Evaluating the effectiveness of a stove exchange programme on $PM_{2.5}$ emission reduction

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Abstract

Residential wood combustion (RWC) is one of the most important sources of particulate matter (PM) in urban areas. As a consequence, different types of regulatory instruments are being implemented to reduce emissions. In this study, we evaluate both the potential and actual effect of a subsidy programme for stove exchange, which has been in place for over 20 years in Oslo (Norway). The subsidy programme provides economic support to the inhabitants for substituting old stoves for RWC with new and cleaner stoves as a measure to reduce PM emissions. Different approaches were selected to assess the potential effect of the Oslo subsidy programme. First, we evaluate the potential for reductions in emissions and pollution levels through the use of emission and dispersion modelling under different scenarios. We then assess the actual reductions associated with the stoves already replaced with the subsidy. We conclude the study by evaluating the time variation (2005 to 2018) in emissions, wood consumption and emission factors in Oslo in comparison with other municipalities with and without subsidy programmes in place. Results from emission and dispersion modelling show that the replacement of old wood stoves for new ones could have a significant effect on the reduction of emissions (up to 46%) and $PM_{2.5}$ levels (up to 21%). Despite that, with near 8% of the total existing stoves in Oslo being exchanged with subsidy, the potential for reduction based on improved emission factors was estimated to be smaller by an order of magnitude. We find no evidence that municipalities with subsidy reduce emissions faster than those without subsidy. We therefore conclude that there is no evidence from our modelling results, supported by available observation data, that indicate that the emissions or concentrations in Oslo have been reduced as a result of the subsidy programme.

Keywords: Air Quality, MetVed Emissions, Stove Exchange Subsidy, Residential Wood Combustion, $PM_{2.5}$ emissions,

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1. Introduction

RWC is an extensive heating source in Nordic countries, and these countries are concerned about local PM levels, especially $PM_{2.5}$ in winter. Emissions from residential heating in

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the Nordic area (except in Island) are dominated by RWC, which is responsible for 50 to 80% of the $PM_{2.5}$ levels (1, 2, 3). Apart from the Nordic area, the use of wood for heating is also increasing in the rest of Europe and also North America, mostly driven by government incentives, the rising cost of other energy sources and the public perception that RWC is a green energy source (4, 5). In Portugal, RWC has been reported to contribute 18% to PM_{10} levels (6). In Austria during winter months, wood smoke was found to be responsible for around 10% of the PM_{10} levels around Vienna, and around 20% in rural areas. Different studies have published compilations of studies on RWC contributions to ambient PM concentrations in Australia and New Zealand (77-95% estimated contribution), USA and Canada (10-80% estimated contribution) and Europe (10-81% estimated contribution), and the health effects of biomass burning in the developed world (5, 7).

Among the various compounds emitted by RWC, special attention is given to $PM_{2.5}$, which is regulated and extensively measured. The importance of RWC as a contributing source to PM levels in urban areas underscores the need for legislation and the designing of effective mitigation measures to reduce PM levels. As RWC is considered carbon neutral and tied to culture and tradition, most efforts to reduce emissions have focused on reducing them through efficiency and cleaner technologies rather than on banning or reducing the overall RWC. Existing legislation to reduce RWC emissions in the Nordic countries have been reviewed by (8). Denmark, Norway and Sweden introduced emission standards for solid fuel stoves and boilers in the late 1980s or early 1990s, whereas Finland has no emission requirements. In addition, the Nordic Council of Ministers established in 1989 the Nordic Swan program to promote a sustainable environment through informing consumers on the quality of the acquired products and services. The Nordic Swan is a voluntary eco-labelling system that evaluates the impact of a product on the environment throughout its life cycle. A stove with a Nordic eco-label must achieve a high efficiency standard and low emissions. Thus, the emission limits values established for Nordic eco-labelled stoves by the Nordic Swan program are set at 2 $g\ kg^{-1}$, 100 $mg\ m^{-3}$ and 1 250 $mg\ m^{-3}$, for PM, OGC (organic gaseous compounds) and CO, respectively, which are more stringent than those established by national legislation. For instance, the current dry fuel emission limit in Norway is 10 $g\ kg^{-1}$ for PM.

In the European Union, the Eco-design Directive (9) will come into force on January 1st, 2022. This Directive includes requirements for energy efficiency, emission limits for various compounds and product information. Regarding $PM_{2.5}$ emissions, the Directive establishes specific requirements for emissions by closed solid fuel space heaters stoves at 2.4 and 5 $g\ kg^{-1}$ (dry biomass matter), depending on the employed method for measuring emissions. The Directive includes, in addition, emission requirements for OGC, carbon monoxide (CO) and nitrogen oxides (NO_X). (8) also summarises other policy measures at local levels implemented through instruments such as information, outreach and guidelines towards consumers. The authors noted that these measures have a low impact on regional emission reductions. Subsidies, on the other hand, may have accelerated changes in local municipalities, but the overall impact in comparison with municipalities without subsidies has not been studied (8). In Norway, some municipalities have subsidy programmes to promote the replacement of old stoves for new, clean-burning appliances. The main aim of the schemes is to reduce emissions and, subsequently, PM levels in urban areas. In the ongoing subsidy programme in Oslo Municipality, residents can apply for economic support to replace old stoves produced before 1998 for newer stoves. This measure has been in place since 1998 and there is a need to evaluate its potential effectiveness. To our knowledge, the overall impact of implementing subsidies to reduce emissions from RWC has not been evaluated based on the assessment of emission changes over time after a long term implementation of such policy measures.

Several studies report on the emissions from RWC from the point of view of the wood burning stove technologies and user behaviour (6, 10, 11). However, few studies report on the effectiveness of subsidy programmes to exchange stoves. A study of a small wood stove exchange in British Columbia found no consistent relationship between the technology upgrades and the outdoor or indoor $PM_{2.5}$ concentration (12). Whereas, (13) established that the contribution to ambient $PM_{2.5}$ from RWC decreased by a factor of four after the implementation of a wood stove exchange programme, the authors also stated that additional analysis considering other winter seasons is needed to verify it. The level of implementation is one of the determining factors, as a 98% substitution of old stove for new installations was reported to reduce winter ambient $PM_{2.5}$ levels by 27% and a reduction in the reporting of bronchitis, cold, throat infection and influenza among children (14). The evaluation of the impact of a full conversion from traditional fireplaces to certified or improved wood stoves has been reported to be feasible measure to reduce PM_{10} levels in winter (6) and significantly associated with improvement in human health (15).

The aim of our study is to assess the impact that the existing subsidy programme has had on $PM_{2.5}$ emissions and potential reduction of pollution levels in Oslo. he results from our study are highly relevant for designing action plans to reduce emissions from RWC to improve air quality and also to reduce emissions of short lived climate forces (SLCF), such as black carbon. RWC is one of the most important sources of black carbon (16); therefore, reducing RWC emissions would have an additional benefit in mitigating climate change. The Environmental Agency in Norway developed an action plan for Norwegian emissions of SLCF in 2013 (17). This action plan includes 14 measures, and among them is the accelerated introduction of new stoves and pellet burners through financial support combined with information and outreach. This measure was evaluated, based on expected emission reduction, as highly cost effective (i.e., -1 433 $NOK\ t^{-1}$), with a moderate effect on climate change (i.e., 300 kt annual reduction of CO_2eq) and a high positive health effect (i.e., 808 $NOK\ y^{-1}$).

