HCØ (urban background) compared to Hvidovre (suburban) while the measurements show the opposite. This indicates that local sources contribute more to measurements at Hvidovre compared to H.C. Ørsted Instituttet, while it is the opposite for the model calculations.

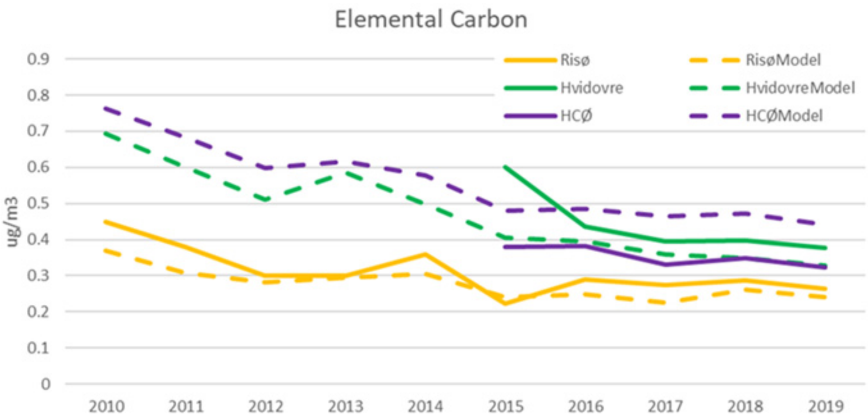

Figure 3.4 Comparisons of measured and model yearly mean concentrations of EC for the period 2010-2019 for three locations in Denmark.

4 Climate effect of residential wood combustion

4.1 Background

Emissions of greenhouse gases are reported annually to the United Nations Framework Convention on Climate Change (UNFCCC) and it covers the direct greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 and NF_3). Additionally, emissions of some indirect greenhouse gases are included in the reporting (SO_2, NO_x, NMVOCs and CO). Indirect greenhouse gases contribute to global warming through reactions in the atmosphere. NO_x, NMVOC and CO can contribute by increasing the ozone concentration in the troposphere through chemical reactions, and SO_2 can form aerosols that can affect the cooling and warming of the atmosphere.

The main greenhouse gas responsible for the anthropogenic influence on the heat balance is CO_2. The atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 ppm to about 390 ppm in 2010 (an increase of about 38 %) (IPCC, 2013), and exceeds the natural range of 180-300 ppm over the last 650 000 years as determined by ice cores.

The main cause for the increase in CO_2 is the use of fossil fuels, but changing land use, including forest clearance, and cement production have also been significant factors. The greenhouse gases CH_4 and N_2O are very much linked to agricultural production; CH_4 has increased from a pre-industrial atmospheric concentration of about 722 ppb to 1803 ppb in 2011 (an increase of about 150 %) and N_2O has increased from a pre-industrial atmospheric concentration of about 270 ppb to 324 ppb in 2011 (an increase of about 20 %) (IPCC, 2013).

The global warming potential (GWP) for various gases has been defined as the warming effect over a given time of a given weight of a specific substance relative to the same weight of CO_2. The purpose of this measure is to be able to compare and integrate the effects of individual substances on the global climate. Typical atmospheric lifetimes for different substances differ greatly, e.g. for CH_4 and N_2O, approximately 12 and 120 years, respectively. So the time perspective clearly plays a decisive role. The lifetime chosen is typically 100 years. The effect of the various greenhouse gases can then be converted into the equivalent quantity of CO_2, i.e. the quantity of CO_2 producing the same effect with regard to absorbing solar radiation.

The climate effect of wood combustion in stoves and boilers are estimated based on the scenarios Basic, 1, 2 and 3, using the global warming potential (GWP) for a time horizon of 100 years, as given in the 5^{th} IPCC assessment report (AR5) (IPCC, 2013). The GWP100 values for CH_4, N_2O, NO_x, VOCs, BC and organic carbon (OC) are shown in Table 4.1. OC is not part of the reporting obligations and following OC emissions for wood combustion are neither included in the national emission inventory nor the scenarios for wood combustion. In current reporting to the UNFCCC, GWP100 values from the 4^{th} IPCC Assessment report (AR4) (IPCC, 2007) is used. However, the information on GWP values in AR5 has been improved including with additional pollutants, so that is the chosen reference for this study.

Table 4.1 Global warming potential (GWP100) for time horizon of 100 years based on the 5th IPCC assessment report.

