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MetVed v.2.0

Improvement and update of the MetVed emission model for residential wood combustion

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ABSTRACT

This report presents the update of the MetVed-model (Grythe et al., 2019). Among the updates are new emission factors and several new species that include climate gases (CO_2, CH_4 and N_2O). There is now a new parameter that describes the emission altitude and a new and improved time variation. Activity data has been updated to the most recent year (2019), which also has required updates to the model and model input variables. The largest update has been the holiday cabin emission module, which is an entirely new addition. Emissions from cabins differ in several ways from residential emissions. The most notable difference is that cabins are spread over more rural areas and are more dispersed than the residential dwellings. The model differentiates alpine and coastal cabins, which is an important distinction as a high density of cabins exists along the coast and they are mainly used during summer.

NORWEGIAN TITLE

MetVed v.2.0. Forbedring og oppdatering av MetVed-vedfyringsutslipps modellen

KEYWORDS

Luftkvalitet Atmosfære og klima Utslippskontroll

ABSTRACT (in Norwegian)

Denne rapporten presenterer den oppdaterte MetVed-modellen (Grythe et al., 2019). Oppdateringene inneholder nye utslippsfaktorer som innbefatter flere komponenter enn tidligere, som også er relevante for klima (CO_2, CH_4 og N_2O); flere nye parametere som utslippshøyde og en ny forbedret beskrivelse av tidsvariasjon. Aktivitetsdata er oppdatert til 2019 og ettersom flere inngangsdata er forbedret er det også noe endring i utslippene fra boliger. Den desiderte største oppdateringen er allikevel hytteutslippene, som er en ny modul bygget opp fra bunnen. Utslippene fra hytter skiller seg fra de fra boliger ettersom hytter er spredt over et større område og er preget av at det er stor variasjon over året med hensyn til når de er i bruk. I tillegg ligger det i modellen en antagelse om at mange hytter er sommerhytter (langs kysten) hvor vinterbruken og dermed vedforbruket, er mer begrenset enn for hytter i skog og fjell. Dette kommer frem ved en rekke data som er samlet inn, og benyttet for å beskrive forbruket på forskjellige typer hytter.

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Preface

This scientific report is the final report of the MetVed-2 project "*Forbedring og vedlikehold til løsning for vedfyringsutslipp*" (In English: Improvement and updating of the model for estimating residential wood combustion emissions). The project is funded by the Norwegian Environment Agency, and started in April 2020.

The MetVed-2 project aims at improving the method to estimate emissions from wood combustion for heating based on the previous developed model MetVed, which is described and evaluated in López-Aparicio et al., (2018) and Grythe et al., (2019). The aim of the project was planned to be achieved through the following secondary objectives:

- Update emission factors for the components available in previous versions (i.e. MetVed v.1) and new components included in MetVed v.2.0.
- Update basic input data to estimate emissions from residential and cabin wood-combustion for the most updated year.
- Improve the model to provide altitude of emissions at the grid level.
- Improve the time variation of emissions.
- Reduce the existing uncertainties concerning emissions from wood-combustion in cabins

The technical work has been carried out by Henrik Grythe in closed cooperation with Susana Lopez-Aparicio who has also led the project. We thank Scott Randall from the Norwegian Environment Agency for his support, help and cooperation during the project. The quality control at NILU has been carried out by Paul Hamer and Matthias Vogt. The report has benefited from the feedbacks and comments from Scott Randall, Silje Aksnes Bratland and Tomas Siem from the Norwegian Environmental Agency

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Sammendrag

Vedfyring er en av de største bidragsyterne til partikkelforurensning, og det er viktig å forstå utslippene for å kunne estimere påvirkning på luftforurensning, helse og miljø. MetVed-modellen er designet for å beskrive når og hvor utslipp fra vedfyring i Norge skjer. I den oppdaterte modellen, presentert i denne rapporten, er også de betydelige utslippene fra hytter beregnet etter lignende prinsipper som for boliger. Modellen inneholder, i tillegg til hytteutslipp, flere oppdateringer og forbedringer fra den tidligere publiserte versjonen (Grythe et al., 2019).