The study has been addressed through three different approaches; 1) we perform emission and dispersion modelling to assess hypothetical scenarios of introduction of new stoves technologies; 2) we estimate the emission reduction associated with the stoves that actually have been replaced with subsidy support since 1998; and 3) we evaluate emissions, wood consumption and emission factors trends from 2005 to 2018 in Norwegian municipalities with and without subsidy. Together, these three methods, supported by findings from observation data, allow us to investigate different aspects of the subsidy programme' success in reducing emissions.

2. Methodology

In this section, we first describe the subsidy programme in Oslo (Subsection 2.1) followed by the description of the data sources used in our study (Subsection 2.2). The potential reductions in emissions and $PM_{2.5}$ levels was evaluated by emission and dispersion modelling under different scenarios of wood stove implementation for the year 2015 (Subsection 2.3). The method used to assess the actual emission reduction associated with the stoves already exchanged with subsidy since 1998 is described in Subsection 2.4. This section concludes with a description of the comparison between Oslo and other Norwegian municipalities with and without subsidy programme (Subsection 2.5).

2.1. The subsidy programme for stove exchange in Oslo Municipality

RWC as a heating source is widespread in Oslo. There are approximately 136 000 RWC registered installations and in 2017 the wood consumption for residential heating reached 39.5 kt, higher than in the previous five years. To reduce emissions from RWC and improve urban air quality, Oslo Municipality has had a subsidy programme to promote the replacement of old stoves produced before 1998 with new ones, and so to increase the share of clean burning appliances. The subsidy programme was implemented in 1998, at the same time is setting emission standard for wood burning stoves in Norway (18), which set the emission limit at 10 $g\ kg^{-1}$ (dry wood) and defined the official division between old stoves (produced before 1998) and new stoves (produced after 1998). Since 1998, Oslo residents have been able to apply for economic support to replace old stoves. Those residents living in central areas of the city are granted around 307 €, whereas residents from areas within the outermost road ring receive 154 €. A typical stove sold in Norway ranges in price from about 1 500 to 2 500 €, thus the subsidy covers a considerable part of the cost. From 1998 to 2019, over 11 000 wood stoves have been replaced in Oslo with granted support (Figure 1).

2.2. Data sources

Several of the methods used to evaluate the potential effect of the subsidy programme rely on data collection processes to establish consistent data-sets. The main data-sets and corresponding sources are described here.

- Number of stoves exchanged per year; The number of stoves exchanged with subsidy support is only available for Oslo Municipality and it was provided by the Climate Agency. The data-set contains the number of applications and the number of those which were granted per year from 1998 to May 2019 (Figure 1). In order to get an application granted, applicants need to provide graphic material (i.e., photographs) of the old stoves and a certified document regarding the installation of the new stove. For the other municipalities with subsidy, information on the number of stoves exchanged with subsidy was not available for this study.

- Wood consumption and RWC emissions at the municipality level were estimated with the MetVed model (19). The MetVed model relies on several data-sets including dwelling number and type, available residential heating technology, location of RWC pipes and wood consumption (for more detail see (19)). Yearly wood consumption and emissions were estimated for several municipalities for the period from 2005 to 2018, the period for which there is relatively consistent data on wood consumption per RWC technology at the county level available from Statistics Norway (20).

- Averaged emission factors; The annual emission factors per municipality are obtained based on emissions and wood consumption per year at each municipality between 2005 and 2018.
- Heating Degree Day (HDD); it is estimated based on average daily temperature from meteorological stations in Norwegian counties. The data is retrieved from the Norwegian Meteorological Institute (21) for the period from 2005 to 2018. The HDD is defined as each degree that the average daily temperature is below a threshold temperature, and in this study, we used 15 °C.
- Population; Yearly population data from 2009 to 2018 was obtained from the City of Oslo Planning and Building Services.
- $PM_{2.5}$ observations in Oslo; annual and seasonal mean $PM_{2.5}$ values from 2010 to 2018 were retrieved from monitoring stations in Oslo. PM levels are measured by continuous monitors and logged with a time resolution of 1 hour. All monitors are equivalent reference instruments (TEOM 1400A, TEOM1405DF-FDMS and Grimm-EDM180).

2.3. Modelling the potential reduction in emission and $PM_{2.5}$ levels

2.3.1. Scenarios

Emission and dispersion modelling was carried out for 4 scenarios described below and simulated with 2015 meteorology. The heating degree days per year since 2005 to 2018 was evaluated along with the average temperature in order to assess whether 2015 was in any way an outlier regarding winter conditions, heating demand and, therefore, exceptional emissions from residential heating. The evaluation showed that 2015 did not have extreme temperature conditions, and therefore we could expect average heating requirements. The scenarios considered in our study are the following:

- Scenario 1; current situation in 2015 based on reported wood consumption per technology and the Norwegian emission factors used in official reporting (22). This scenario is considered as a reference.
- Scenario 2; All old stoves are substituted for new stoves produced after 1998 with Norwegian emission factors of 11.2 $g\ kg^{-1}$ for new wood stoves as used in official reporting (22).
- Scenario 3; A continuous improvement in stove technology. The introduction of stoves in the market has a linearly improved emission factor from the official 11.2 $g\ kg^{-1}$ in 1998 to today's stoves classified as eco-design with emission factor 5.5 $g\ kg^{-1}$. This

results in an average emission factor of 9.96 $g\ kg^{-1}$ for the total wood consumption reported in the year 2015.

- Scenario 4; Same as Scenario 3 but today's stoves with emissions factor of 2.2 $g\ kg^{-1}$, which is similar to the emission factors claimed by wood stove producers today. This results in an average emission factor of 7.4 $g\ kg^{-1}$ for the total wood consumption reported for the year 2015.

2.3.2. Emissions

All emissions represent 2015 and are mainly estimated based on high resolution input data, that thereafter are aggregated to a 1 km grid, and combined with time variation functions to result in emissions at 1 $km^2\ h$ resolution. We include in our study all sources that contribute to PM levels. Due to the requirement of the dispersion modelling, emissions are developed for a rectangular area including the populated area of Oslo municipality and partially surrounding municipalities.

RWC is the largest single source of $PM_{2.5}$ in Oslo (2). RWC emissions are estimated using the MetVed model that provides emissions at high spatio-temporal resolution (19). The model combines downscaling with bottom-up principles to estimate wood burning potential at a 250 m grid, which are thereafter re-grid to the 1 km resolution of the atmospheric dispersion model. The MetVed emission model combines several databases that include housing number and types of dwellings with a spatial resolution of 250 meters, statistics for energy consumption in households at the municipality level and per type of dwelling, placement of fireplaces as points and the geographical position of dwellings with information on the types that they belong to, as well as the available technologies for heating. To obtain hourly RWC emissions, the MetVed model estimates hourly wood consumption through a calendar year by combining the heating degree day concept, based on outdoor temperature, with information on the time of the day and the day of the week when wood burning occurs based on consumer statistics (for more detail see (19)). The RWC emissions for the different scenarios are estimated based on the emission factors that represent each scenario as previously presented.