Pollutant	GWP
CH_4	28
N_2O	265
NO_x	-15.6
VOCs	5.6
BC	2900
OC	-160

4.2 Estimates for climate effect of residential wood burning in Denmark

Based on the latest Danish emission inventories (Nielsen et al., 2020c & 2020d) for the pollutants identified with a GWP in Table 5.1 as well as the latest projections (Nielsen et al., 2020b and Nielsen at al., 2021b) estimates of the combined greenhouse gas effect has been calculated for 2005, 2018 and 2030. In addition, the impacts of the three scenarios described in Chapter 2.2 have been estimated.

Combustion of wood also leads to CO_2 emissions. However, under international reporting guidelines these emissions are considered to be neutral to the atmosphere and not included in the national total CO_2 emissions. For the purposes of this report, we have also included information on the CO_2 emissions associated with residential wood combustion to provide a more complete view of the overall climate impact. In the international reporting guidelines, these emissions are accounted for in the Land Use – Land Use Change and Forestry (LULUCF) sector for the country where the biomass is harvested.

Figure 4.1 shows the estimates of the emissions expressed as CO_2 equivalents including CO_2 from wood burning for the basic scenario for the years 2005, 2018 and 2030, and for the scenarios 1, 2 and 3 in 2030. The emissions from wood burning increase by 11 % from 2005 to 2018, and show a slight decrease from 2018 to 2030 of -0.2 % in the basic scenario. The change from 2018 to 2030 for the scenarios 1, 2 and 3 is -0.3 %, -1.3 % and 0.9 % respectively.

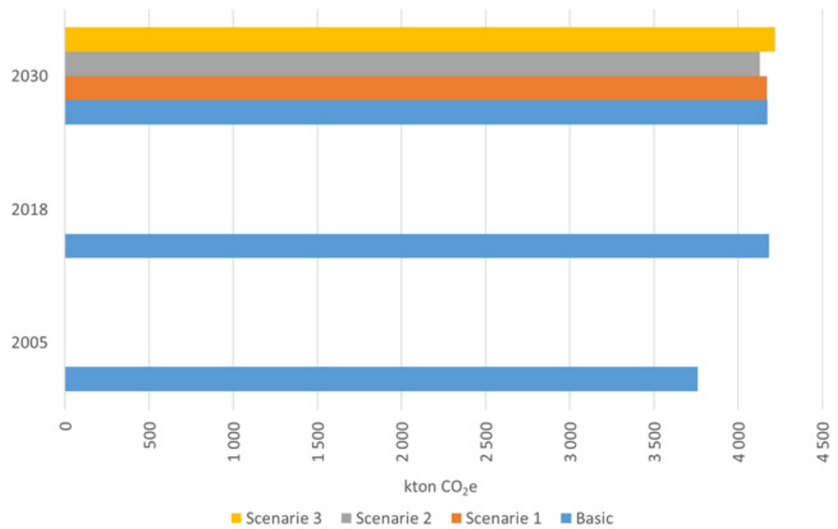

Figure 4.1 Emissions in 2005, 2018 and 2030 for small scale wood combustion for the basic scenario, and for 2030 for scenarios 1, 2 and 3.

Emissions of CO_2, CH_4, N_2O, NO_x, NMVOCs and BC for the basic scenario are included in Table 4.2 in tonnes and tonnes CO_2 equivalents (CO_2e). NO_x has a negative GWP100 value, which indicates a net decrease in the atmospheric heat trapping potential. BC has the largest climate effect per tonnes (GWP100 =2900) for the listed pollutants.

The CO_2 emissions in the basic scenario are 2676 kton, 2751 kton and 2752 kton in 2005, 2018 and 2030. CO_2 contributes the most to the climate effect for wood combustion in all the years 2005, 2018 and 2030 (71 %, 66 % and 66 %). The BC emission is 308 tonnes, 450 tonnes and 466 tonnes for the years 2005, 2018 and 2030, but as BC is more potent as a heat trapping gas than CO_2, BC contributes second most to the climate effect.

Table 4.2 Basic scenario emissions.

	Emission, tonnes			GWP100	Emission, tonnes CO_2e		
	2005	2018	2030		2005	2018	2030
CO_2	2 676 015	2 751 461	2 752 458	1	2 676 015	2 751 461	2 752 458
CH_4	4 229	2 755	1 337	28	118 416	77 140	37 430
N_2O	96	98	98	265	25 327	26 041	26 050
NO_x	1 301	1 815	1 720	-15.6	-20 291	-28 314	-26 837
VOCs	11 893	9 228	5 759	5.6	66 602	51 674	32 252
BC	308	450	466	2900	894 166	1 305 363	1 352 696
Sum					3 760 233	4 183 365	4 174 049

Figure 4.2 illustrates the estimated emissions in 2030 for the scenarios basic, 1, 2 and 3 by pollutant. As is the case for that basic scenario, CO_2 contributes the most to the climate effect from wood burning in the scenarios 1, 2 and 3.

