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Model development for high-resolution emissions from residential wood combustion

Susana Lopez-Aparicio, Henrik Grythe and Matthias Vogt

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AUTHOR(S) Susana Lopez-Aparicio, Henrik Grythe and Matthias Vogt		QUALITY CONTROLLER Dag Tønnesen
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ABSTRACT

In this report, we describe the MetVed model developed to estimate emissions from residential wood combustion (RWC) at high spatial-temporal resolution. The model uses a downscaling method approach, which builds on bottom-up principles and derive a wood burning potential for each grid based on the housing type, size and heating technology, energy demand and outdoor temperature of each grid. The model builds on the combination of several databases with information at high level of detail. The databases contain geo-localised information about dwelling number and type, energy consumption statistics, fireplace and stove locations, and the available technology for residential heating. The datasets are combined and the dependencies between the different variables are analysed. MetVed includes the time variation for RWC based on the heating degree concept combined with time-variation from consumer statistics, and the vertical distribution based on the RWC shared in apartment buildings versus houses. The results from the MetVed-model have shown to improve the accuracy of dispersion modelling results when compared with predictions based on previous emission inventories.

NORWEGIAN TITLE

Utvikling av modell for høyoppløselig utslipp fra vedfyring

KEYWORDS

Air quality	Atmosphere and climate	Emission control

ABSTRACT (in Norwegian)

I denne rapporten beskriver vi MetVed-modellen. Denne modellen estimerer vedfyringsutslipp med høy oppløsning. Metved-modellen kombinerer nedskalering med bottom-up prinsipper for å estimere vedfyringspotensiale i modellgrid. Den baserer seg på boligtyper, størrelse, oppvarmingsteknologi, energibehov og utendørs temperatur. Modellen baserer seg på å kombinere flere databaser med høyt detaljert informasjon. Databasene inneholder boligtall og boligtyper med 250 meters romlig oppløsning, statistikk av energibruk i husholdninger, plassering av ildsteder som punktkilder, og geografisk posisjon av boliger med informasjon om boligtyper og tilgjengelige teknologier for oppvarming i husholdningene. Databasene blir i MetVed-modellen kombinert og forhold mellom ulike variabler analysert. MetVed-modellen inkluderer en tidsvarisjon av vedforbruket som baserer seg på oppvarmingsgradkonseptet kombinert med tidsvariasjon fra forbrukerstatistikk. Vertikalfordeling av utslippene baserer seg på vedforbruk fordelt på leiligheter og hus (enebolig, tomannsbolig og rekkehus). Resultater fra spredningsmodellberegninger viser at utslippsdata fra MetVed-modellen gir bedre samsvar med målinger enn spredningsberegninger basert på utslipp fra tidligere metoder for å estimere vedfyringsutslipp.

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Preface

This scientific report is the final report of the project MetVed "Metodeutvikling for beregning av utslipp fra vedfyring med høy romlig oppløsning" (*In English: Model development for estimating high resolution emissions from residential wood combustion*). The project is funded by the Norwegian Environment Agency, and it started in October 2017.

The MetVed-project aims at providing improved data on residential wood combustion (RWC) by developing a method to estimate national emissions based on bottom-up principles that will give more precise emission data at local level. In addition, a first approach to estimate emissions from cabin wood combustion (CWC) is presented. The aim of the project was planned to be achieved through the following secondary objectives:

- Prepare RWC emission estimate for Norway at high spatial resolution (250 x 250 m; 2016)
- Prepare high spatially resolved emissions of particulate matter (PM_{10} and $PM_{2.5}$), polycyclic aromatic hydrocarbons (PAH_{TOTAL}), carbon monoxide (CO), methane (CH_4) and black carbon (BC), components that are relevant for human health and climate change.

The work has been led by Susana López-Aparicio and carried out in close collaboration with Henrik Grythe and Matthias Vogt. Thanks to Silje Aksnes Bratland from the Norwegian Environment Agency for her support and cooperation during the project. The quality control at NILU has been carried out by Dag Tønnesen. The NILU team would like to thank the members of the reference group for their feedback, which has contributed to the final outcomes from this project. The reference group consisted of Kristin Aasestad (SSB), Bruce Rolstad Denby (Met.no), Morten Seljeskog (SINTEF), Franziska Goile (SINTEF), Vigdis Vestreng (Miljødirektoratet), Ketil Flugsrud (Miljødirektoratet) and Isabella Kasin (Miljødirektoratet).

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Sammendrag

Vedfyring er en av de viktigste oppvarmingskildene i Norden. I Norge er vedfyring den nest viktigste oppvarmingskilden etter strøm fra vannkraft. Hovedsakelig er ildstedene åpne peiser og vedovner som varmer opp små områder, og antall ildsteder i Norge er estimert til over 2.5 millioner. Utslipp fra vedfyring spiller en viktig rolle for luftkvaliteten i norske byer. Vedfyring er en av de største kildene til helseskadelige komponenter som svevestøv (PM_{10} og $PM_{2.5}$), polysykliske aromatiske hydrokarboner (PAH) og karbonmonoksid (CO) og en viktig kilde til klimapådrivere som metan (CH_4) og sot-partikler (BC). Vedfyring kan lokalt bidra med 75% av de totale $PM_{2.5}$ utslippene.

Både for beregning av luftkvalitet og for utslippsestimater som skal inngå i klimagassregnskapet, er det derfor behov for utslippsdata for vedfyring av høy kvalitet. For vurderinger av luftkvalitet på lokalt nivå, trengs det i tillegg utslippsdata med høy romlig oppløsning, samt at det er viktig å ha en god beskrivelse av hvordan utslippene varierer over tid.

De er ulike metoder til å estimere og fordele utslippet geografisk innen et område, og ulike metoder gir ulike resultater. I denne rapporten beskriver vi MetVed-modellen. Denne modellen estimerer vedfyringsutslipp med høy oppløsning. Metved-modellen kombinerer nedskalering med *bottom-up* prinsipper for å estimere vedfyringspotensiale i modellgrid. Den baserer seg på boligtyper, størrelse, oppvarmingsteknologi, energibehov og utendørs temperatur. Modellen baserer seg på å kombinere flere databaser med høyt detaljert informasjon. Databasene inneholder boligtall og boligtyper med 250 meters romlig oppløsning, statistikk av energibruk i husholdninger, plassering av ildsteder som punktkilder, og geografisk posisjon av boliger med informasjon om boligtyper og tilgjengelig teknologier for oppvarming i husholdningene. Databasene blir i MetVed-modellen kombinert og forhold mellom ulike variabler analysert. MetVed-modellen inkluderer tidsvarisjon av vedforbruk, som baserer seg på oppvarmingsgradkonseptet, kombinert med tidsvariasjon fra forbrukerstatistikk. Vertikalfordeling av utslippene baserer seg på vedforbruk fordelt på leiligheter og hus (enebolig, tomannsbolig og rekkehus). Resultater fra spredningsmodeller viser at utslippsdata fra MetVed-modellen gir bedre samsvar med målinger når vi sammenligner med spredningsresultater basert på utslipp fra tidligere metoder for å estimere vedfyringsutlipp.

Som en del av dette prosjektet er det blitt overlevert høyoppløste utslippsoversikter til Miljødirektoratet. Dette omfatter forbruk av ved, samt utslipp av komponentene PM_{10}, $PM_{2.5}$, PAH, CO, CH_4 og sot (BC) per 250m grid for 2016.

Summary

Residential Wood Combustion (RWC) is one of the most important residential heating sources in the Nordic Countries. In Norway, it is the second most important heating source after electricity produced by hydropower. RWC-installations mainly consist of small space heaters as open fireplaces and stoves, which are estimated to reach over 2.5 million installations in Norway. RWC is a significant source of air pollutants, and among the most relevant are particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), black carbon (BC), organic carbon (OC), carbon monoxide (CO), methane (CH_4) and dioxins, components relevant for air pollution, human health, and climate change. RWC constitutes a significant source of $PM_{2.5}$, and the contribution can reach values up to 75% of total emissions of $PM_{2.5}$ at local level.

The accuracy of estimated emissions is crucial as RWC has an impact on the air pollution level. Several methods exist to estimate and spatially distribute emissions from RWC. However, the different methods have shown significant discrepancies when evaluating the impact at local level. In this report, we describe the MetVed-model developed to estimate emissions from RWC at high spatial-temporal resolution. The MetVed-model uses a downscaling method approach, which builds on bottom-up principles and derive a wood burning potential for each grid based on the housing type, size and heating technology, energy demand and outdoor temperature of each grid. The model builds on the combination of several databases with information at high level of detail. The databases contain information on the dwelling number and type at 250 meters resolution, energy consumption statistics, fireplace and stove locations as point sources, and geo-localised information about dwellings, the type they belong to and the available technology for residential heating. The different datasets are combined and the dependencies between the different variables are analysed. The MetVed-model includes the time variation for RWC based on the heating degree concept combined with time variation from consumer statistics, and the vertical distribution based on the wood consumption shared in apartment buildings versus houses. The results from the MetVed-model have shown to improve the accuracy of dispersion modelling results when comparing with predictions based on previous emission inventories.

As part of this study, an emission inventory for Residential Wood Combustion (RWC) at high resolution has been delivered to the Norwegian Environment Agency. The emission inventory includes PM_{10}, $PM_{2.5}$, PAH, CO, CH_4 and black carbon (BC) at 250 metres grid resolution, along with wood consumption at the grid for 2016.