Exhaust emissions from road traffic were calculated for 2015 with NILU's emission model. The model calculates PM_{10} and $PM_{2.5}$ emissions for each road link. The emission calculations use detailed emission factors based on HBEFA v.3.3 (Handbook of Emission Factors for Road Transport) (23). The HBEFA emission factors are defined for different speeds and driving patterns such as traffic flow, urban driving, slope percentage, etc. The same applies to fuel type, Euro technology class, engine volume and vehicle age, all of which influence emission factors for the individual vehicle classes. Road dust emissions are the dominant contribution to PM_{10} emissions and also represent a contribution to $PM_{2.5}$ levels. In order to calculate the road dust contribution, the model NORTRIP, specially developed for Nordic conditions, was used (24). NORTRIP calculates the most important parameters that influence the accumulation of road dust on the road surface and also calculates the moisture on the road surface that influences the suspension. This is done based on input data on meteorology, traffic volume and vehicle distribution, and road maintenance, among other parameters (for more details see (24)). The PM_{10} and $PM_{2.5}$ emission inventories include other sectors (e.g., off-road machinery, shipping), the contributions of which to total emissions is 4% and 2%, respectively. For more detail about these emissions see (19).

2.3.3. Dispersion Modelling

In order to evaluate to what extend substituting old stoves for new clean stoves affects PM levels, we use the air quality model EPISODE (25), an off-line Eulerian dispersion model. EPISODE uses emissions, background concentration and meteorological data as input data. $PM_{2.5}$ background concentration from CAMS (26) for 2015 is used to estimate the contribution from outside the model domain. Meteorological data such as wind speed, wind direction and atmospheric stability from AROME (27) for 2015 was used on 1x1 km^2 resolution.

2.4. Emission reduction from the stoves exchanged with subsidy

From 1998 to May 2019, over 11 000 stoves are reported to be exchanged with granted support 1. We have analysed the emission reduction associated only with these exchanged 11 000 stoves to isolate the effect of the subsidy programme. This assessment is carried out for the three emission factors for new stoves considered in this study and shown in Fig. 1:

- Norwegian emission factors for new stoves used in official reporting (22) and that correspond to emissions factors used in Scenarios 1 and 2;
- Emission factor that represents a continuous introduction of new wood stoves to today with eco-design wood stoves with an emission factor of 5.5 $g\ kg^{-1}$, corresponding to emission factors used in Scenario 3;
- Emissions factor that represent gradual introduction of new wood stoves to today's emission factor of 2.2 $g\ kg^{-1}$, corresponding to emission factors used in Scenario 4;

Whilst in the scenario analysis we assess the potential effect of a complete exchange of wood stove for new ones (Scenario 2) or a continuous introduction of new stoves (Scenario 3 and 4) in emission and pollution levels for the year 2015, in this analysis, we modelled the potentially achieved emission reduction over time by the exchanged stoves with subsidy for the given set of emission factor assumptions.

All the analysis in our study are done under the constraint that exchanging a stove does not affect the wood consumed in that stove. This constraint is not necessarily realistic. Consumption in a new stove may be different from the consumption in the old stove that it replaces. On average, a new stove produces somewhat more heat per kg wood (acts to reduce consumption). Oppositely, it may also increase consumption, as a new stove will be a more practical and better heat source, and subsequently will be used more frequently ("rebound effect"). In addition, it is possible that some of the stoves exchanged through the programme are stoves that would have been exchanged anyway. As it is not possible to evaluate the annual number of stoves installed within geographical areas outside of the exchange programme, we support our study with the analysis of trends in wood consumption, which are since 2005 differentiated for new and old stoves. And we compare the trends in areas with and without subsidy programmes for stove exchange (Subsection 2.5).

2.5. Time variation of emissions and wood consumption in municipalities with and without subsidy

We have evaluated to what degree the subsidy has contributed to lower RWC emissions over time based on the assessment of the time evolution of emissions, wood consumption and emission factors at municipality level. For this purpose, consistent data are available from 2005 to 2018 from different municipalities, thus Oslo is compared with other municipalities with and without subsidy. We found 9 municipalities with similar subsidy programmes although none of them has been running over 20 years as in Oslo. The subsidies range from a payout of 300 to 500 €after the stove is exchanged, thus requiring a replacement stove. We selected 7 comparable municipalities without any subsidy programme based on population numbers and geography. The municipalities with subsidy are: Oslo, Lillehammer, Bergen, Bærum, Stavanger, Kristiansand, Moss, Skien and Løten, while the selected municipalities for comparison without any subsidy programme are: Drammen, Trondheim, Sarpsborg, Lørenskog, Bodø and Steinkjer.

3. Results and Discussion

3.1. Observations of $PM_{2.5}$ concentrations in Oslo

Previous to the modelling exercises and the comparative assessment among municipalities, we evaluate ambient $PM_{2.5}$ levels in Oslo based on observation. The reason is that with the introduction of new stoves over time, it can be assumed that average emission factor has been gradually reduced towards what is claimed by regulation or the producers. This would entail a reduction in emission and $PM_{2.5}$ concentration that would be reflected in the observation data in Oslo. There are, however, limited observations of $PM_{2.5}$ and the only long time series of urban background concentrations is at Sofienbergparken (location shown in Fig 3 A as "Urban Background" station) from 2010 to 2018.

Traffic and RWC are the two main emission sources of $PM_{2.5}$ in Oslo (2). Exhaust particle emissions from vehicles have been significantly reduced since early 2000s due to the introduction of diesel particles filters and electric vehicles. Unlike traffic emissions, RWC emission is most intense during winter (Dec.-Feb.) and is limited to the heating season (HS), taken in this study as October through March. Therefore, it should be possible to distinguish the difference in spatial and temporal distribution of emissions from these two sources. Table 1 shows the ambient $PM_{2.5}$ change in % at six monitoring stations classified as traffic and at the one urban background station. All stations show a decrease in $PM_{2.5}$ levels in the period and for all seasons. This could be due to meteorological variability or emissions reductions. Both the urban background site and the average of the traffic sites show a lower reduction in the heating season than in the remainder of the year (non-HS). This does not seem to indicate that the decrease in concentration is due to lowering RWC emissions, which would decrease in the HS and winter season only. The reduction at the urban background location, less influenced by traffic emissions, is similar to the average from traffic locations. This could indicate that also emissions from RWC have been reduced.

Table 1: Average change in mean $PM_{2.5}$ monthly concentration in units % y^{-1} obtained from the first order regression line for seven monitoring stations in Oslo (2010-2018). Also the average of the traffic stations is shown. HS: heating season from October to March. non-HS: non heating season.

Station	Station type	Winter	HS	non-HS
Alnabru	Traffic	-4.73	-4.85	-6.63
Bygdøy Alle	Traffic	-4.46	-4.22	-3.23
Hjørtnes	Traffic	-3.07	-2.58	-1.93
Kirkeveien	Traffic	-1.46	-2.55	-4.98
Manglerud	Traffic	-3.48	-3.02	-2.54
Rv 4, Aker Sykehus	Traffic	-4.32	-5.17	-5.36
Average	Traffic	-3.59	-3.73	-4.11
Sofienbergparken	Background	-3.71	-3.57	-4.38

3.2. Modelled potential reductions in $PM_{2.5}$ emissions and pollution levels

Fig. 2 shows modelled RWC emissions in Oslo municipality for the 4 scenarios modelled in our study. The highest $PM_{2.5}$ total emissions from RWC in 2015 are the 384 tonnes of the reference Scenario 1. The highest emission rates are observed in the area with high dwelling density and a high proportion of wood burning stoves. The highest emission per dwelling occurs in areas with detached houses and semi-detached houses, but these areas are generally less densely populated.