Disse oppdateringene omfatter nye utslippsfaktorer som innbefatter flere komponenter enn tidligere, som også er relevante for klima (CO_2, CH_4 og N_2O); flere nye parametere som utslippshøyde og en ny forbedret beskrivelse av tidsvariasjon. Aktivitetsdata er oppdatert til 2019 og ettersom flere inngangsdata er forbedret, er det også noe endring i utslippene fra boliger. Den desiderte største oppdateringen er allikevel hytteutslippene, som er en ny modul bygget opp fra bunnen. Utslippene fra hytter skiller seg fra utslipp fra boliger ettersom hytter er spredt over et større område og er preget av at det er stor variasjon over året med hensyn til når de er i bruk. I tillegg ligger det i modellen en antagelse om at mange hytter er sommerhytter (langs kysten) hvor vinterbruken og dermed vedforbruket, er mer begrenset enn for hytter i skog og fjell. Dette kommer frem ved en rekke data som er blitt samlet inn og benyttet for å beskrive forbruket på forskjellige typer hytter.

I denne rapporten blir oppdateringer beskrevet i detalj og den må sees på som en oppdatering til tidligere dokumentasjon (Lopez-Aparicio et al., 2018; Grythe et al., 2019). Resultatene og evalueringen av modellresultatene er basert på modellberegningsåret for 2019. Det er ikke foretatt noen detaljert verifisering av resultatene for hytteutslipp da dette i liten grad er mulig. Endringene i boligutslipp er ikke store nok til at det bør være nødvendig å foreta en ny vurdering av dette.

Summary

Residential wood-combustion is one of the largest contributors to aerosol emissions in Norway and it is important to understand its emissions in order to evaluate its contribution to air quality, health and the environment. The MetVed-model is designed to describe when and where emissions from residential wood-combustion happen. The updated model presented here includes an addition to residential emissions in the form of the significant emissions arising from holiday houses of cabins. There are also several other improvements and updates to the model from the previous version presented in Grythe et al., (2019).

Among the updates are new emission factors and several new species that include climate gases (CO_2, CH_4 and N_2O). There is now a new parameter that describes the emission altitude and a new and improved time variation. Activity data has been updated to the most recent year (2019) which also has required updates to the model and model input variables. The largest update has been the holiday-cabin emission module, which is an entirely new addition. Emissions from cabins differ in several ways from residential emissions. The most notable difference is that cabins are spread over more rural areas and are more dispersed than residential dwellings. The collected data show that cabins also have large variations in the time they are in use, both weekly and over a year. The model differentiates alpine and coastal cabins, which is an important distinction as a high density of cabins exists along the coast and they are mainly used during summer.

This report builds on previous documentation (Lopez-Aparicio et al., 2018; Grythe et al., 2019) and all updates to that prior work are described in detail. Results are presented and evaluated for the year 2019. No detailed validation is done on the spatial distribution for the cabins as there are no good data sources available to validate emissions. The changes in residential wood burning emissions are not so large that a new validation of these is necessary.

MetVed v.2.0

1 Introduction

Residential Wood Combustion (RWC) is one of the most important residential heating sources in the Nordic Countries (e.g. Kukkonen et al., 2020). 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 $PM_{2.5}$ in urban areas, and the contribution can reach values up to 60% of total $PM_{2.5}$ levels (Kukkonen et al., 2020).

The accuracy of estimated emissions is crucial as RWC has a large impact on the air pollution level in most Norwegian cities (Tarrason et al., 2018a; 2018b). 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. To improve the accuracy of RWC emission inventories, the MetVed-model was developed to estimate emissions at high spatio-temporal resolution. The MetVed-model, which is described in Grythe et al. (2019), combines downscaling with bottom-up principles to derive a wood burning potential for a grid based on the housing type, size and available heating technologies, building energy demand and outdoor temperature of each grid. The model builds on the combination of several databases with information at a 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 day (HDD) concept combined with time variation from consumer statistics and has a vertical distribution of emissions based on the wood consumption in apartment buildings versus other houses. The results from the MetVed-model have shown to improve the accuracy of dispersion modelling results against observations when compared to several previous emission inventories (Grythe et al. 2019). Figure 1 shows a diagram of the input data and the data processing in the MetVed-model used to establish the wood consumption weighted average emission factor (EF) and the wood consumption to finally estimate emissions at the grid level. The wood consumption at the grid level depends on the wood burning potential of each type of dwelling, the probability of having a RWC installation and the ratio of RWC installations to dwelling (Figure 1).