Model Development for high-resolution emissions from residential wood combustion

1 Introduction

Residential Wood Combustion (RWC) is one of the most important residential heating sources in the Nordic Countries. The reasons are that many buildings rely on heating using wood burning during winter period. This is associated with a large amount of wood easily available and a strong Nordic tradition tied to wood burning. The use of wood as fuel for residential heating is moreover increasing in Europe, which is mostly driven by government incentives, as it is considered a CO_2 neutral source of energy. Other reasons are the rising cost of other energy sources, and the public perception that wood burning is a green option (Viana et al., 2016). Even though RWC is widespread in the Nordic area, there are significant differences among the Nordic countries, especially concerning the technology. For instance, in Sweden and Denmark boilers are commonly used, whereas masonry and sauna stoves are widespread in Finland. In Norway, RWC technologies mainly consist of small space heaters as open fireplaces and stoves, conversely to boilers which are typically larger heating devices. Figure 1 shows examples of common wood burning installations used in Norway, which typically are divided among fireplaces, stoves produced before 1998 and stoves produced after 1998.

Figure 1: RWC appliances commonly used in Norway. A and B: Fireplaces. C and D: old stoves produced before 1998. E and F: new stoves produced after 1998. (Photos are from finn.no)

As emission per wood consumed differs between technologies, the intensity of emissions and spatiotemporal distribution will be different among the Nordic Countries. Figure 2 shows the $PM_{2.5}$ emissions from domestic heating in Denmark, Finland, Norway and Sweden officially reported under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP). Emissions in Denmark, Finland and Norway seems to be at similar level in the last years, whereas emissions in Sweden are much lower. The main reason behind these differences, apart from the different technologies, is the emission factors (EF) used to estimate emissions. Those used in Sweden are lower as they only account for the primary particulate matter (PM), whereas the emission factors used in Denmark, Finland and Norway account also for the condensed phase particles (ACAP 2014). Emissions from RWC in Norway are the highest and they reach values above 20 kt of $PM_{2.5}$ from 1993 to 2012 and thereafter decrease to about 15 kt. This decrease has predominantly been explained by warmer winters and therefore lower heating demand.

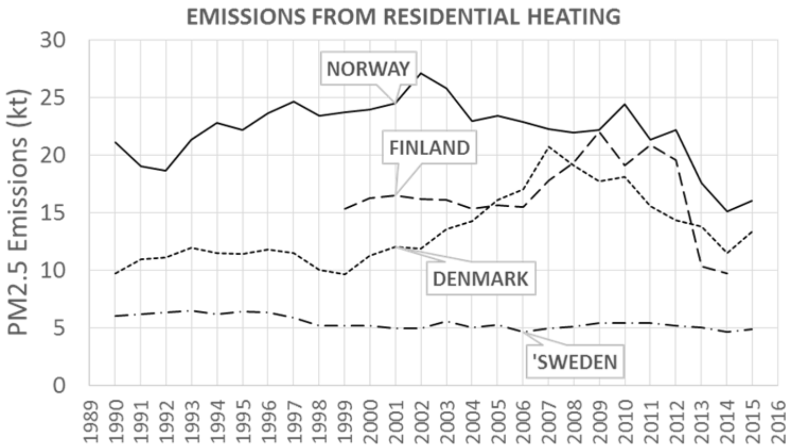

Figure 2: $PM_{2.5}$ emissions from residential heating in Nordic Countries. (Source: Emissions submitted to the CLRTAP; http://www.ceip.at/).

In Norway, RWC is the second most important heating source after electricity produced by hydropower, and it is moreover an intense activity widespread in the national territory. RWC is a significant source of air pollutants. Among the most relevant are particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), black carbon (BC), organic carbon (OC), carbon monoxide (CO), methane (CH_4) and dioxins, components relevant for air pollution, human health, and climate change. Figure 3 shows $PM_{2.5}$ emissions at national level and in Oslo area. In national reported values for 2015, the sector classified as other stationary combustion sources contributes 58% to national $PM_{2.5}$ emissions. The sector includes residential, commercial, agriculture/forestry/fishing and other stationary sources. Around 98% of these emissions are from the residential sector. Within the residential sectors, emissions are associated with the consumption of biomass (i.e. wood), liquid fuels, gaseous fuels, and solid fuels, which share is around 84%, 15.2%, 0.7% and 0.1%, respectively. Other main sources of $PM_{2.5}$ emissions are industry (20%), road transport (5%) and off road (5%). At local level, emissions show a similar contribution patterns. In Oslo for instance, RWC contribution to 82% of local $PM_{2.5}$ followed by traffic (14%), and other sources (Figure 3).

In Norway, official emissions from RWC are estimated based on multiplying the amount of wood consumed per type of technology (i.e. open fireplace, closed stove produced before

1998 and closed stove produced after 1998) and the corresponding emission factors (Norwegian Environment Agency, 2018). Since 2005, the activity data is derived from responses to questionnaires in the Statistics Norway's Travel and Holiday Survey, which are distributed quarterly. Based on this, wood consumption is aggregated, reported at county level and the associated emissions are estimated at national level on a yearly basis (Norwegian Environment Agency, 2018).

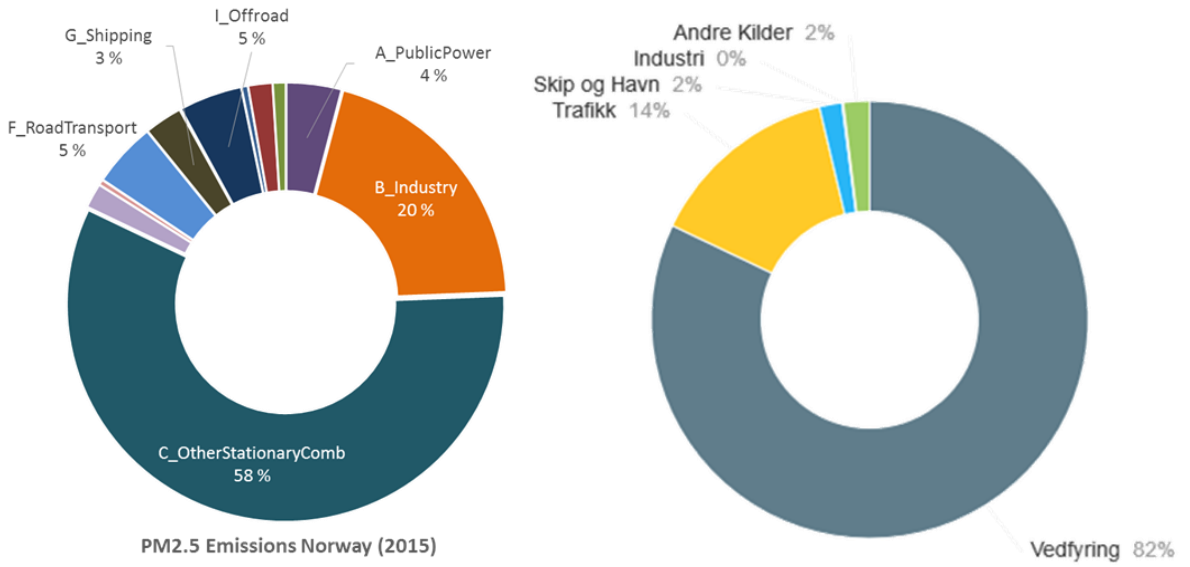

Figure 3: PM$_{2.5}$ emissions in Norway (Left; 2015; Source: http://www.ceip.at/) and in Oslo and surroundings (Right; Source: http://www.luftkvalitet-nbv.no/).

The accuracy of emissions estimates is crucial as RWC has an impact on air pollution level, and therefore on the population. Measures to reduce this impact are being designed and implemented in urban areas. Among the measures are incentive programs for upgrading or shifting from old wood burning stoves to cleaner and more efficient technologies (Levander and Bodin, 2014), banning wood burning during pollution episodes (Mena-Carrasco et al., 2012), the implementation of environmental legislation through setting emissions standards for wood stoves (Levander and Bodin, 2014), or awareness campaigns on "How to fire correctly" and cleaner technologies.

To evaluate the effectiveness of air quality measures, air quality models at local scale are commonly used as an essential tool to support decision-making processes. To produce accurate results, air quality models rely on meteorology, boundary conditions and emission inventories as input data. The quality of the latter is critical and very much relies on the method used to develop the emissions. Emission inventories are developed at local, regional and national scales, based on different methods that very much depend on the purpose, emission source intensity and input data availability. The EMEP/EEA emission inventory guidebook (EMEP/EEA, 2013) states that emissions can be estimated at different levels of uncertainty, which are expressed as three tiers of increasing complexity with decreasing uncertainty. Accordingly, tier 1 is based on statistical activity rate and default emissions factors; tier 2 uses more specific information, e.g. specific emission factors per type of process or technology; and tier 3 that involves greater level of disaggregation of activity data and emissions factors than tier 2. The selection of the tier will depend on data availability and the importance of the source. Apart from direct measurements of specific emissions, which usually are scarce and only available for large industrial point sources, emission inventories at regional and local scale are built based on two types of methods, namely “bottom-up” and “downscaling”. In both cases, emissions are estimated as the product of an activity (A) and the corresponding EF. The most significant difference is the spatial aggregation of the activity data. Figure 4 illustrates the difference between both methods. Under downscaling approaches, activity data or emissions at course resolution such as at regional or national level are distributed in space using proxies that rely on ancillary data such as population density, land cover data, dwelling number, among others. Whilst in “bottom-up” methods, the activity data is collected at a fine spatial scale (e.g., point source, road links or households) and thereafter aggregated at the required spatial resolution. Bottom-up approaches are commonly used for traffic emissions, where the activity data (e.g. traffic flow, technology vehicle composition) is collected at road link level, emissions are thereafter estimated at the same road link level and, if needed, gridded at a specific grid resolution for the air quality model. Several studies have established that bottom-up principles give more accurate emission results at urban scale than downscaling methods (e.g. Guevara et al., 2014; Lopez-Aparicio et al., 2017a).