The total emission in the scenarios 1, 2 and 3 are 1434 kton CO_2e, 1378 kton CO_2e and 1487 kton CO_2e, respectively. This corresponds to a reduction of the total emission in scenario 1, 2 and 3 compared to the basic scenario of 3 kton CO_2e, 44 kton CO_2e and -46 kton CO_2e, respectively.

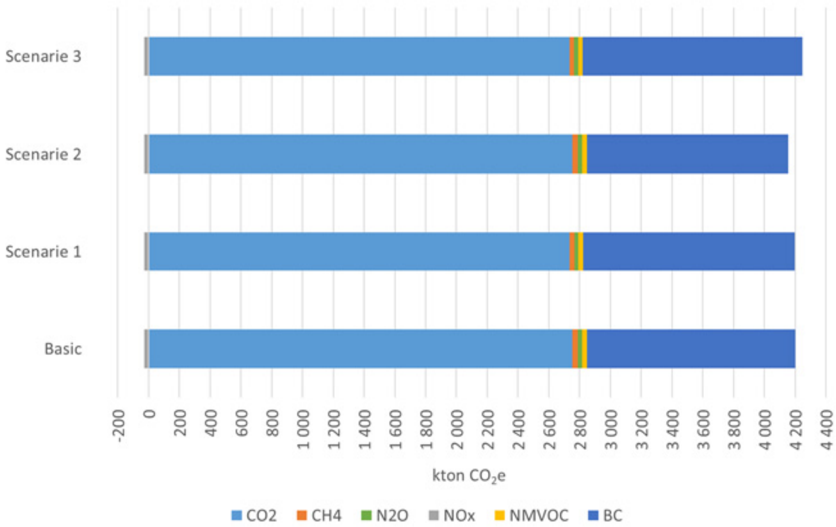

Figure 4.2 Emissions in 2030 for small scale wood combustion for the scenarios basic, 1, 2 and 3.

The largest reduction of the climate effect is estimated for scenario 2 (Table 4.3). Installation of particle filters on stoves and boilers that do not meet the Nordic Ecolabel requirements cause a decrease of the BC emission of 15 tonnes, corresponding to 3 %. Particle filters reduce the emissions of particles and BC, but do not affect the remaining pollutants.

Scenario 3 result in an increase of the climate effect of 46 467 kton CO_2e (corresponding to -1 %) in 2030 compared to the basic scenario. This is due to an increase of the BC emissions of 26 tonnes, corresponding to 6 % of the BC emissions in 2030 in the basic scenario. The increase of the climate effect due to the increased BC emission is counteracted mainly by a reduction of the CO_2 emission (18 572 kton CO_2e) and the CH_4 emission (6 496 kton CO_2e).

Table 4.3 Scenario emissions in 2030, tonnes CO_2e.

	Basic	Scenario 1	Scenario 2	Scenario 3
CO_2	2 752 458	2 736 765	2 752 458	2 733 886
CH_4	37 430	30 809	37 430	30 934
N_2O	26 050	25 902	26 050	25 874
NO_x	-26 837	-27 075	-26 837	-27 353
VOCs	32 252	29 651	32 252	29 286
BC	1 352 696	1 375 077	1 308 852	1 427 889
Sum	4 174 049	4 171 128	4 130 205	4 220 516

Figure 4.3 shows the national total emissions (excluding emissions from the LULUCF sector) of CO_2, CH_4, N_2O, NO_x, NMVOCs and BC in 2030 based on the 2020 projection of greenhouse gas (Nielsen et al, 2020b) and air pollution (Nielsen et al., 2021b). Further, Figure 4.3 show the estimated emissions from wood burning for the scenarios basic, 1, 2 and 3. The emission estimates for the scenarios include CO_2 from wood burning, which make up a significant part of the climate effect (65 %-67 %). The national total emission in Figure 4.3 does not include CO_2 from burning of wood and other biogenic fuels, as biogenic CO_2 is not included in the international reporting guidelines for reporting of greenhouse gas emissions to the UNFCCC.