In a situation where all wood stoves are replaced by new clean-burning installations (Scenario 2), $PM_{2.5}$ emissions are reduced by 17.9% ($PM_{2.5}$ emissions: 315 tonnes; Fig. 2). The highest emission reductions are within Ring 2. In this area, there is high dwelling density with a high proportion of wood burning installations. In scenarios 3 and 4, where there is continuous improvement from 11.6 g/kg in 1998 to today's wood-burning stoves with emission factor 5.5 $g\ kg^{-1}$ or 2.2 $g\ kg^{-1}$, respectively, even larger emission reductions are obtained. In scenario 3, the emission reduction is 29% (273 tonnes of $PM_{2.5}$) relative to the reference, and in scenario 4, the reduction amounts to 46.5% (205 tonnes of $PM_{2.5}$). This large difference in emissions between the scenarios highlights the importance of the difference in emission factor between the exchanged stoves.

$PM_{2.5}$ levels in Oslo were modelled for all scenarios for the year 2015 and taking into account all the contributing sources. The $PM_{2.5}$ annual average concentration in Oslo obtained with scenario 1 emissions is shown in Fig. 3 A. In central Oslo and at the city suburbs is where the highest concentrations are modelled at levels above WHO guidelines of 10 $\mu g\ m^{-3}$, but within the regulated limits of 15 $\mu g\ m^{-3}$. The high concentrations around central Oslo is a good reason for the double payout of the replacement scheme for installations in this area, as residents living within Ring 2 receive 307 €versus 154 €for those outside.

The relative changes in concentration from the baseline are shown for scenarios 2-4 in Fig. 3 B-D, respectively. In scenario 2, the complete introduction of new wood stoves would result in a reduction of $PM_{2.5}$ levels on average of 3%, with levels up to 8% (Fig. 3) in central Oslo, resulting in a total reduction of 0.2 and 0.8 $\mu g\ m^{-3}$ in $PM_{2.5}$. The obtained reduction is the largest where the concentration is the highest, showing the relevance of reducing RWC emissions. The more optimistic emission factors in scenarios 3 and 4 have the same spatial reduction pattern but are stronger in magnitude. Scenario 3 has average concentration reductions of 5.4% and up to 12.9% in central Oslo, whereas the same numbers for Scenario 4 are 8.9% and 21.1% for average and central reductions, respectively (Fig. 3 C and D).

There are no accurate data on the age of all the individual installations in Oslo, neither of the exact number of old and new stoves nor their spatial distribution. However, wood consumption data is available per type of technology. The fraction of consumed wood in new installations was 50% of the total wood consumption in 2015. This suggests that there are more new ovens than the $\sim$ 8% of stoves exchanged since 1998 through 2015. The reduction in concentrations could be feasible, but it would only be in part due to the subsidy programme. The high contribution of RWC to annual average reductions in $PM_{2.5}$ levels in central Oslo found in the scenarios shows that the subsidy programme targets well the areas where reductions is intended. Therefore, the scheme overall shows a vast potential for further reduction if all old installations are replaced. However, this depends on the assumption that wood consumption does not change. New stoves are reported to be more efficient, and therefore will reduce wood consumption. At the same time, rebound effects are common, so inhabitants may shift from a old stove to a new one that they use more frequently. This would result in an increase in total wood consumption.

Modelled $PM_{2.5}$ levels in winter 2015 have been compared with measurements for the same period. The comparison has been done for the baseline scenario representing the situation in 2015 based on Norwegian emission factors used in official reporting (Scenario 1) and for the scenarios that account for the continuous introduction of new technologies over time (Scenarios 3 and 4). With this comparison, we aim to shed light on the understanding of uncertainties in the use of emission factors. Table 2 shows the bias for the three scenarios. While the average of all considered stations indicates that the lowest bias is obtained for scenario 1, the individual stations seem to show lower bias for scenario 3. The average is driven by Alnabru and RV4. Aker sykehus stations, which show a significantly higher bias than for the rest of the stations. Comparing results from the same model used here with observations (19) also established the need to evaluate the official emission factors used in Norway, as well as the possibility of considering emissions factors that evolve over time based on the introduction of new technologies. This was mainly based on $PM_{2.5}$, where the coupled emission and dispersion model overestimates daily $PM_{2.5}$ concentrations in winter when compared with observations. Similarly, (28) evaluated organic carbon emissions from RWC in Europe and established that while emissions are underestimated in most of Europe, in Norway emissions are overestimated. The results obtained in our study support the need for establishing emission factors for Norway that better represent real-world emissions and also represent the technological improvement over time.

3.3. Emission reduction from the stove exchanged with subsidy

The total number of stoves that have been exchanged through the subsidy programme in Oslo municipality is shown in Fig. 1. The number of stoves sums up to $\sim$ 11 000 stoves,

Table 2: Observed (Obs) and modelled (Mod) winter means (November to March) of daily $PM_{2.5}$ concentrations in 2015 in scenarios 1, 3 and 4 and the bias. Subscripts indicate the scenario. Units: $\mu g/m^3$. Bias is represented in % as (Obs-Mod)/Mod.

Station	Obs	Mod_1	Mod_3	Mod_4	$Bias_1$	$Bias_3$	$Bias_4$
Sofienberparken	9.00	9.80	8.57	7.80	-9	5	13
RV4. Aker sykehus	6.54	9.66	8.81	8.28	-48	-35	-27
Manglerud	8.28	7.81	7.16	6.75	6	14	18
Kirkeveien	8.86	10.24	9.08	8.36	-16	-2	6
Hjørtnes	8.58	9.41	8.50	7.93	-10	1	8
Bygdøy Alle	8.80	9.82	8.70	7.99	-12	1	9
Alnabru	13.9	9.49	8.81	8.38	32	37	40
Akerbergveien	8.28	8.77	7.85	7.27	-6	5	12
Average	9.03	9.38	8.44	7.85	-4	7	13

about 8% of the total registered stoves in Oslo. Based on the number of exchanged stoves in Oslo per year, assuming that old and new stoves both use 290 kg dry wood in 2015, the emission reduction obtained through the subsidy programme was calculated for the three emission factors situations and compared to a reference.

The reference case represents emissions as they would have been if the 11 000 stoves had not been exchanged. First we used the official emission factors in Norway as it was done in scenario 1 and 2 and then we calculate emissions reduction based on the cumulative sum of stoves exchanged over time. The dashed blue line in Fig. 4 A shows the emission factor of the new stoves, and the solid blue line shows the total emission reduction obtained in each year. We use the same approach but then, the applied emission factor for the new stoves that improve over time as in scenario 3 and 4, i.e., a continuous introduction of new technologies until today's emission factors of 5.5 and 2.2 $g\ kg^{-1}$, orange and yellow dashed lines in 4 A, respectively.

The total emission reduction achieved each year from the substituted stoves increases over time from about 3-5 t in 2005 to approximately 10-22 t in 2018, depending on the considered emission factor. When using constant emission factor for new stoves (dashed blue line in 4 A), there is a direct connection between the total number of exchanged stoves and the emission reduction. When continuous improvement of new stoves over time are assumed, emission reductions show an increasing effect of the subsidy programme over time. This is a consequence of assuming that the stoves that are replaced late in the period provide a greater reduction than those that were replaced at the beginning. The total $PM_{2.5}$ emission reductions achieved in 2018 is between 10 and 22 tonnes for the three emission factors situations (Fig. 4), which represents between 2% and 4.4% of the total 501 tonnes of $PM_{2.5}$ emitted in 2015.