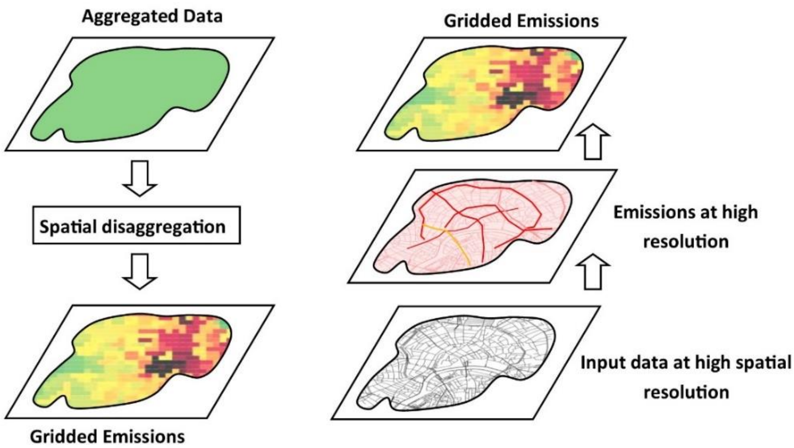

Figure 4: Outline of a downscaling method (left) and bottom-up approach (right) to prepare gridded emissions. Modified after Tuia et al., (2007).

In this report we describe the MetVed model developed to estimate emissions from RWC at high spatial-temporal resolution. The MetVed model uses a downscaling method approach, which builds on bottom-up principles and derive a wood burning potential for each grid based on the housing type, size and heating technology, energy demand of each grid and outdoor temperature. The model builds on the combination of several databases with information at high level of detail. The databases are described in detail in Section 2; Model Input Data. They consist of information about dwelling number and type at 250 meters resolution. In addition they consist of energy consumption statistics per residential energy commodity and type of dwelling at municipality level, fireplace and stoves locations as point sources for some municipalities, and geo-localised information about dwellings. Information on dwellings classify the type they belong to and the available technology for residential heating. These data are collected from a real estate market portal. The different datasets are combined and the dependencies between the different variables is analysed in order to define a wood burning potential at a 250 metres grid. The MetVed model includes the time variation for RWC based on the heating degree concept (Section 3.4 Time Variation) combined with time variation from consumer statistics, and the vertical distribution based on the wood consumption shared in apartment buildings versus houses (Section 3.3, Vertical distribution). A submodel is included in the MetVed model to estimate emissions from cabins and holidays houses (CWC) which due to the resolution of the input data is resolved at 1 km grid.

2 Model Input Data

In this section we described the datasets used as input data for the MetVed model, i.e. 1) Dwelling number, 2) Energy consumption from the Norwegian energy labelling system, 3) Fireplaces / stoves locations from the Fire and Rescue Agencies, 4) Webcrawling database, 5) Wood consumption 6) Emission Factors and 7) Outdoor temperature.

2.1 Dwelling number

The data regarding dwelling type and number gridded at 250 metres resolution is obtained from Statistics Norway (http://www.ssb.no/natur-og-miljo/geodata). The dataset consists of:

i) Number of dwelling distributed as total number ("Boliger i alt");
ii) Detached houses ("Antall boliger i eneboliger");
iii) Duplexes ("Antall boliger i tomannsboliger");
iv) Townhouses ("Antall boliger i rekkehus, kjedehus og andre småhus");
v) Number of dwellings in apartment blocks ("Antall boliger i boligblokk");
vi) Number of dwellings in sharing housings ("Antall boliger i bofellesskap");
vii) Others ("Antall boliger i andre bygningstyper").

Figure 5 shows as example the distribution and number of detached houses and apartments in the area of Tromsø. The figure shows that this urban area is characterized by a higher number of detached houses than apartments and the latter one appear to be more common in Tromsøya and around the city centrum. In addition, we include the distribution in Trondheim, which shows that apartments are more common in the city centre, where detached houses are less abundant.

In the case of cabins, the information concerning the number of cabins is obtained from the building statistics at 1 000 metre resolution (http://www.ssb.no/natur-og-miljo/geodata). In this case, the database provides the number of buildings split in 43 categories. In our study, we use the number of holiday houses, cabins or similar ("Fritidsbolig, koie, seterhus og lignende").

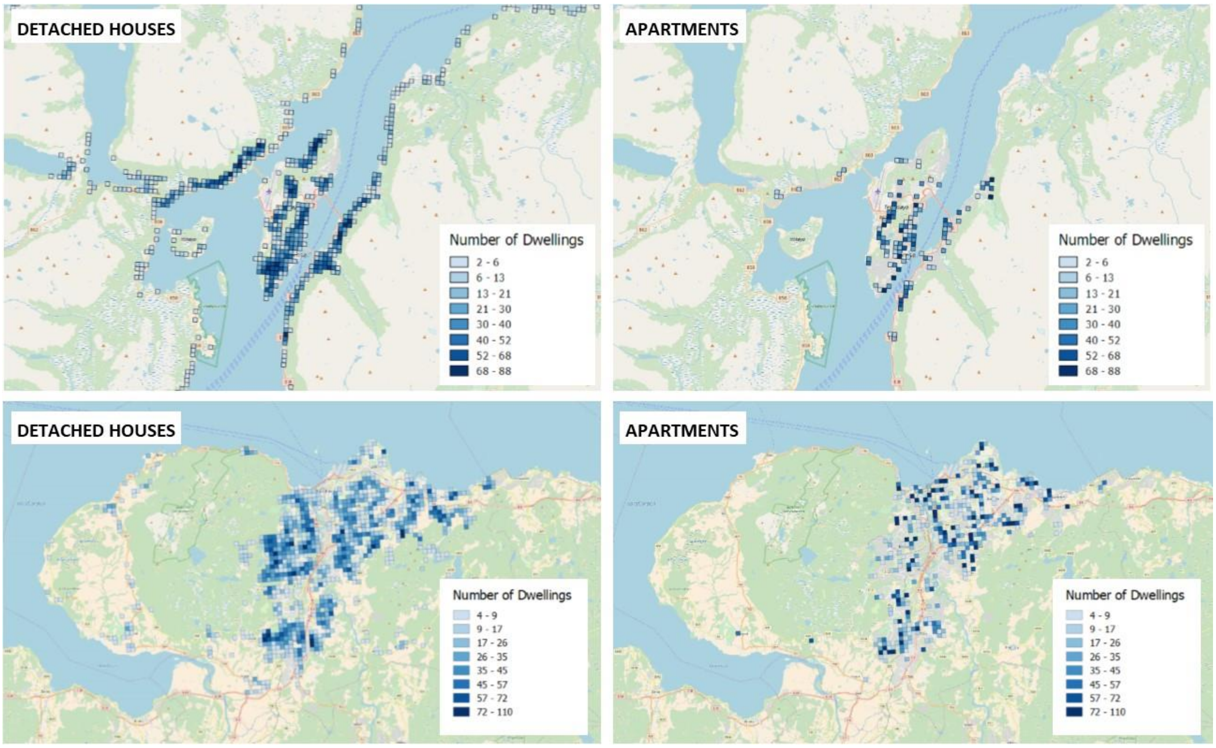

Figure 5: Distribution of detached houses and apartments at 250 meters resolution in the municipalities of Tromsø and Trondheim (Source: see the text).

2.2 Energy consumption from the Norwegian energy labelling system

Enova SF, an institution owned by the Norwegian Ministry of Petroleum and Energy, has provided a database containing information about energy consumption based on the energy labelling system for dwellings in Norway. The energy labelling system was implemented in Norway in July 2010, and it is a self-assessment report performed by owners of dwellings and buildings, or qualified experts in the case of new buildings, in connection with the sale of the property. The dataset consists of about 650 000 entries that include:

i) the size of the dwelling;
ii) building type (e.g., small house, apartment, office building, cultural building);
iii) building year;
iv) energy consumption of the dwelling (kwh);
v) primary and secondary heating appliances;
vi) energy consumption based on RWC;
vii) geographical location of the dwelling (county, municipality and post code number), among other variables.

The data is self-reported, which might include errors. This was especially observed in the self-reported geographical municipality codes, therefore we used this data at county level, which seems to show higher precision.

2.3 Fireplace / stove locations from the Fire and Rescue Agencies registry

In Norway, the Fire and Rescue Agencies at the municipalities are responsible for inspecting and assessing the burning appliances for residential heating. During this inspection, information is collected in a database by each agency at the municipality. In this study, we contacted about 270 fire and rescue agencies in Norway. These represent all agencies in Norway based on the information and contact details provided by the Norwegian Directorate for Civil Protection. From the fire and rescue agencies, we got access to the location of fireplaces, stoves or chimneys, covering 101 municipalities in Norway. The dataset contains over 1 000 000 points and for most of the municipalities the dataset provides information about the residential address, the geographical position of the pipe, the type of dwelling, the type of technology and model (e.g., Jotul 306), and if the technology may be classified as clean burning technology (i.e., TRUE/FALSE). The different municipalities and agencies uses different systems for data management, involving different dataset formats and different type of information across datasets. In few cases the databases provide information about the frequency that the stoves are used. For the remaining 325 municipalities where these datasets are not available, regional proxies were used based on statistics of housing in the area and the share of residential heating sources obtained from the webcrawling database (described in the following section).

Figure 6 shows an example of this database for Stavanger municipality. The database contains 952 entries and also include types of residential heating installations running on a different type of fuel than wood, such as oil, paraffin, pellets or gas (Figure 6). The databases used in our study have been filtered by removing all entries that make reference to residential heating technologies non applicable to RWC. In order to show the density of fireplaces / stoves, a heat map has been produced and it shows that the highest density is in Stavanger city and surrounded agglomerations, associated with population (Figure 6).