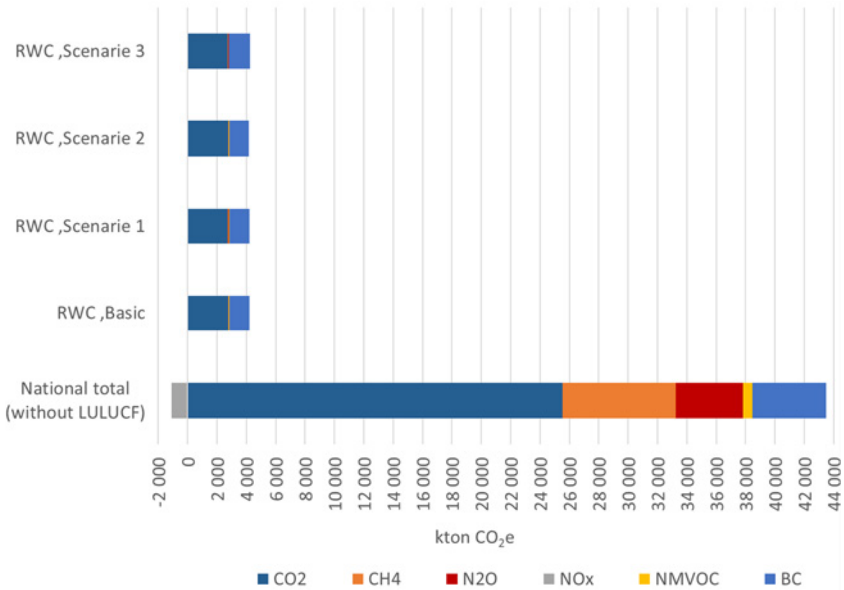

Figure 4.3 National total emission in 2030 excluding biogenic CO_2 emissions, compared to the emissions for small scale wood combustion for the scenarios basic, 1, 2 and 3.

CO_2 emissions from combustion of biogenic fuels have been calculated based on fuel consumption according to the 2020 projection of greenhouse gas (Nielsen et al., 2020b) and emission factors for 2018 (Nielsen et al., 2020c), despite the biogenic CO_2 emission is not included in the national emission inventory. The estimated biogenic CO_2 emission is included in Figure 4.4. The biogenic CO_2 emission make up a large contribution to the national total CO_2 emission (42 % in 2030). By including the biogenic CO_2 emission in Figure 4.4, the comparison with the emissions in the wood burning scenarios give a more accurate impression of the proportions.

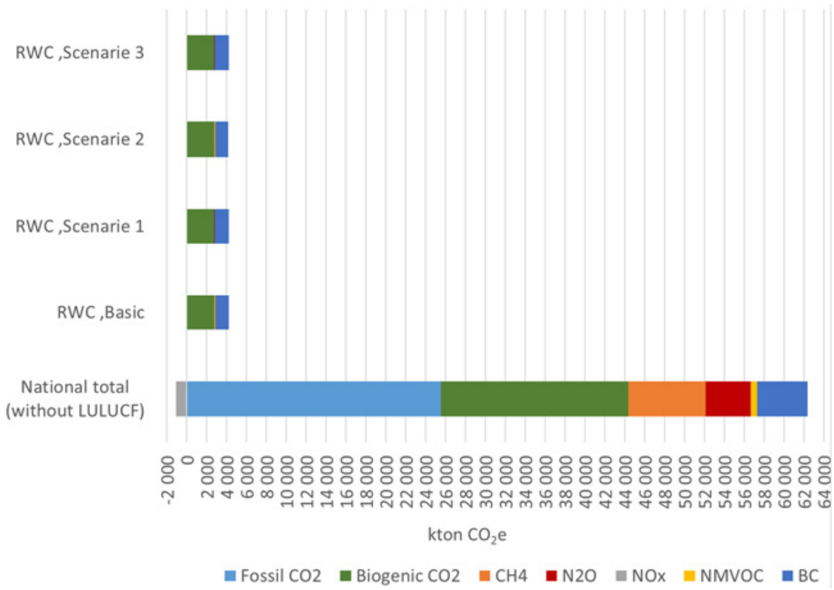

Figure 4.4 National total emission in 2030 including biogenic CO_2 emissions, compared to the emissions for small scale wood combustion for the scenarios basic, 1, 2 and 3.