The emission reduction shown in this evaluation depends on the assumptions made. We assume that the stoves exchanged with subsidy would have not been replaced otherwise, and that consumption does not change. On the one hand, the potential for emission reduction will increase if the replaced wood stove is used more actively than the average stove. Similarly, the heating effectiveness increases with newer stoves, meaning that it will require less wood fuel for the same amount of heat output. On the other hand, it is possible that wood consumption increases by acquiring a new stove.

3.4. Emissions trends at Municipality level

The changes in emissions of $PM_{2.5}$ from RWC in Norwegian municipalities with and without subsidy programmes for exchanging wood stoves for new clean-burning stoves was evaluated. This evaluation aims to establish the potential systematic changes among municipalities with and without subsidy programmes. Emissions from 2005 to 2018 were compared and the results are shown in Fig. 5.

All municipalities have a negative trend in emissions in the period 2005-2018. The largest absolute reduction can be found for the municipalities with the highest population (i.e., Trondheim, Oslo, Bergen, Stavanger, Kristiansand). The annual percentage change of $PM_{2.5}$ emissions relative to 2005 shows a small difference between the municipalities. The average emission reduction is below 5% per year in all municipalities. The lowest average reduction, estimated to be 1.7% per year, is found in Oslo, whereas the highest reduction is observed in Trondheim and Steinkjer (4.6%), which do not have a subsidy programme. It is noteworthy to highlight that there is no systematic difference among municipalities with and without subsidy.

In order to understand and further assess the potential influence of the subsidy programme on emission reductions, we have evaluated changes in total wood consumption and emission factors over time. This will support the understanding of the most important underlying reasons for the changes for each municipality. Fig. 6 shows the annual average change in wood consumption (orange bars) estimated based on the linear regression line obtained from wood consumption from 2005 to 2018 for each municipality (A) and the relative consumption change relative to 2005 consumption (B). Every municipality shows an annual reduction in total wood consumption, and there is no systematic difference between municipalities with and without subsidy. The lowest relative wood consumption reduction (Fig. 6B) is estimated to be in Oslo at 1% per year, whereas the strongest reduction is in Trondheim and Steinkjer municipalities at 4.3% per year.

Changes in wood consumption over time could be affected by various factors. For instance, heating demand, and therefore wood stove use, could be affected by temperature and winter conditions. Another factor that can affect changes in wood consumption at the municipality level over time is changes in population. In Oslo, for instance, population increased by 18.2% from 2009 to 2019. Therefore, we have evaluated wood consumption trends at the selected municipalities adjusting for trends in winter conditions and population.

Fig. 6 shows the changes in wood consumption (blue bars) adjusted for total annual heating degree day and population at each municipality between 2009 and 2018. Municipal population data is only available from 2009 and that is the reason for a shorter time series in this analysis. The results show a stronger reduction in wood consumption for most of the municipalities except Kristiansand, Bergen and Steinkjer, which have a weaker reduction. For most of the municipalities, winter conditions each year and changes in population have on average increased total wood consumption. The strongest adjusted reduction in wood consumption is again found for Trondheim, whereas Oslo still shows one of the lowest reductions (2.8% relative to 2009). This evaluation shows that Oslo municipality has one of the slowest reductions in wood consumption over time compared to other municipalities, both with and without incentives to reduce emissions. The annual reduction is one of the lowest even after the effects of winter conditions and population increase are adjusted for.

We associate the low reduction in consumption in Oslo with several factors. The exchanged old stoves in Oslo can be those that are rarely or never used, and which are substituted for new ones that are used more frequently. Another reason could be that there is a shift from other heating technologies to wood burning in new stoves. These reasons can be supported by existing data at Oslo municipality on wood consumption per technology (i.e., open fireplace, stoves produced before 1998 and stoves produced after 1998) from 2005 to 2018. Wood consumption in open fireplaces is relatively constant and is reduced in stoves produced before 1998. However, wood consumption in new stoves has increased even though these are claimed to be more efficient, therefore requiring less fuel. For instance in 2017 and 2018, wood consumption in old stoves was 6.2 kt and 10.2 kt, whereas consumption in new stoves was 29.2 kt and 16.5 kt, respectively. These values represent a decrease of about 72% (2017) and 53% (2018) in wood consumption in old stoves regarding 2005 versus an increase of about 204% (2017) and 72% (2018) in new ones.

The implementation of programmes to exchange old stoves for new ones aims to reduce the average emission factor. We have evaluated the time variation of emission factors in the selected municipalities. The yearly emission factors were estimated based on the yearly emissions and wood consumption for each municipality. The selected municipalities in our study show a reduction in the weighted emission factors over time that range between 0.09 and 0.15 $g\ kg^{-1}\ y^{-1}$. One of the strongest emission factor reductions was observed for Oslo (0.14 $g\ kg^{-1}\ y^{-1}$). Fig. 7 shows the results for Oslo municipality (orange lines), the weighted emission factor for Norway (blue lines) and the average values for the selected municipalities with (black line) and without (grey line) subsidy. In 2005, the average $PM_{2.5}$ emission factor in Oslo municipality was higher than the national emission factor, and from 2005 to 2018 the emission factor reduction in Oslo municipality is stronger (0.14 $g\ kg^{-1}\ y^{-1}$ in Fig. 7) than that at national level (0.11 $g\ kg^{-1}\ y^{-1}$ in Fig. 7). The stronger reduction of emission factor could be associated with a faster shift of old stove for new ones. However, this faster introduction of newer wood stoves could not be associated with the subsidy as the reduction of emissions factors in the municipalities with and without subsidy does not show discernible results.

Emissions from RWC depend on wood consumption per technology and the corresponding emission factor. In order to guaranty emission reductions, both wood consumption and emissions factors need to be targeted. If wood consumption increases when emissions factors are reduced, the overall effect of the measure to reduce emissions is marginal. The increase in energy consumption associated with improved energy efficiency, known as "rebound effect", has been previously documented (29) and it poses significant challenges for policy makers in designing effective measures to reduce emissions associated with users' energy consumption. Our study based on real wood consumption data and emissions at different municipalities shows that emission reductions are not as strong as previously proposed in actions plans for Norwegian emissions of SLCF (17). The results from our study would affect the conclusions regarding cost effectiveness of the accelerated introduction of new stoves to reduce SLCF.

4. Conclusions

In our study we have assessed both the potential of emissions reduction and to what extend the subsidy programme to exchange wood stoves, implemented over 20 years ago, has succeeded in reducing emissions of $PM_{2.5}$ from RWC in Oslo.

The potential effects of the introduction of new stoves was evaluated through emission and dispersion modelling for the year 2015. The different scenarios constructed represent a complete transfer to new stoves or continuous introduction over time under different assumed emission factors. $PM_{2.5}$ emissions and concentration levels were modelled to be reduced by an average 18-46% and 3-9%, respectively. In Oslo, the largest concentration reductions were modelled in the areas with the highest $PM_{2.5}$ concentrations. The range in modelled average concentration reduction shows that the benefit that the subsidy could have on reducing emissions and pollution levels is strongly dependent on emission factors. Only 3% concentration reduction was obtained with official emission factors, whereas higher reductions were modelled for new stoves emission factors resembling stove manufacturers' claims.