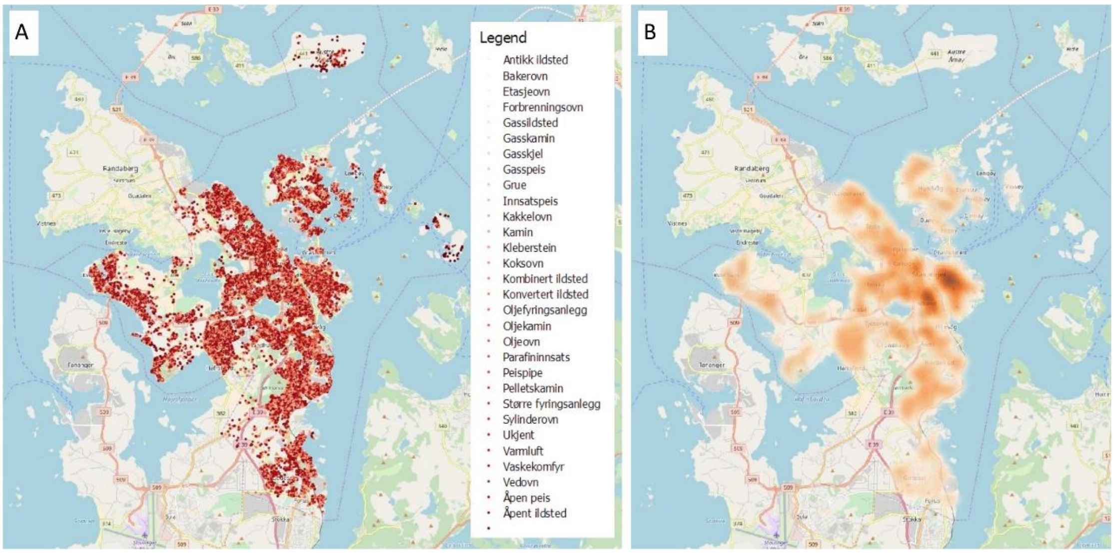

Figure 6: Location of burning technologies for residential heating in Stavanger Municipality (left) and produced heat map (right) based on the data from the fire and rescue department on the left figure.

2.4 Webcrawling database

The webcrawled database was built through a data mining process that collects the geographical location of dwelling from the real state advertisement portal, Finn.no, satisfying certain search criteria (More details in López-Aparicio et al., 2018). Along with the geographical location, the data extraction method collects information regarding the dwelling type (i.e., detached house, townhouse, duplex and apartment) and the energy system available in the housing for residential heating (i.e. wood burning appliance, district heating, heat pump). The database consist of 437 000 geo-positioned data points distributed in Norway and collected from October 2016 to October 2017 from Finn.no. Figure 7(a,b) shows the distribution of dwellings in the webcrawling database with and without available wood burning technologies. The data analysis over the webcrawling database allows us to establish the areas with different shares of wood based technologies. The grid areas in Figure 7(c,d) presented in light colour indicate low share and the ones in dark colour show high share of wood-based technology versus others such as district heating, heat pump or none, which is interpreted as electricity as main heating source.

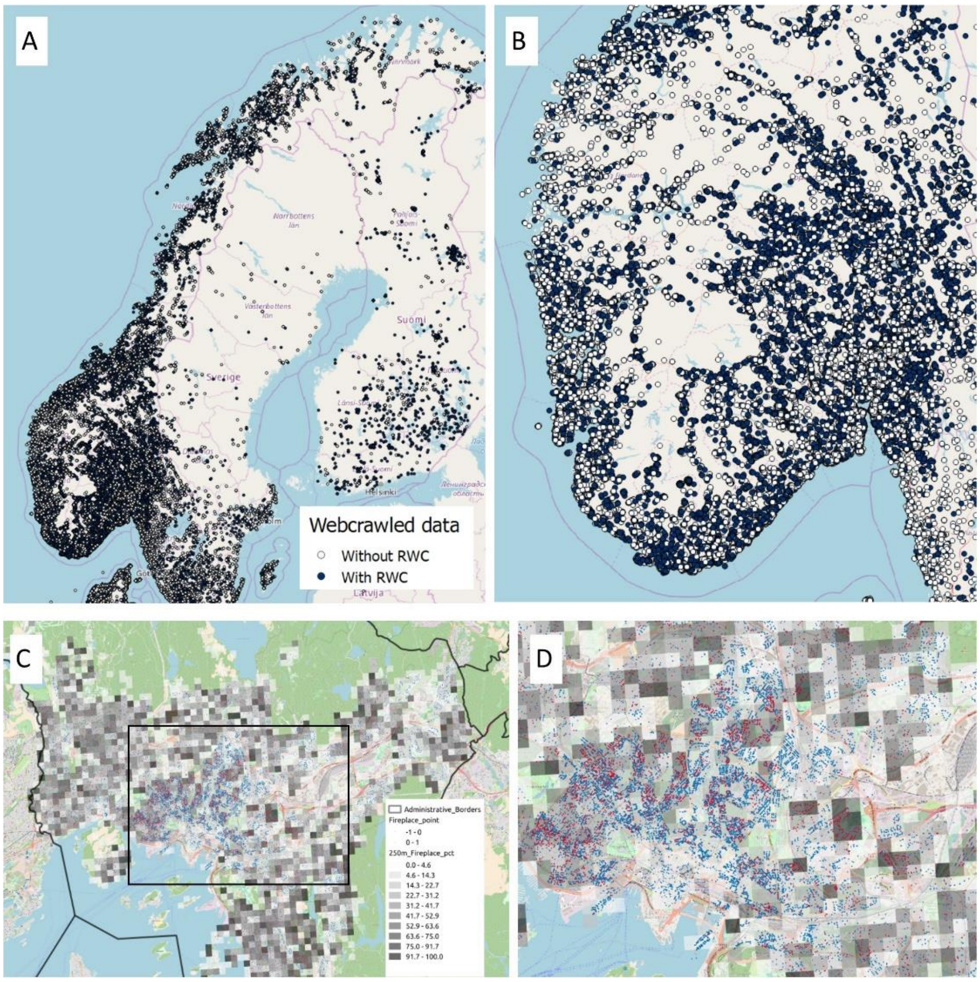

Figure 7: Webcrawling database in Norway (A) and in south Norway for higher detail (B). C and D shows the webcrawling database as dwellings with technologies for RWC (red points) and without (blue points). The gridding (C and D) represents different shares of technologies for RWC in the area of Oslo and surroundings. White grid: 0-5% share of wood burning technology at the grid. Black grid: 92-100% share of wood burning technology at the grid. For more detail see the text (Source: López-Aparicio et al., 2018)

2.5 Wood Consumption

Wood consumption officially reported by Statistics Norway at county level is used as original input data to downscale wood consumption to municipality level and finally to the 250 meters grid based on the wood burning potential. The data is collected by Statistics Norway according to two different surveys (Norwegian Environment Agency, 2018). For the years from 2005 to 2016; the use of wood is provided based on the responses to the Statistics

Norway's Travel and Holiday Survey. The survey gathers data in four quarterly surveys covering the preceding twelve months. The figure used to defined wood consumption, and subsequently estimate the official emissions in Norway, is the average of five quarterly surveys. The survey contains 25 questions regarding wood burning for residential heating and among the questions are; have you burned wood at your residence in the period between e.g. April 2008 to 31st march 2009? Which type of wood stove do you use most? How old is your wood stove? Do you have access to wood as bags of 40/60/80 l? How many bags of 40 litres did you use in the reporting period? How many bags of 60 litres did you use in the reporting period?, amongst others. The sampling of the survey is drawn at nationwide level and is considered representative of all municipalities. As an example and based on the survey carried out for 2009, the net sample was 1 274, 1 161, 1 110 and 1 206 responders for the 1st, 2nd, 3rd and 4th quarterly reports, respectively. For the years before 2005 and for 2012, the figures to estimate wood burning emissions are based on the amount of wood burned from the annual survey on consumer expenditure, covering purchase and self-harvest. These figures refer to quantities acquired, which not necessary corresponds to use. The survey gathers monthly data that cover the preceding twelve months, and the figure used in the emission calculations is the average of the survey figures from the year in question and the following year. In 2012 for instance, the sample was 7 000 households, whereas earlier samples were around 2 200 persons annually.

In the case of wood consumption at cabins and holiday houses, the data is also officially reported by Statistics Norway. In this case it represents wood consumption aggregated for all technologies and split in regions at courser resolution than county, i.e. Oslo and Akershus, Hedmark and Oppland, Sør-Østlandet, Agder and Rogaland, Vestlandet, Trøndelag, and Nord-Norge.

To estimate emissions from RWC, and as the emissions factors are defined as grams of pollutant per kilogram of dry wood, the wood consumption is recalculated to represent mass of dry wood. We used the same assumption as it is done by Statistics Norway to estimate official national emissions; a 18% water content is assumed, and therefore a factor of 0.82 is applied to obtained the wood consumption as the mass of dry wood.

According to Statistics Norway, there are several elements of uncertainty in the wood consumption data, such as the surveyed sample and the employed conversion factors. Statistics Norway concluded that the coefficient of variation of the total wood consumption is below 3% based on an uncertainty study carried out in 2011 (Statistics Norway 2018). The uncertainty is higher at municipality level as the values are based on smaller samples. The uncertainty will increase when decreasing the number of quarterly reports considered in the calculation of wood consumption (Table 1).

Table 1: Uncertainty in the national wood consumption based on the number of surveys considered in the estimates (Statistics Norway, 2018).