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Annex 2 Overview of references

Overview of references for boilers

Reference	Appliance	Technology	Abatement	Pollutant	Efficiency, %	Range	Note
Azizaddini et al., 2018	Wood stove		ESP	TSP	70		
				PM10	88		
Schleicher et al., 2011	Wood stove	Morsø 1440 (1990 til 2007)	Zumikon ESP, Airbox ESP, cleanair ESP	PM	0		No significant effect
				PM2.5	0		No significant effect
Brunner et al., 2018	Old residential wood burning systems	Boiler and stove	ESP	TSP	83	Highest efficiencies	Field test show efficiencies similar to lab tests
				PM1	93	Highest efficiencies	Field test show efficiencies similar to lab tests
Hartmann et al., 2010	Stoves		ESP	PM	38	12-69	No stove mean given (APP: 55 & 69; Zumikron: 12 and 17; average=38)
Bologa et al., 2009	Stove		ESP		62	59-65	Strong corona quenching conditions
					72	66-78	Without corona quenching conditions in the ionizing stage
					64	60-78	ESP mass collection efficiency (no mean given)
Bologa et al., 2010	Stove		ESP	PM	88	85-91	ESP mass collection efficiency
Migliavacca et al., 2014	Pellet stove		ESP	PM	85		Short ESP, 1st day
					80		Short ESP, 5st day
					70		Long ESP, 1st day
	Wood stove				60		Short ESP, 1st day
Obernberger and Mandl 2011	Modern stove		R_ESP	TSP	69	52-95	
	Old stove				55	11-93	
					75	50-99	Depending on fuel, load, stove, etc. (no mean given)
	Log wood stove		Carola	TSP	87	84-90	
	Modern stove		Zumikron	TSP	17	-62 – 73	
	Old stove			TSP	11	-45 – 70	
	Stove		Airbox		70	60-80	(No mean given)
Obernberger et al., 2012	Old stove		Oekotube	PM1	85		
				TSP	55		
	Modern stove		Oekotube	PM1	90		
				TSP	70		
	Mean total dust precipitation efficiencies			TSP	75	50-90	(No mean given)
Exodraft	Stove		Exodraft ESP	TSP	73	70-75	(No mean given)
PHX innovation aps	Stove		Exodraft røgsuger	TSP			UP to 20 % less particles (unclear if mass or number)
Sanders Smoke Clean	Stove and boiler		Sanders Smoke Clean	PM0.1	0		In the ignition phase (0-10 min.) The filter almost doubled the ultrafine particle emission, whereas

							it reduced the particle emission around 85 percent in burning phase (10-40 min.).
				PM2.5	**87**		The newest (summer 2016) investigation by Ellen Marie Drastrup from DTU Environment as part of her master thesis at the Technical University of Denmark shows, that some filters (developed by Tonny Sander Holm and PHX Innovation) have high (85-99%) removal rates for soot particles, fine particles and ultrafine particles.
ENERVEX	Stove		ENERVEX	TSP	**73**	70-75	(No mean given)
EU commission	Small combustion facilities for solid fuels		ESP	TSP	**73**	57-81	Assumption for field (unclear if mass or number)
					70		Assumption for field (unclear if mass or number)
Poujoulat.co .uk	Stove and boiler		TOP CLEAN ESP	TSP	**92**		Especially PM2.5. According to manufacturer

Overview of references for boilers

Reference	Appliance	Technology	Abatement	Pollutant	Efficiency, %	Range	Note
Hartmann et al., 2010	Boiler			TSP	**80**		
Migliavacca et al., 2014	Pellet boiler			PM	**85**		Short ESP, 1st day
					40		Short ESP, 5st day
					15		Short ESP, 10th day
					90		Long ESP, 1st day
Obernberger and Mandl 2011	Boiler		Zumikron	TSP	**41**		
				PM1	**53**	20-76	
	Pellet boiler		Oekotube	PM	**97**	96.7-97.5	
	Modern automatic wood chip boiler		Ruff-KAT	TSP	**70**		>70%
	Boiler		AL-Top	TSP	**66**	81; 82; 48; 52	(No mean value given)
	Boiler		SF20	TSP	**68**		
				PM1	**60**	45-73	
	Old log wood boiler			TSP	**50**	11. -41. -89. 37. 66. 40. 69. 80. 50. 86. 96. 61. 55. 94. 88	Mean 25 or 80. Most values above 50 %
	Modern boiler			TSP	**80**	86. 81. 89. 89. 75. 75. 72. 75. 79. 76	Most values above 70 % (No mean given)
	Modern log wood boiler			TSP	**83**	93. 78. 86. 82. 91. 92. 94. 85. 85. 25. 85. 81. 85. 90. 88	Most values above 70 % (No mean given)
			Airbox	TSP			
	Boiler		Nasu ESP	PM1	85	80-90	According to manufacturer