The number of stoves actually replaced with the subsidy through the period was just over 11 000, an estimated 8% of all stoves in Oslo. Emission reductions obtained from these stoves was calculated and showed an increased effect in reducing emissions over time that reached 3-6% reduction in 2018. This is assuming that the stoves would not otherwise be exchanged and that consumption was not affected.

Available observations of ambient $PM_{2.5}$ levels in Oslo indicate a declining trend 3-5% yr^{-1} between 2010 and 2018. During winter and the heating season, concentration reductions in the urban background station are similar to those at the traffic stations, and the reductions appear similar to the remainder of the year. This indicates that the reductions are mainly caused by the other main source, traffic, which have emissions throughout the year. Therefore it is not possible to conclude, based on observation data, whether the subsidy programme has had an significant effect in reducing $PM_{2.5}$ concentrations in Oslo.

The comparison between municipalities with and without subsidies shows no discernible difference between the two sets. However, Oslo shows a somewhat stronger reduction in emission factors compared with national values, which can point to an accelerated stove renewal. On the other hand, Oslo also shows the slowest reduction in RWC emissions and total wood consumption of all selected municipalities at 1.7% and 1% per year, respectively, which may indicate that an accelerated stove exchange leads to an increase in wood consumption.

The modelled scenarios show that the subsidy programme could be beneficial for reducing $PM_{2.5}$ concentrations in central Oslo. The potential depends on the emission factors applied, on how consumption is affected by exchanging a stove and that the stove would not otherwise be exchanged. We see no evidence that municipalities with subsidies reduce emissions faster than other municipalities. Therefore, if additional measures targeted at reducing pollution from RWC activity are needed, an option could be, for instance, regulatory or voluntary "no burn" days or measures to reduce overall consumption of wood.

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FIGURES

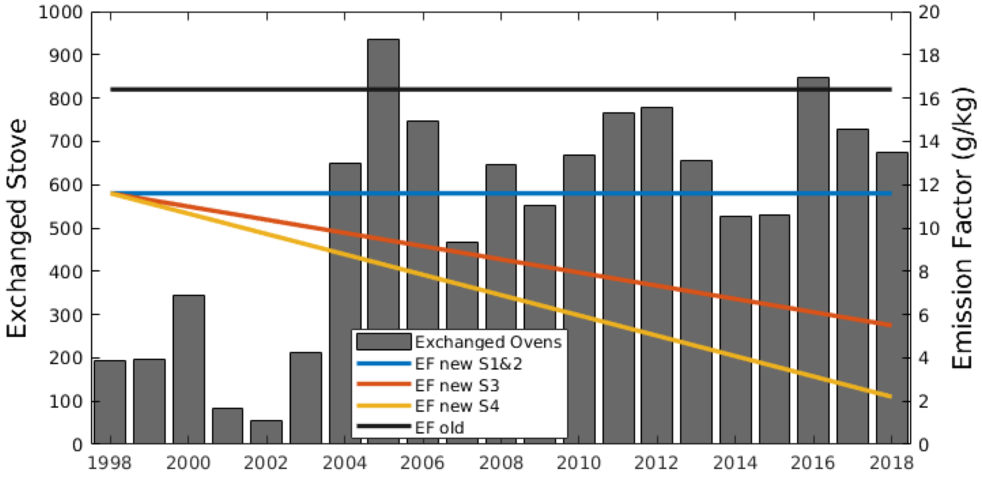


Figure 1: Number of stoves exchanged with subsidy and emissions factors considered in our study. 2005 represents the accumulated value since 1998. "EF old": emission factors for stoves produced before 1998 used for official reporting (22). "EF new S1&2": emission factors for stoves produces after 1998 used for official reporting (22). "EF new S3" and "EF new S4" refer to emissions factors for new stoves considering a continuous improvement over time until today's emission factors of 5.5 and 2.2 $g\ kg^{-1}$, respectively.

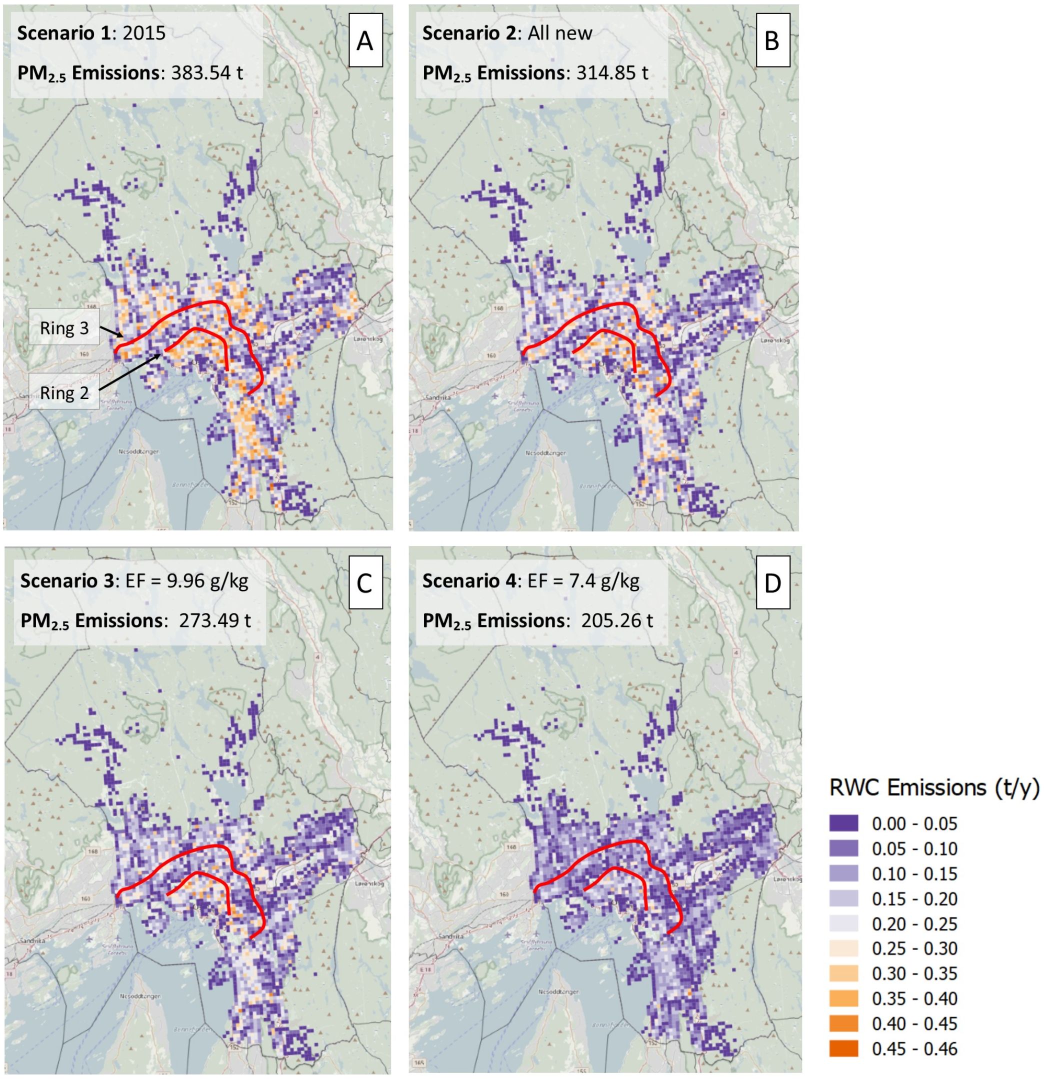
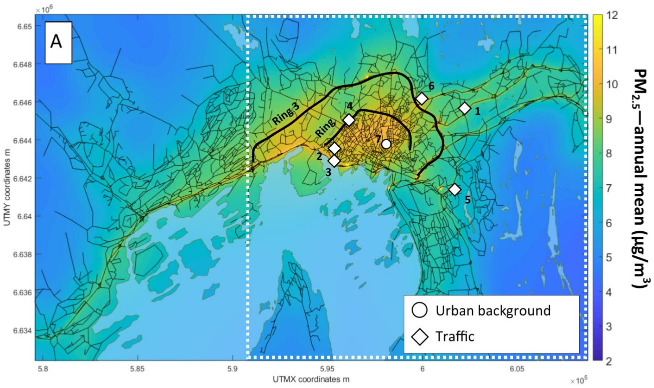