# Quarterly Studies	Coefficient of variation (%)
1	6.6
2	4.8
3	3.9
4	3.4
5	3

2.6 Emission Factors

Emission factors (EFs) for wood burning for residential heating are established for different technologies; i) open fireplaces, ii) stoves produced before 1998 and iii) stoves produced after 1998. In this study, we used two set of emission factors, shown in Table 2 as MetVed-set1 (Seljeskog et al., 2013) and MetVed-set2 (Seljeskog et al., 2017). The MetVed-set1 is used in the MetVed model and in the official Norwegian emission inventory (Norwegian Environment Agency, 2018). The emissions factors are determined based on wood stove experiments following the Norwegian Standard for testing enclosed wood heaters and smoke emissions (NS3058/NS3059). The emission factors established by Seljeskog et al. (2013) are considered as representative of “real -world” conditions. The particle sampling is carry out in a dilution tunnel in order to mimic the dilution and cooling effects when the smoke exists the chimney. In this way, the particle sampling account for the condensed matter. A comprehensive overview of emission factors for $PM_{2.5}$ and BC from different stoves technologies and different countries is presented in ACAP (2014). Norwegian $PM_{2.5}$ emission factors from different types of stoves are high but comparable to EFs used in other countries. For instance, the Norwegian $EF_{PM2.5}$ for stoves with new technology (EF = 754 mg/MJ) is at a similar level as $EF_{PM2.5}$ for stoves used in Finland (EF = 639 mg/MJ), in Denmark for new and old stoves (EF = 810 mg/MJ) and in Canada (EF = 756 mg/MJ). It is important to highlight the discrepancies between the emission factors used in Norway (EF = 754 - 1265 mg/MJ) and in Sweden (EF = 100 mg/MJ). The reason of this difference is that the Swedish EFs only account for the primary PM.

In the Norwegian national emission inventory two sets of emissions factors are used for PM, one for the large cities and the other for the rest of the country (Table 2). This is based on the assumption that wood stove users in the countryside fill up their stoves to the maximum and then close the combustion air to achieve heating during the night time, whereas in large cities less part load of the stove is assumed. In our study, we assume the same firing habits in large cities and in the countryside. The reason for this assumption is that there is not updated study that support different firing habits in cities and the countryside in Norway.

The second set of emissions factors used in this study (Metved-set2 in Table 2) are defined for national level and elaborated based on experimental activities performed over different types of stoves in the last decades (Seljeskog et al., 2017). These emission factors are weighted assuming a division between stove technologies, and then each technology is divided into part load and nominal load operating conditions. Part load is when the stove is operated below its maximum capacity according to the specifications of the producer, which is defined as the nominal load. The weighting is based on the same share between old and new stoves, and a division between wood consumed as part and nominal loads of around 65/35 and 70/30%, respectively (for more detail see Seljeskog et al., 2017).

Table 2: Emission Factors (g/kg dry wood) used in the official emission inventory for Norway and selected in this study. In brackets are the EF used in the official emission inventory for non-large cities. OF: Open Fireplace.

	EF used in Official Norwegian Emissions and Metved-set1 (Seljeskog et al. 2013)			EF Metved-set2 (Seljeskog et al. 2017)
	OF	**Stove (-98)**	**Stove (98-)**	**Stoves**
CO (g/kg)	126.3	150	50.5	95.2
CH_4 (g/kg)	5.3	5.3	5.3	9.76
PM_{10} (g/kg)	17.0 (17.0)	17.1 (22.2)	12.0 (13.1)	15.7
$PM_{2.5}$ (g/kg)	16.4 (16.4)	16.5 (21.6)	11.6 (12.7)	14.38
BC (% $PM_{2.5}$)	9	1.01 (0.96)	0.9 (0.86)	0.91
PAH_{TOTAL} (g/ton)	17.4	52	0.0226	25.41

2.7 Outdoor temperature

The seasonal time variation of emissions is determined applying the heating degree concept (HHD; Quayle and Diaz, 1980), which depends on average daily temperature (The HHD is explained with more detail in Section 3.4). In order to apply this concept, a database containing average daily outdoor temperature data from approximately 50 meteorological stations was built. The database covers all the counties in Norway and includes data from 2005 to 2016. The data is downloaded from eklima (www.eklima.no) from the Norwegian Meteorological Institute. The database contains information about the meteorological station (e.g. name, station number, altitude, longitude and latitude, municipality, county) and as parameters, it contains average, minimum and maximum daily temperature.

3 The MetVed Model

The MetVed model is divided in four modules designed to treat the needed input data described in previous chapters, and modules for calculating emissions from RWC and writing them. In addition, the MetVed model contains functions for areal re-gridding and for extracting emission data within specific geographical domains. The model is set up to read input data as spatial data (i.e., .shp .nc), ASCII / csv or excel files. The model output is organized as gridded shapefiles with auxiliary information in ASCII text files. The default option for the ouput file is to write emissions for all the components (i.e., PM_{10}, $PM_{2.5}$, PAH_{TOTAL}, CO, CH_4 and BC), with options to write also statistical information such as gridded wood consumption.

MetVed is set up with five different levels of input spatial resolution and can accept input data of variable detail. The levels should overlap completely or as a minimum, they have to correspond within the calculation domain. The resolution of each level used in the MetVed model is listed in Table 3. The spatial resolution of the input data determined the final resolution of the emission inventory, especially the gridded data on dwelling number and type (i.e., 250 x 250 m).

Table 3: Resolution of the input data for the MetVed model and acronym

Resolution	Variable Subscript
National level	N
County	F
Municipality	K
Grid	G
Building points	P

3.1 Spatial distribution of wood consumption

The MetVed model requires three parameters as input data, i.e., type/size of dwelling, and primary heating share by wood fuel distribution. The Norwegian dwelling dataset distinguishes type of dwelling, and to utilize this information, MetVed uses different wood consumption per dwelling types (*ht*). In our study, these dependencies are established from the data analysis carried out with the webcrawled- and ENOVA datasets, establishing the dependencies for each municipality in the case of residential buildings and at national level in the case of wood combustion in cabins.

Wood consumption defines the activity with which emissions are associated. In order to obtain an emission inventory at high spatial resolutions, wood consumption needs to be estimated for each grid. Since the highest resolution of the wood consumption input data for Norway is defined per county, the initial step in the MetVed model is to downscale the consumption to municipality. This is done based on housing size and type in each municipality:

$$C_k = \frac{C_f}{D_f} \times \sum_{ht} CW_{k,ht} \times D_{k,ht} \qquad \text{Equation 1}$$

where (CW_k) is the consumption weight of each dwelling in the municipality, *C* is the wood consumption, *D* is the number of dwelling per house type (*ht*), at the resolution defined by the subscripts (see Table 3). The initial downscaling is done with emission weight, so that the different distribution of housing types in each municipality is considered. That means that before wood is distributed to each municipality the *CW* of each house type needs to be calculated for each municipality.

The emission weight for dwelling type considers the average size and energy consumption for residential heating of that type at the municipality. The emission weight includes information on the frequency of installations for RWC in the different types of dwellings at the grid. This information is established by the Fire and Rescue Agencies Registry dataset and the dependency on type of dwelling is determined with the webcrawling dataset. The fire department data are originally on building point resolution and has additionally been pre-processed to the 250 m grid for data analysis and comparison with model output. The highest resolution accurate statistics that could be obtained was county level.

The model also accounts for differences in usage of heating devices. The use of RWC could be the primary or secondary heating source in a dwelling type. The difference in wood consumption between a RWC installation that is used as a primary heating source and another that is used as a secondary source must be established. At the moment, there is not enough information to allow us to establish which of the listed installations are in disuse with sufficient accuracy, so these are combined with the installations used as secondary heating source. Some of the municipalities provided information about the usage frequency of the installations as a scale from 1 to 6. However, we have not been able to utilise this information as the number of municipalities is few and some of them were small (i.e., Fet, Skedsmo, Sund, Fjell, Namsos, Fosnes municipalities).

Based on previous studies (López-Aparicio et al., 2017b), consumption in a house with wood as primary heating is defined as four times larger than the average wood consumption in these dwellings, in this way:

$$R = \frac{c_{Prim}}{c_{Supp}} \approx 1/4$$ *Equation 2*

With this ratio RWC primary heating with wood burning as the main heating source occurs only in detached houses at about 10%. Thus, the ratio (R) between wood consumption for a residential building with primary (h_1) and secondary (h_2) RWC heating source (R= h_2/h_1) can be used to calculate the consumption of primary and secondary wood installations:

$$C_k = C_{Prim} + C_{Supp} = C_k(N_{Prim} \times (1 - R) + N_{Supp} \times R)$$ *Equation 3*

where the number of installation per municipality (N_k) is calculated from the webcrawling dataset, the fire department registry (where available) together with the total number of dwelling of each housing type in the municipality. This is obviously not the best approximation as usage of fireplaces will vary greatly. Therefore, the division of consumption on the number of fireplaces will only be the average of all fireplaces. In broad terms we distribute the usage rate of fireplaces into three categories:

1. Inactive; existing fireplace, which are not used;
2. Secondary; used as supplementary heating and / or social burning.
3. Primary; used as primary heating source.

To support the usage rate, data analysis has been performed to obtain additional information from the webcrawling dataset and the geographical distribution of heating technologies (López-Aparicio et al., 2018). This provides good statistics on the partition between occurrence of wood burning installations and other heating technologies (e.g., district heating, heat pump, electricity), with high spatial resolution.

As the model is set up now, it maintains the technology share and consumption statistics from Statistics Norway. There is in part large differences in official consumption per technology share and the technology share in the fire department and webcrawled data. To avoid inconsistencies, each grid gets a technology share equal to the county consumption share. For instance, in the best covered county, i.e. Rogaland, there were around 25% of residential wood burning installations classified as clean in the fire department data, whereas the consumption statistics from Statistics Norway report that around 62% of the wood is consumed in new wood stoves in 2016. This share of consumption in new stoves would imply that these stoves consume ≈ 4 times more wood than old stoves. This is not supported by any of the underlying data, and consequently the consumption is assumed independent of the technology.