The MetVed-model v.1 provided an emission inventory for RWC in Norway at 250 metres resolution for (2005-2018), of which emissions for the year 2016 were delivered to the Norwegian Environmental Agency (Lopez-Aparicio et al., 2018). The emission inventory included PM_{10}, $PM_{2.5}$, PAH, CO, CH_4 and black carbon (BC) at 250 m grid resolution, along with wood consumption at the grid level for 2016. In addition, an independent module (MetCab) was developed to estimate emissions from cabins' wood combustion (CWC) for the same compounds but at a resolution of 1 km grid.

This report summarises the work carried out in 2020 with the aim to improve the methodology for calculating wood burning emissions and also to update both basic data and emission estimates to represent the most recent available year. Regarding MetVed, the improvements include establishing the average height of emissions at the grid level and evaluating the need for improving the time variation of emissions based on the HDD. In addition, new compounds have been added (i.e., PAH-4, N_2O, NO_x, CO_2, NMVOC, OC and SO_2) and the emission factors (EFs) for RWC has been updated to updated factors presented in Seljeskog et al. (2017). The most important difference between these EFs and the ones previously applied (Seljeskog et al., 2013) is that the new factors consider different shares of partial and nominal load operating conditions.

The updated version of MetVed (namely MetVed v.2.0 in this report) produces emissions from RWC in 2019 based on wood consumption and dwelling number at 250 metres resolution for the same year. Regarding emissions from cabins (namely MetCab in this report), significant new developments have been included to account for the characteristics of the cabins in Norway. The most relevant feature has been to distinguish between cabins mainly active in summer (coastal) versus whole-year cabins (alpine). The determination of the cabin features and classification have been done based on data regarding the distance to the coast, altitude, the distance to city centres and the annual average ambient temperature of the location of the cabin.

This report presents first the details concerning the update of MetVed emission model regarding emissions from RWC, followed by the new MetCab emission module to estimate wood burning emissions at cabins. The report finalizes with an assessment of the updates performed and an identification of the main aspects to be updated or improved in the future.

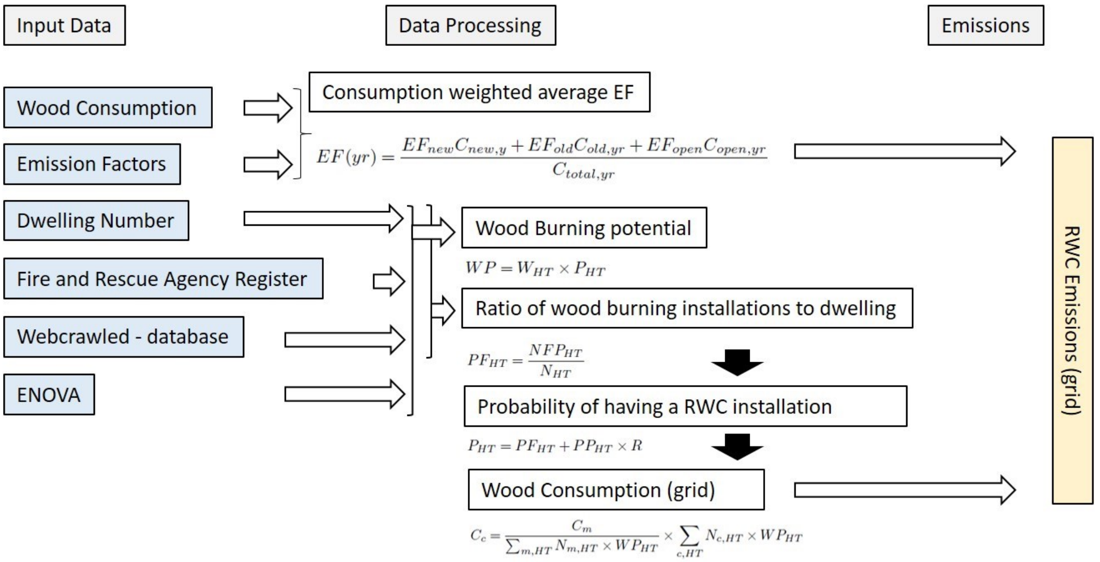

Figure 1: Schematic representation of the input data and processing in MetVed (from Grythe et al., 2019).