Figure 2: $PM_{2.5}$ emissions from RWC in the 4 scenarios considered in the dispersion modelling. Scenario 1: current emissions in 2015. Scenario 2: complete substitution of stoves for new ones and official emission factors in Norway. Scenario 3 and 4: continuous improvement in stove technology since 1998 to today's emission factor of 2.2 and 5.5 $g\ kg^{-1}$



#	Station Name	Winter	HS	non-HS
1	Alnabru	27.3	27.2	9.4
2	Bygdøy Alle	41.1	41.9	16.3
3	Hjortnes	34.1	34.2	12.2
4	Kirkeveien	40.6	41.3	14.9
5	Manglerud	35.1	35.4	12.8
6	Rv 4, Aker Sykehus	37.9	37.3	13.3
7	Sofienbergparken	45.9	46.2	19.4

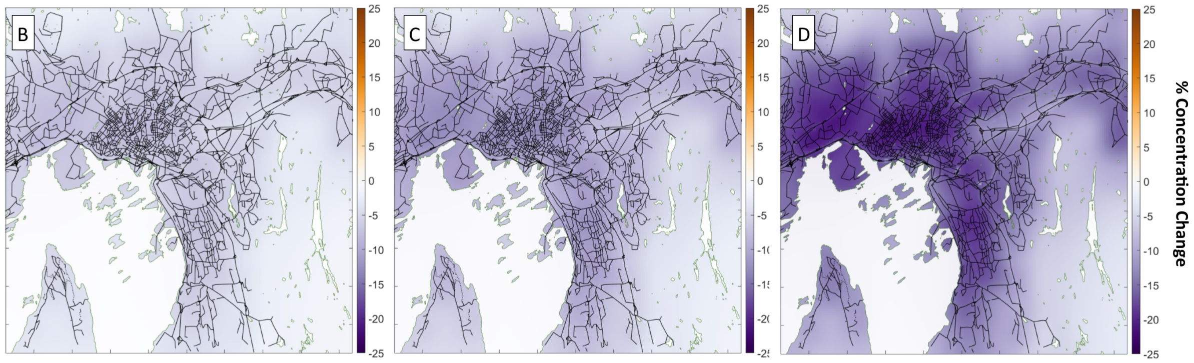


Figure 3: A: $PM_{2.5}$ annual mean values in 2015. The circle and diamonds represent the location of the monitoring stations labelled from 1 to 7. The name of the stations is shown in the table along with the modelled wood burning contribution to $PM_{2.5}$ at station receptor point in winter, heating season (HS) and non-heating season (non-HS). B, C and D represent changes in $PM_{2.5}$ pollution levels in scenario 2, 3 and 4 regarding the reference scenario 1, respectively. The dashed line square in figure A represents the areas zoomed in figures B-D.

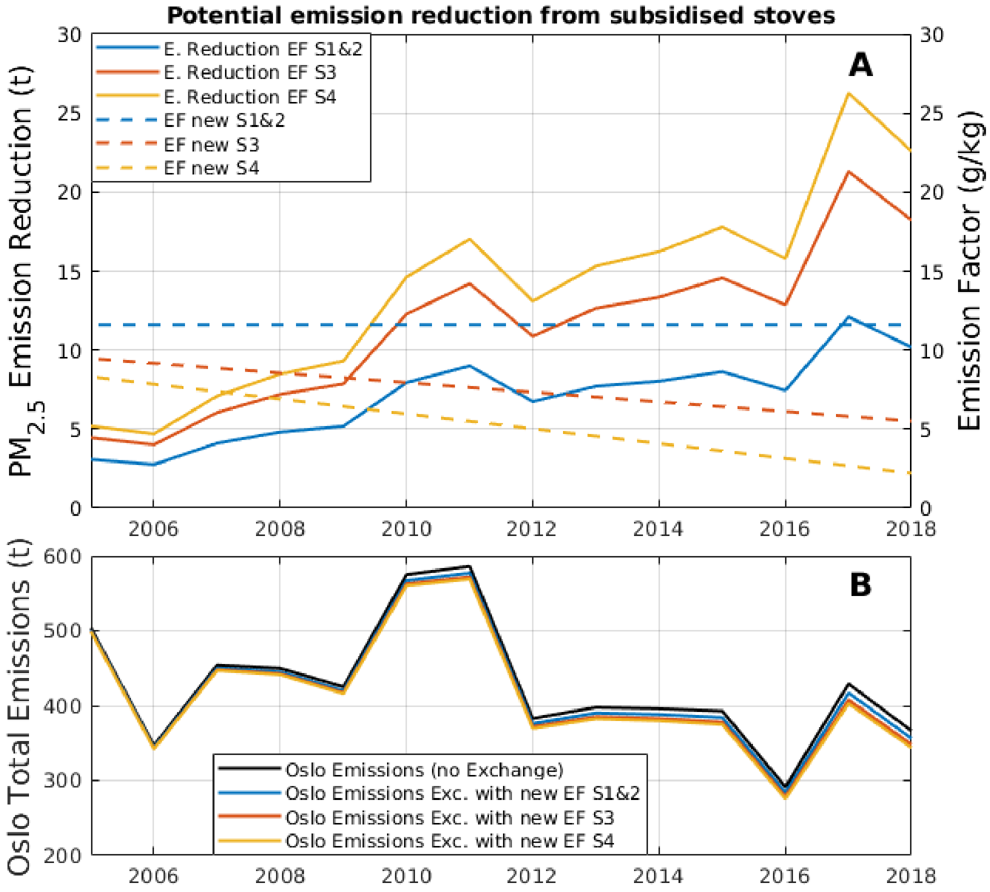


Figure 4: A: $PM_{2.5}$ emission reduction associated with the number of wood stoves replaced per year with subsidy support in Oslo Municipality (straight lines) according to three emission factors for new stoves (dashed lines). B: total $PM_{2.5}$ emissions in Oslo since 2005 to 2018 (black line) and emissions as a results of the reductions associated with the exchanged stoves with support for the 3 evaluated emission factors).