The consumption weight is thus dependent on the a) housing type b) wood technology share c) the housing size. The energy consumption per dwelling is established at the county level. MetVed assumes a linear dependence on size on top of a minimum consumption, established by the ENOVA data. It is done per dwelling type per county:

$$EC_{k,ht} = W_{min} + W_{m^2} Hs \qquad \textit{Equation 4}$$

The CW for each municipality is then calculated

$$CW_{k,ht} = P_{FP,k,ht} \times EC_{k,ht} \qquad \textit{Equation 5}$$

Where P_{FP} is the probability that a house has a wood installation. In this probability, wood installations for primary heating are calculated as 4 installations for supplementary heating. The consumption of the county is then distributed to each municipality as in Equation 1.

Further redistribution to the grid now follows the same method, where consumption in each municipality is redistributed to the grid based on the *CW* and the number of dwellings in each grid:

$$C_g = \sum D_{ht} P_{FP,ht} CW_{ht} \qquad \textit{Equation 6}$$

In Equation 5 the P_{FP} is either used directly from the fire agency database or statistical values from the webcrawled sample. With the exception of a few major cities, statistics on county level is used.

$$P_{FP,ht} = N_{FP,ht} / N_{dwe,ht} \qquad \textit{Equation 7}$$

Where N_{FP} is the number of fireplaces (maximum 1 per dwelling is considered) and N_{dwe} is the number of dwellings. The total annual emissions (*EM*) of each grid is then calculated by multiplying emission factors on the consumption.

$$EM_{tot,g} = C_g \times EF_g$$ *Equation 8*

As previously described, the technology share of consumption should be maintained, and thus the most detailed resolution of technology distribution is thus not applied in the grid, so $EF_g = EF_f$.

3.2 Emission estimates

Once wood consumption is defined at the grid level, emission factors are applied using the ratio of wood consumption per type of installation for each grid. The final output of the model is gridded emissions with a resolution of 250 x 250 meters. The output is produced as shapefile for easy visualization of the spatial distribution of emissions. The output file contains the SSBID number that corresponds to the reference grid of the dwelling number database, the municipality and county numbers, the wood consumption at the grid, and emissions of $PM_{2.5}$, PM_{10}, BC, CH_4, CO and PAH_{TOTAL}. An evaluation of the resulting emissions from the point of view of their spatial distribution, the resulting aggregated national emissions, and the comparison with official emissions reported to the CLRTAP and emissions at local level is shown in Section 4.

3.3 Vertical distribution

The vertical distribution is based on the wood consumption per type of houses in each grid. We have defined wood consumption from the detached, duplex and townhouses in a bottom layer and emissions resulting from consumption in apartments in a separate level. In the emission files, the variable called “lole” defines the fraction of emissions in the lowest level. The effective emission altitude of the two layers are 15 and 30 meter in our validation runs.

3.4 Time Variation

The estimated annual emissions are distributed on hourly values based on time variation factors. The distribution of emissions in the days of the week and hour of the day is done based on information from Statistics Norway from consumer statistics (Aasestad, 2010). This information is based on self-reporting questionnaires and, as it is shown in Figure 8, the wood burning activity increases at the weekend and evening hours. The daily distribution of emissions is defined according to the energy demand depending on outdoor temperature. To apply this, we use the concept of heating degree day (HDD; Quayle and Diaz, 1980), which is defined as each degree that the average daily temperature is below a threshold temperature. In MetVed we have applied it as 15 °C, as it is commonly used in other Scandinavian studies (e.g. Stohl et al., 2013):

$$HDD = max[(15 - T), 0]$$ *Equation 9*

The annual wood consumption is distributed to each day according to the number of HDD on that day. The final hourly consumption, and therefore hourly emissions, are obtained by multiplying the daily consumption, defined based on the HDD, with the factors that define consumption per hour of the day and weekday (Aasestad, 2010). Figure 8 shows as an example the HDD for 2013 for Stavanger. During winter months the HDD is higher, and it is reduced through spring until summer where the HDD is mostly 0.

Since the number of HDD in a year is not used to determine the annual consumption, the threshold temperature selected would affect only the seasonal distribution of wood consumption within that year. However, based on our analysis, HDD is able to capture annual variations in wood consumption statistics. This means that HDD can also be used to predict consumption changes in the future in connection to climate model simulations.

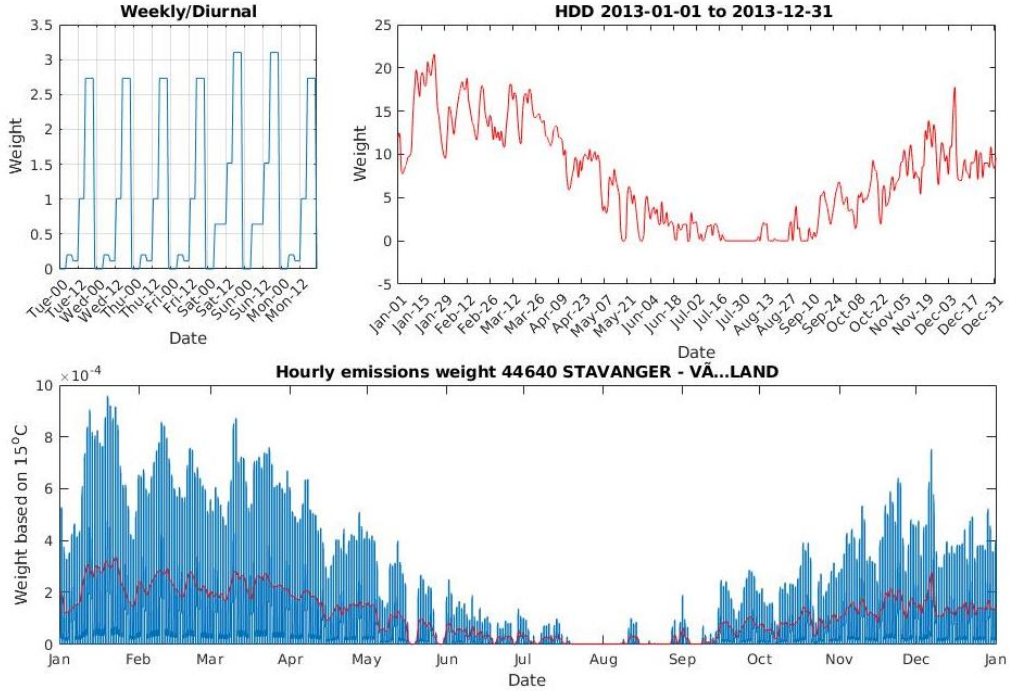

Figure 8: Time variation factors for hour of the day and day of the week (top-left), HDD for Stavanger in 2013 (top-right) and resulted hourly $PM_{2.5}$ emissions (bottom) after applying time variation factors.

4 MetVed Results and Evaluation

4.1 Spatial distribution of emissions at high resolution

Figure 9 shows the spatial distribution of emissions in Norway from RWC and CWC in 2016 at different levels of detail. The main difference between the spatial distribution of emissions from RWC and CWC is the geographical distribution. Emissions from residential heating are located exclusively in areas with residential buildings defined by the dwelling number and type at 250 meters resolution, whereas emissions from heating at cabins and holiday houses are more widespread in the geography. Emissions seem to be higher in south Norway than in north Norway in agreement with the population distribution. The high spatial resolution (250 meters) allows us to get high level of detail in urban areas as it is shown in the area around Oslo which corresponds to the area with the highest population density (Figure 9). The figure of the area covering Jotunheimen, Rondane and Mjøsa shows in detail the distribution of emissions from heating in cabin. In this case, emissions are more spread in the area, and the hotspots correspond to areas with high density of cabins.

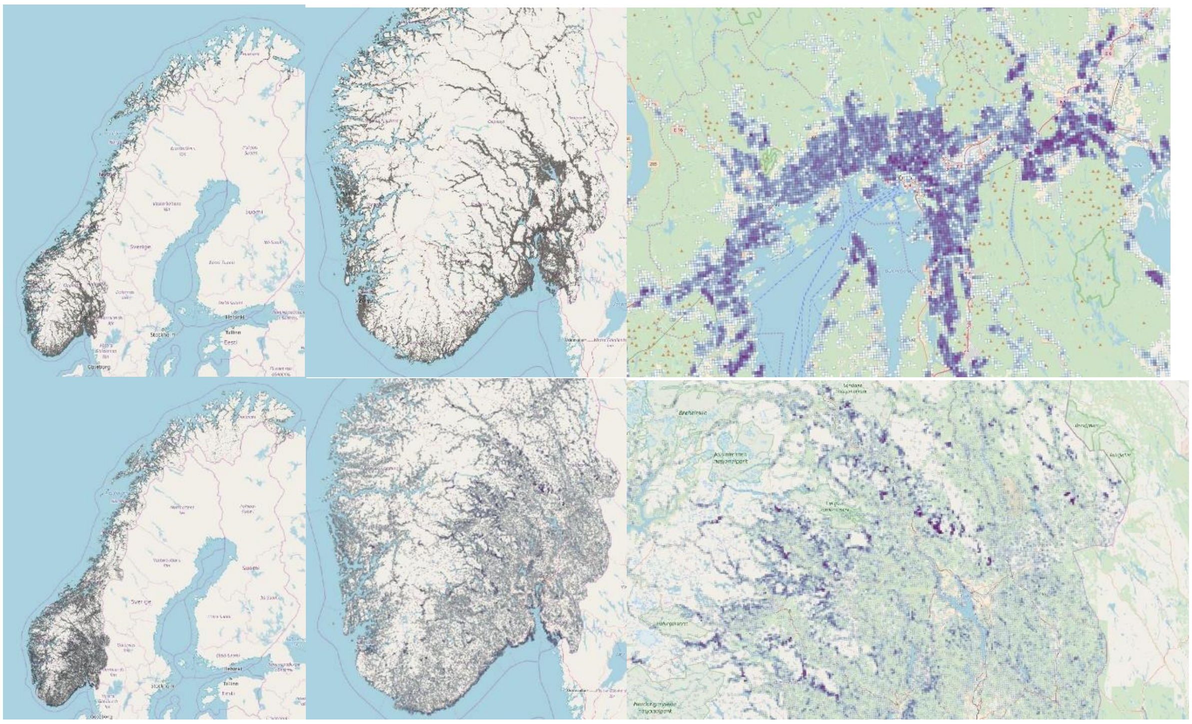

Figure 9: Distribution of national emissions from RWC at 250 x 250 meters (top) and CWC at 1 000 x 1 000 meters (bottom) in Norway (left, south Norway (middle), area centred in Oslo (top rigth) and in an area covering Jotunheimen, Rondane and Mjøsa (bottom right). Note: figures on the right are at different scales.