2 Update of the MetVed model

The code of the MetVed model has been updated and is now available at GitHub https://github.com/henrig/MetVed/. The new code (MetVed v.2.0) produces emissions on a slightly modified spatial pattern and also include wood combustion emissions in cabins. The main updates since Grythe et al., (2019) are the inclusion of the cabin emissions, emission altitude at the grid, a new time variation based on an improved holiday calendar that considers school holidays and partial holidays, new emission factors based on Seljeskog et al., (2017) and several minor performance improvements and bugfixes. The most important update to the code is the parametrization that considers the recent or foreseen changes in the municipal and county administrative boundaries of Norway. In addition, modifications have been done to make it a more dynamic system, in this way the model uses year-specific basic input data (i.e., wood consumption, building and temperature). There is also new updated input data that has required some adjustment to the code such as using year specific building data. The specific details of the updates and improvement are included in the following sections.

2.1 Emission factors

The EFs for RWC includes both the addition of new compounds and the update of EFs for compounds previously included in the emission model. Table 1 shows the EFs used in MetVed v.1 and MetVed v.2.0, and the compounds included in both versions. The EFs used in MetVed v.1 for RWC were those established by Seljeskog et al., (2013) and previously used for the official reporting of emissions (Norwegian Environment Agency, 2018). As for the earlier applied EFs, the updated ones are also specific for three different types of installations or technologies; i) open fireplace, ii) stove produced before 1998 (old stoves in this report) and iii) stoves produced after 1998 (new stoves in this report). In MetVed v.2, the EFs for open fireplaces are the same as those used in MetVed v.1, whereas the EFs for stoves are updated based on Seljeskog et al. (2017). The EFs are obtained via particle sampling in a dilution tunnel to mimic the dilution and cooling effects when the smoke exits the chimney, in this way accounting for also the condensable matter formed. The updated EFs are taking account that there are differences depending on operating conditions. EFs are given for part-load and nominal-load operating conditions for each type of stove. MetVed follows the suggested split of 65% part-load and 35% nominal-load for old stoves, and 70% and 30% part-load and nominal-load operating conditions for new stoves (Seljeskog et al., 2017).

Table 1: EF factors (g/kg dry wood or g/ton of dry wood) used in MetVed v.1 and v.2 (see text for details). OF: open fireplace; Stove (-98): stove produced before 1998; Stove (98-): stove produced after 1998. The EFs for OF have not been modified regarding the previous version. The CO2 EF for OF corresponds to the EF under nominal load conditions for a new stove installation based on recommendations from the Norwegian Environment Agency.

Compound	**MetVed v.1**			**MetVed v.2**		
	OF	**Stove (-98)**	**Stove (98-)**	**OF**	**Stove (-98)**	**Stove (98-)**
CO (g/kg)	126.3	150	50.5	126.3	102.03	85.73
CH_4 (g/kg)	5.3	5.3	5.3	5.3	16.14	3.88
PM_{10} (g/kg)	17.0	17.1	12.0	17.0	23.13	8.30
$PM_{2.5}$ (g/kg)	16.4	16.5	11.6	16.4	20.86	7.85
BC (g/kg)	1.48	0.17	0.10	1.48	1.04	0.65
PAH_{TOTAL} (g/ton)	17.4	52	0.0226	17.4	52	0.026
PAH-4 (g/ton)	-	-	-	3	2.7	0.025
N_2O (g/kg)	-	-	-	0.03	0.03	0.03
NO_x (g/kg)	-	-	-	1.3	0.97	0.97
CO_2 (g/kg)	-	-	-	1 768.0	1 527.4	1 642.0
NMVOC (g/kg)	-	-	-	7.0	22.28	15.22
OC (g/kg)	-	-	-	7.87	13.24	4.5
SO_2 (g/kg)	-	-	-	0.35	0.34	0.35

2.2 Basis and Activity data

The fundamental input data behind the MetVed model (Figure 1) to define the consumption, activity and the spatio-temporal distribution of emissions is: 1) wood consumption from Statistics Norway; 2) dwelling number from Statistics Norway, 3) Energy consumption from the Norwegian energy labelling system (ENOVA), 4) Fireplace/stove locations from the Fire and Rescue Agencies register, 5) Web-crawled database from finn.no (more detail in Grythe et al., 2019) 6) Outdoor 2 m temperature from eKlima.no.

As described in Grythe et al., (2019), data from fire and rescue agencies on the number of fireplaces in each grid, the energy consumption in specific buildings and the web-crawled database are static databases and so they do not represent any specific year. They share some common properties that makes their direct applicability limited; they are gathered over time and they do not cover the entirety Norway. These three datasets also have in common that they contain data at the resolution of specific dwellings and that prevents their direct publication due to the protection of data that contains personal information. The datasets are continuously updated by the data holders, and while it is desirable to update them at certain frequency, this was not done for this update. Updates should be considered when the data has grown in coverage or information and should be re-processed to incorporate improved or new information.