	Old log wood boiler		Feinstaubkiller	TSP	64	26-94	
	Automatic pellet boiler		Dry ESP	PM1	77	71-83	ELPI (no field tests)
				PM1	69	64-83	BLPI (no field tests)
				TSP	73	68-78	
Brunner et al., 2018	Old residential wood burning systems	Boiler and stove	ESP	TSP	83	Highest efficiencies	Field test show efficiencies similar to lab tests
				PM1	93	Highest efficiencies	Field test show efficiencies similar to lab tests
Carroll and Finnan 2017	Boiler	Wood	AL-Top old	PM1	85		
				TSP	72		
			Al-top new	PM1	86		
				TSP	72		
			Oekotube	PM1	68		
				TSP	68		
		Willow	AL-Top old	PM1	75		
				TSP	70		
			Al-top new	PM1	93		
				TSP	90		
			Oekotube	PM1	87		
				TSP	87		
		Tall Fescue	AL-Top old	PM1	51		
				TSP	10		
			Al-top new	PM1	73		
				TSP	71		
			Oekotube	PM1	36		
				TSP	34		
Poujoulat.co.uk	Stove and boiler		TOP CLEAN ESP	TSP	92		Especially PM2.5. According to manufacturer
Obernberger et al., 2012	Pellet boiler			PM1	92		Approximate value from chart
				TSP	92		Approximate value from chart
	Modern boiler			PM1	82		Approximate value from chart
				TSP	77		Approximate value from chart
	Old boiler			PM1	71		Approximate value from chart
				TSP	68		Approximate value from chart
Miljøprojekt no. 1705	Boiler		Oekotube	PM	89		
			Oekotube+sug	PM	54.6		
			Oekotube+luft+sug	PM	86.2		
			Ruff-KAT	PM	36.8		
			Ruff-KAT+sug	PM	14.1		
			Ruff-KAT+luft+sug	PM	66.8		
			APP R-ESP	PM	78.6		
			APP R-ESP+sug	PM	92.8		
			APP R-ESP+luft+sug	PM	82.2		
	Teknologisk Institut citat		ESP	PM	90		
Sanders Smoke Clean	Sotve and boiler		Sanders Smoke Clean	PM0.1	0		In the ignition phase (0-10 min.) The filter almost doubled the ultrafine particle emission, whereas

							it reduced the particle emission around 85 percent in burning phase (10-40 min.).
				PM2.5	**87**		The newest (summer 2016) investigation by Ellen Marie Drastrup from DTU Environment as part of her master thesis at the Technical University of Denmark shows, that some filters (developed by Tonny Sander Holm and PHX Innovation) have high (85-99%) removal rates for soot particles, fine particles and ultrafine particles.
EU commission	Small combustion facilities for solid fuels		ESP	TSP	**73**	57-81	Assumption for field (unclear if mass or number)
					70		Assumption for field (unclear if mass or number)
Bologa et al., 2010	Multi-fuel boiler	Mixed pellets	ESP	PM	**77**	76-78	
	Multi-fuel boiler	Wood pellets	ESP	PM	**81**	72-89	
	Pellet boiler	Wood pellets	ESP	PM	**82**	80-84	

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EMISSION SCENARIOS AND AIR QUALITY MODELLING FOR RESIDENTIAL WOOD COMBUSTION

Impact analysis of measures for small wood burning appliances in Denmark and effect on transport of black carbon to the Arctic

In this project, the emission impacts for particulate matter (TSP, PM_{10} and $PM_{2.5}$) and black carbon (BC) of three scenarios for residential wood combustion have been estimated and the impacts of the concentrations of BC have been modelled over Denmark and the Arctic using the Danish Eulerian Hemispheric Model (DEHM). Additionally, the modelled concentrations have been compared to the measurement results. The overall greenhouse gas effect of residential wood burning in Denmark has been estimated considering the pollutants where the IPCC Fifth Assessment Report provides global warming potentials (CH_4, N_2O, NO_x, VOC and BC). The basic scenario have been compared to three scenarios which includes banning older wood stoves in areas with district heating, installing particle filters on stoves and boilers not being ecolabelled and requiring older stoves to be scrapped or replaced when a property is sold.

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