4.2 MetVed and the official emissions reported to the CLRTAP

The national emissions obtained with the MetVed model are compared with those officially reported as part of the CLRTAP for the year 2016. This comparison needs to be taken carefully as the MetVed model produced emissions associated with wood combustion (i.e. residential buildings and cabins), whereas CLRTAP emissions are from the overall residential sector including heating with different fuels. Table 4 shows the fuel activity reported to CLRTAP. Biomass, which is mainly fuel wood, constitutes around 85% of the fuel activity followed by liquid fuel (14%; e.g. light fuel oil), gaseous (<1%) and solid fuels (<1%; e.g. coal and coke).

Table 4: Fuel activity reported in the official national emission inventory for residential (stationary) combustion for the year 2016. (Source: http://www.ceip.at/)

Fuel	Liquid	Solid	Gaseous	Biomass
Activity (TJ NCV)	3 335.34	16.16	151.58	19 458.94

Taking into account that official emissions from residential heating include emissions from other fuels than wood, it would be logic to expect lower emissions by MetVed (Table 5) than emissions reported to CLRTAP. In the case of $PM_{2.5}$ and PM_{10}, MetVed national emissions, the sum of RWC and CWC, are slightly lower than CLRTAP. This difference could be due to the different fuels considered in the activity data but also to an additional difference. As previously stated, the PM CLRTAP emissions are estimated taking into account different EFs for large cities and for small cities or country side, whereas MetVed assumed the same emission factors for the national territory.

In the case of BC, the EF is defined as a share of the $PM_{2.5}$, we obtain much lower values than those reported in the official emissions, i.e. 0.888 kt versus 0.184 kt obtained with MetVed. The national BC MetVed emissions are in agreement with the share of national $PM_{2.5}$ emissions defined by the EF_{BC}, i.e. 9%, 1.01% and 0.90% of $PM_{2.5}$ for open fireplaces, old stoves and new stoves, respectively.

In the case of CO and PAH, MetVed emissions are higher than those reported to CLRTAP. These results are unexpected as $EF_{CO,PAH}$ in MetVed and CLRTAP are the same, and we also assume that both emissions are based on the same set up of wood consumption data. The national wood consumption in MetVed (2016) is around 911 kt (747 kt of dry wood) and the sum up of wood consumption at county level used as input data is around 907 kt. Additional information about the estimate of emissions reported to the CLRTAP is needed to evaluate these differences.

*Table 5: National emissions reported to CLRTAP (2016) and based on the MetVed model. RWC: residential wood combustion. CWC: cabin wood combustion. *Corresponds to 2015 (Source: www.norskeutslipp.no)*

Compound	CLRTAP (2016; kt)	MetVed (2016; kt) RWC + CWC
$PM_{2.5}$	15.30	14.08
PM_{10}	15.78	14.59
BC	0.888	0.184
CO	88.80	103.43
PAH_{TOTAL}	n.a.	0.026
PAH_4	0.001	0.0012
CH_4	6.12*	5.2

4.3 MetVed at local scale and comparison with existing urban emissions

Figure 10 shows a comparison of $PM_{2.5}$ emissions from RWC obtained using different methods for the same model domains. Emissions labelled as "NBV_v1 (unadjusted)" (NBV; Nasjonalt beregningsverktøy; Tarrasón et al., 2017) were obtained by downscaling wood consumption per technology at county level to local scale based on dwelling number at district level, and applying the corresponding emissions factors established by Seljeskog et al., 2013. "NBV_v1 (unadjusted)" emissions were used as input data for dispersion modelling and, based on the comparison with observations, it was concluded that emissions were overallocated in densely populated areas (Tarrason et al., 2017). Subsequently, emissions were adjusted using different correction factors for the various model domains in (Tarrason et al., 2017). These factors were determined from the comparison of modelled $PM_{2.5}$ concentration and observations, and the resulting total emissions are labelled as "NBV_v1 (adjusted)" in (Figure 10). Emissions labelled as "NWA (2014)" (NWA; NordicWelfAir project) are obtained based on downscaling wood consumption per technology from county level to local level based on dwelling number and type (250 x 250 metres), different distribution of wood consumption in houses and in apartments (70% and 30%), and the corresponding emission factors per technology established by Seljeskog et al., 2013. The share of wood consumption per houses and apartments was assumed based on a study carried out in Oslo, Akershus, Sarpsborg and Fredrikstad as part of the iResponse project (e.g. López-Aparicio et al., 2017b).

The comparison of emissions based on other methods shows that MetVed is in agreement with NBV_v1 (adjusted), indicating that total emissions in the model domain with the spatial distribution of the MetVed model is in agreement with validated emissions (green and orange bars in Figure 10). The comparison between MetVed emissions and NWA emissions indicate the importance of taking into account the different variables that emissions depend on. For instance, the spatial distribution of emissions in the NWA takes mainly into account the different wood consumption per type of dwelling, whereas MetVed model is based on the type of dwelling, heating as primary or secondary source, and the heating technology including both wood and non-wood based. Total NWA emissions in the model domains are in general higher than MetVed and NBV-adjusted, although for some domains as Stavanger and Drammen the differences are small.

An advantage of MetVed model over the “NBV-adjusted” is that MetVed is a consistent methodology applied at national level, and the results are local level seem to show an improvement regarding the NVB-adjusted method. This comparison only refers to total emissions in the different model domains. A validation exercise comparing modelling results with observations will provide a better understanding on the improvement associated to a better spatial and temporal distribution of emissions. Section 5, Validation with observations, shows the outcomes from the comparison of dispersion modelling results and observations.

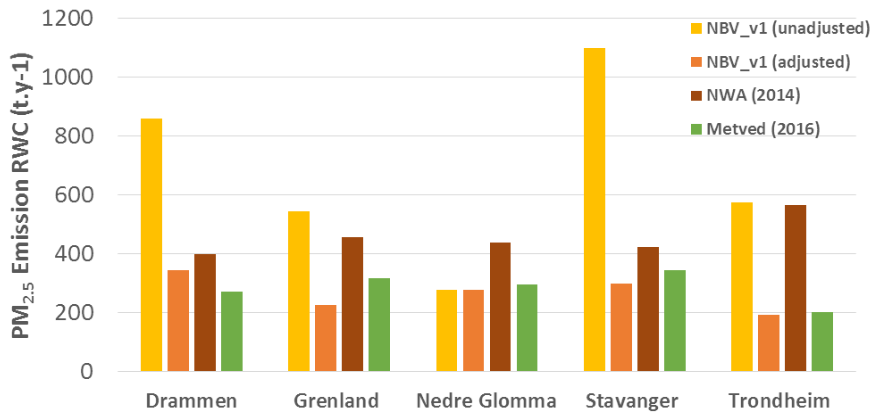

Figure 10: $PM_{2.5}$ emissions from RWC in 5 urban domains unadjusted and adjusted based on observations (NBV_v1_adjusted, NBV_v1 unadjusted, Source: http://www.luftkvalitet-nbv.no/), MetVed emissions and NordicWelfAir (NWA) extracted for the same domains.

4.4 Emissions from wood combustion with adjusted emission factors

The EFs constitute one of the sources of highest uncertainty when developing emission inventories as they depend on the type of fuel, technology, firing conditions, among others. Seljeskog et al., (2017) recommend a revision of EF for Norwegian wood stoves. They suggest using weighted emission factors which were developed taking 2013 as reference year. The division of technologies between fireplaces, old stoves and new stoves should be around 4.3%, 47.4% and 48.3% for wood consumption in large cities. For the rest of the country a division of wood used in old and new stoves should use be 6.3% and 93.7%. The part load and nominal load should be around 65/35 and 70/30%, respectively (for more detail see Seljeskog et al., 2017).

In this study, we compare national emissions obtained by the MetVed model (RWC + CWC emissions) based on EF from Seljeskog et al., (2013) and national emission obtained by the MetVed model (RWC + CWC emissions) based on from Seljeskog et al., (2017). We select the year 2013 as the weighted recommended EF are developed using this year as reference. The wood consumption at national level is taken as national values reported by Statistics Norway as it includes both wood consumption at residences and cabins (≈1296 kt; 2013). Table 6 shows the national emissions along with CLRTAP for 2013 for comparison. The use of the weighted EF recommended by Seljeskog et al., (2017) does not entail significant differences for most of the pollutants except for CH_4, which seems to increase by 100%.

Table 6: National emissions (2013) reported to the CLRTAP, MetVed emissions based on EF from Seljeskog et al. (2013), and national emissions based of EF from Seljeskog et al. (2017).

Compound	CLRTAP (kt)	MetVed, (RWC + CWC; kt) (EF _ Seljeskog et al. 2013)	MetVed (kt) (EF _ Seljeskog et al. 2017)
$PM_{2.5}$	17.54	15.68	15.28
PM10	18.09	16.19	16.68
BC	1.00	0.21	0.14
CH_4	6.66*	5.83	10.37
CO	103.13	112.72	101.16
PAH_{TOTAL}	n.a.	0.029	0.027
PAH_4	0.001	0.005	0.004

5 Validation with observations

$PM_{2.5}$ and PM_{10} emissions from RWC has been produced with MetVed model for two local model domains and thereafter used as input in the air dispersion model EPISODE. EPISODE is an off-line Eulerian dispersion model previously applied to assess air quality in Norwegian cities. The domain is Nedre Glomma, which includes the towns of Sarpsborg and Fredrikstad. This domain has been previously used in the Norwegian Air Quality Planning Tool (https://www.luftkvalitet-nbv.no/), and the evaluation pointed out that emissions from RWC involved the highest uncertainties (Tarrasón et al., 2017). The modelled concentration has been compared with observation at receptor points defined by the location of monitoring stations.