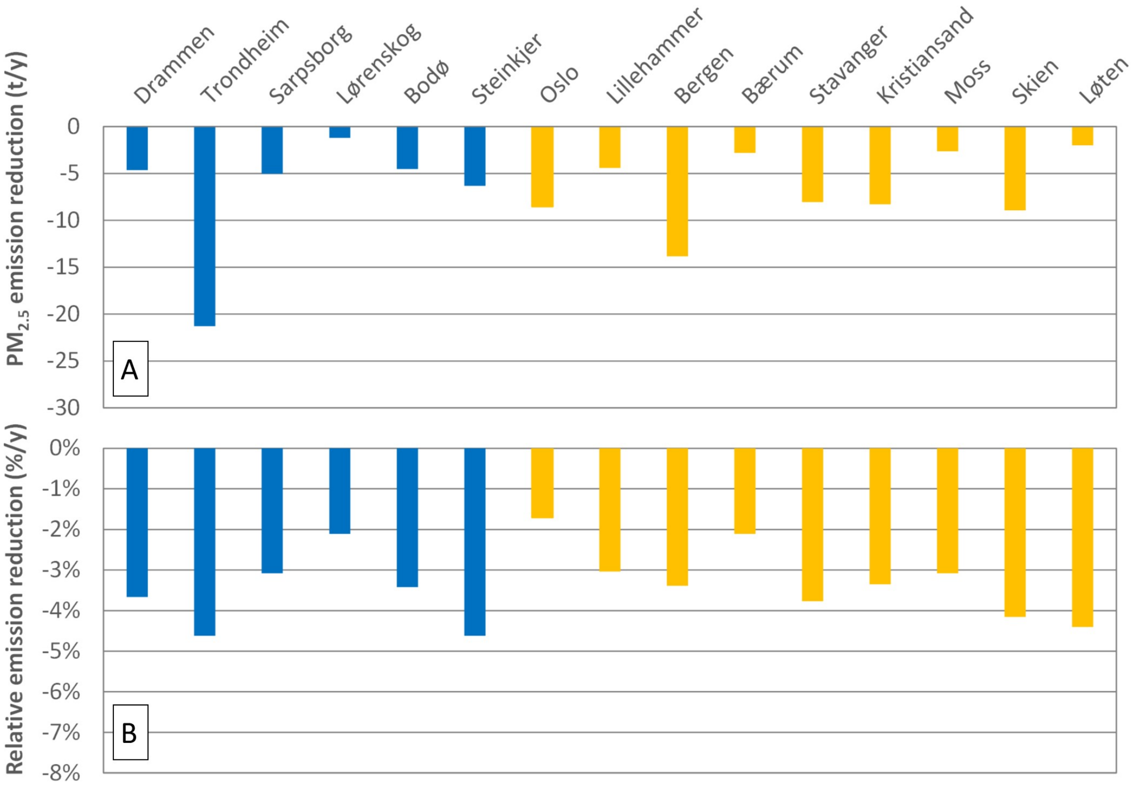


Figure 5: A: $PM_{2.5}$ emission reductions (t/y) at municipalities with (orange bars) and without (blue bars) subsidy to exchange stoves for RWC obtained from the slope of the linear regression line from emissions from 2005 to 2018. B: annual emission reduction relative to emissions in 2005.

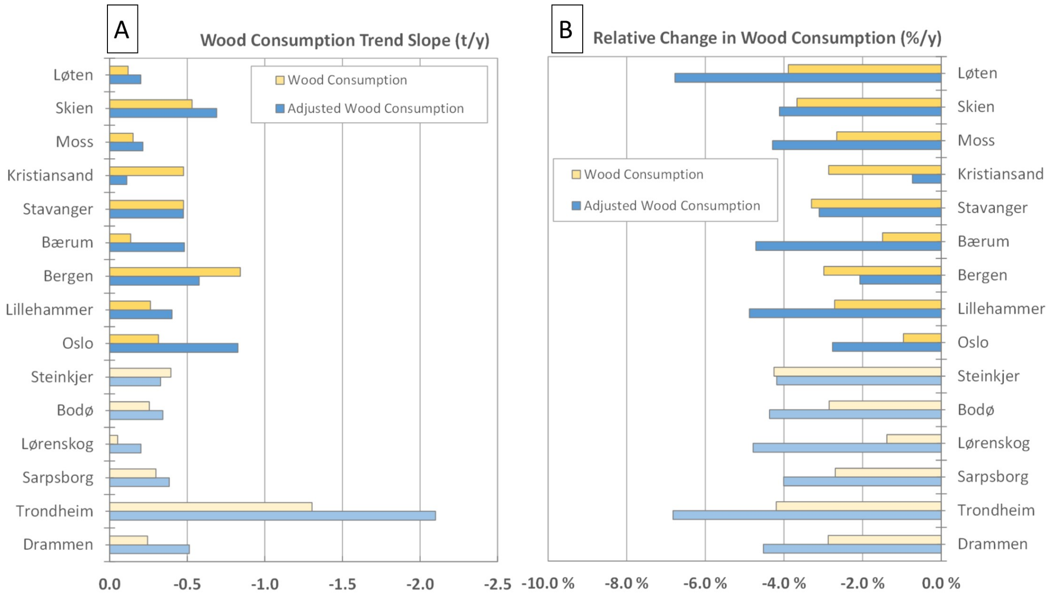


Figure 6: Changes in wood consumption ($kt\ y^{-1}$) in selected Norwegian municipalities (orange bars) obtained from the slope of the regression line from wood consumption from 2005 to 2018 (A) and the relative change in wood consumption per year relative to consumption in 2005 (B). The blue bars represent the changes in wood consumption ($kt\ y^{-1}$) (A) and the relative change regarding consumption in 2009 (B) adjusted by HDD and population at each municipality. The dark colour bars represent municipalities with subsidy, whereas the light colour bars represent those municipalities without subsidy.

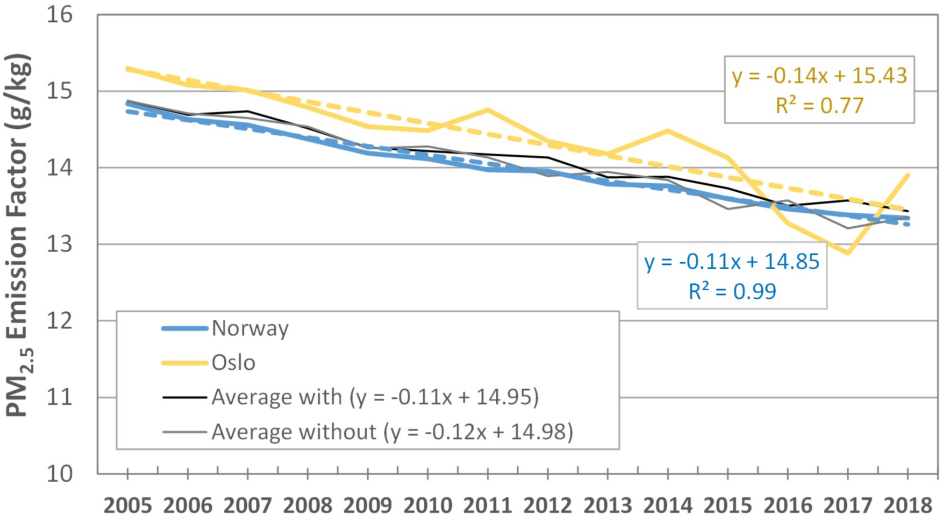


Figure 7: Time variation of the weighted $PM_{2.5}$ emission factor in Oslo Municipality (orange), Norway (blue), and the average of municipalities with (black) and without (grey) subsidy. The corresponding linear regression lines are added for Oslo (orange dashed line) and Norway (blue dashed line). The equations for the averages represent the linear regression lines.