Figure 11 shows PM_{10} modelled concentration based on MetVed emissions from RWC at the receptor point defined by St. Croix monitoring station, and the modelled contribution from the different sources (Torleif Weydahl et al., 2018). The model is able to reproduce several of the episodes associated with RWC. For instance, $PM_{2.5}$ and PM_{10} pollution levels reach 100 μgm^{-3} during an episode in winter and both levels practically coincide indicating that PM_{10} levels mainly consist on fine particles. In this case, the dispersion model based on MetVed emissions predict such a level and associates the episode to RWC as main contributing sector. The correlation between modelled concentration and observation is about R = 0.76. Comparing this correlation with those obtained in the Norwegian Air Quality Planning Tool (Tarrasón et al., 2017), we observed significant improvements. In the Norwegian Air Quality Planning Tool evaluation, the correlation expressed as R between hourly modelled PM_{10} concentration and observations at St. Croix was estimated to be around 0.45 and 0.46, with the emission inventories named version 0 and version 1, respectively, whereas the correlation with MetVed emissions is estimated to be 0.76.

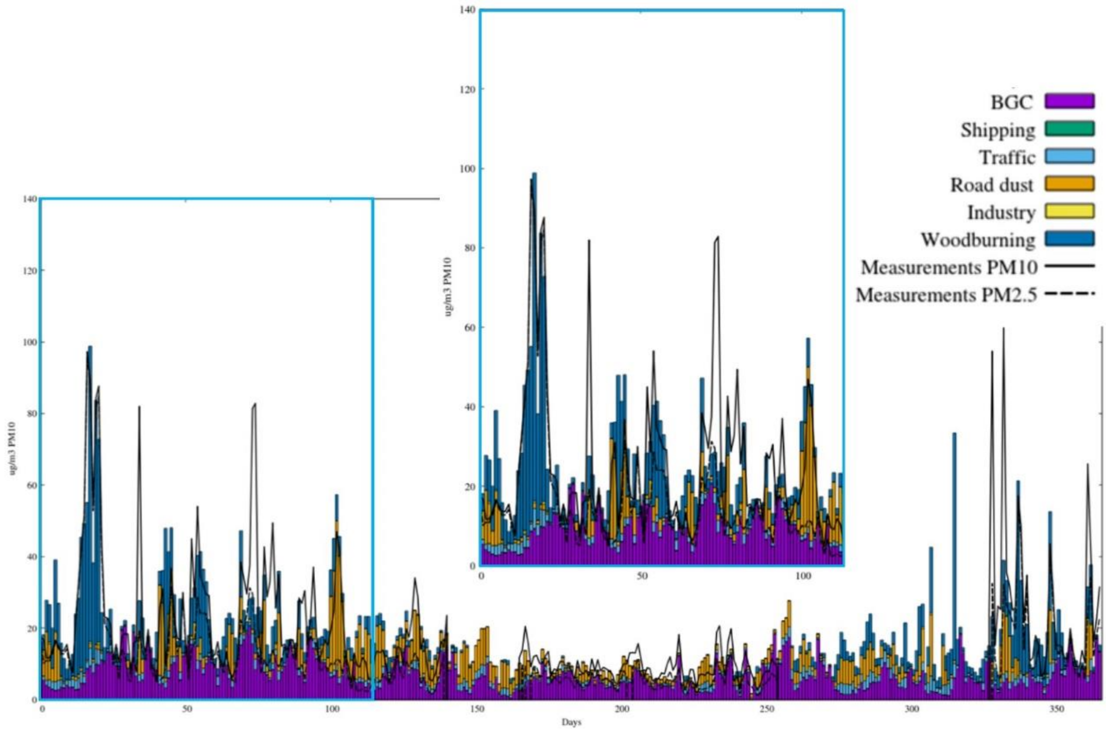

Figure 11: PM_{10} modelled concentration per contributing sector compared with PM_{10} (straight black line) and $PM_{2.5}$ (dashed black line) observations at St.Croix monitoring station as receptor point. The rectangle represents the part of the diagram zoon in.

6 Concluding Remarks

We have developed a methodology ("The MetVed model") to improve emissions from RWC. The methodology is based on bottom-up principles, which has been achieve by data collection processes and data analysis. We have combined several dataset at high resolution and established the relationship between wood consumption, type of dwelling, residential heating technology (i.e., wood based, district heating, heat pump, electricity) and outdoor temperature. This has allow us to get a better understanding on emissions from RWC and its dependencies. In addition, an emission inventory for Residential Wood Combustion (RWC) at high resolution was produced and delivered to the Norwegian Environment Agency. The inventory includes PM_{10}, $PM_{2.5}$, PAH, CO, CH_4 and black carbon (BC) at 250 metres grid resolution for 2016, along with wood consumption at the same resolution.

The MetVed resulted emissions have been compared with previous emission inventories at local scale, where emissions from RWC were pointed out as highly uncertain and overestimated. Based on this comparison, we are able to establish that MetVed improves the spatial and temporal distribution of emissions, and the total emissions at local scale. This evaluation has been complemented with a validation supported by the comparison between modelled pollution levels, based on MetVed emissions, and observation. The used of RWC emissions from MetVed has shown an improvement in the correlation between modelled results and observations, compared with previous modelling activities based on less accurate emission inventories.

Even though the model has showed significant improvement regarding previous emissions, we still rely on official data regarding the activity data (i.e., wood consumption per technology at county level) and emission factors. Both activity data and emission factors are known to be very uncertain.

We have compared MetVed emissions based on Norwegian official emission factors (Seljeskog et al., 2013) and MetVed emissions estimated with the recommended revision of emissions factors for Norwegian wood stoves by Seljeskog et al., (2017), which takes into account part load and nominal loads for old and new stoves. The comparison of emissions showed small differences for most of the pollutants except for CH_4, which seems to increase by 100% when using the new recommended emissions factors. The reason for the CH_4 increase was already highlighted by Seljeskog et al., (2017), as higher emission factors are recommended based on experiments. The comparison does not allow us to establish which emission factors represent better emissions under real conditions. To establish which emission factors represent better real-world conditions, emission measurements at real conditions would be required for several compounds, including chemical composition of the PM. In addition, current observational data is available for bulk PM concentration at mostly traffic stations. This does not allow a detailed characterization of the different sources contributing to the PM levels. In addition, this does not allow for a decomposition of uncertainties between the activity data and emissions factors for RWC emissions. It is recommendable to perform a detailed measurement campaign targeting at RWC as a source of PM and other compounds (e.g., BC, PAHs, dioxins).

One of the uncertainties in MetVed is the usage of the wood burning installation, the frequency. This information is not available at wide scale. Some of the datasets provided by the fire and rescue agencies have the frequency as one of the data collected (i.e., scale from 1 to 6). However, this subdataset represent very few and small municipalities (i.e., Fet, Skedsmo, Sund, Fjell, Namsos, Fosnes municipalities). We were not able to use them as part of the model. It would be recommendable to include this in the data collection at national scale. In addition, Metved uses the wood consumption technology share established by Statistics Norway at county level as information. When data from the fire department at higher level of detail is available, they show inconsistencies with official information about technology shares.

Regarding the **potential improvements** of the method and the input data, different aspects could be considered. For the improvement of the method, first, it is advisable to carry out validations activities in several urban areas, based on the use of MetVed emissions as input data for dispersion modelling and thereafter comparison with observations. This will provide insights regarding the quality and the potential uncertainties behind MetVed emissions. Regarding input data, the dataset on energy consumption and from the fire and rescue departments covers several years. In the case of the fire and rescue department, even though some information is available on the installation technology, there is not enough information on the criteria used for the classification and the year when the inspection was performed. Thus, we do not have enough information to establish how this data represent current situation. We also identify the need for additional information which could provide higher accuracy or facilitating an effective processing of information. For instance, the dataset from the fire and rescue agencies has proved to be of great value. However, we identify some challenges, for instance we obtained information from 101 municipalities out of 429 in Norway. Even though this could affect the completeness to represent the whole of Norway, these municipalities encompass most of the Norwegian population, so we are confident that they may represent a high proportion of the residential areas in which RWC is of importance. An important aspect is that each municipality uses different providers to manage the databases. Therefore, these databases have different formats and type of information. In this case, it would be recommendable to have a national harmonized database that will facilitate the data handling for this application or others. This database should contain, at least, information about the geographical position of the wood burning installation, when the inspection was carried out and the type of technology (e.g., year of production). In addition, some of the databases (e.g. from Fire and Rescue Agencies) have shown inconsistencies with other data sources or incompleteness (e.g., amount of installations in the municipality, type of installation). Moreover, and as previously stated, the MetVed model relies on wood consumption reported by SSB. It is recommendable to improve the quality of the survey and sample representativeness.

Emissions from MetVed can be updated to represent coming years. For yearly updates, and as the model is currently set up, the wood consumption at the county as reported by SSB is the required input data, and outdoor temperature to establish the time variation. Other dataset that could be updated is the dwelling number and type at 250 x 250 metres resolution. Taking into account that the residential building stock does not go through significant changes on a yearly basis, it would be recommendable to evaluate possible updates once per 5 years.

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NILU – Norwegian Institute for Air Research
P.O. Box 100, NO-2027 KJELLER, Norway

E-mail: nilu@nilu.no
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