On an annual basis, the data that needs updating is wood consumption, temperature and the gridded dwellings. The annual wood consumption data is produced by Statistics Norway. It consists of officially reported data at county level collected via surveys (for more detail see López-Aparicio et al., 2018). MetVed can produce annual emission for years between 2005-2019, the years for which there are available wood consumption data on county level from Statistics Norway. As EFs are defined as grams of pollutant per kilogram of dry wood, the wood consumption reported by Statistics Norway is recalculated to represent mass of dry wood do fit with emission factors. We used the same assumption as it is done by Statistics Norway to estimate official national emissions, and hereby an 18% water content for all consumed wood is assumed.

The dwelling data originates at the tax registry database (SERG) and updated maps are now made annually available (2008 - 2020) gridded at 250 m resolution by Statistics Norway (SSB, 2020a). This is a recent addition, as previously the data were only available for a few select years. MetVed v.1 relied on 2015 residence data for all calculation years, whereas MetVed v.2 uses the dwelling data year that correspond to the emission year. For years of missing data (prior to 2008) MetVed uses the closest year for which it finds data. The data used from this database is:

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 shared communities (“*Antall boliger i bofellesskap*”)
vii) Others (“*Antall boliger i andre bygningstyper*”)

2.3 Emission height

In MetVed v.1 the emission height was separated in two levels, one for apartments (UPLE) and another for all other dwellings (LOLE). Current grid emissions estimated by MetVed v.2 are based on the type of buildings individual emission height. The emission height is calculated as the mean consumption weighted emission height in each grid. Emission height of detached, townhouses and duplexes are independently set to 15 m, whereas apartment buildings are set to 30 m. The grid emission height at the grid is contained in the emission database as "*EmH*" in the MetVed output shapefile.

2.4 Time variation

For RWC, the time variation of emissions is the same as in MetVed v.1, except now it considers school holidays as "weekends" with the implications that these days have a diurnal burning pattern as weekends and thus, total consumption is weighted as for weekends (for details see Grythe et al., 2019).

As in previous versions of MetVed, the diurnal and weekday weight are coupled with a HDD function. The daily HDD is calculated based on observations from measurement stations. All available stations with temperature measurements in Norway are used and each grid gets its HDD from the daily average 2 m temperature ("*TAM"*) at the closest station. The exact number of stations with valid observations varies from year to year but is in the order of 100s for recent years. MetVed only considers stations with more than 300 days coverage and uses a linear interpolation for missing data.

The method to distribute wood consumption is independent of the number of HDD in a given grid. This means that the HDD does not predict residential wood consumption, but it rather temporally distributes the calculated wood consumption and therefore emissions within the calendar year. This choice has many implications, both advantageous and disadvantageous. The main reason for this choice is that the county consumption data suggest that there is a low dependence on the number of HDD a county has and the annual consumption. However, on a national scale a strong relationship between HDD and annual wood consumption was previously found (see Grythe et al., 2019 for details). This suggest that the wood consumption in a geographical area does not depend heavily on the temperature, but in a cold or warm year consumption can go up or down, respectively. This implies that geographic areas' average consumption is reliant on different factors than temperature. On an even finer scale, it is not evident that there is a difference between municipalities or grids within the same region with different amounts of HDD per year.

3 The cabin emission module (MetCab)

3.1 The MetCab module

A first approach to estimate emissions from CWC (MetCab v.0) at high resolution was developed in 2019 as an independent module (López-Aparicio et al., 2018). In MetCab v.0, the number of cabins was obtained from the georeferenced building statistics (SSB, 2020a). At the time, the gridded building data for cabins was only available at 1 km grid resolution, and subsequently, the final emission results were on a 1 × 1 km grid. The complete building statistics database provides the number of buildings split in 43 categories, and in order to define cabins, we selected those classified as holiday houses, cabins or similar (“*Fritidsbolig, koie, seterhus og lignende*”). This gives the same number of cabins as reported by Statistics Norway published statistics as “Hytte”, the term also used to define CWC (SSB, 2020b).

Wood consumption at cabins and holiday houses was obtained from the officially reported information from Statistics Norway for 2016. It represented wood consumption aggregated for all technologies and split in regions (which is not an administrative unit and it is at a coarser resolution than county); i.e. Oslo and Akershus, Hedmark and Oppland, Sør-Østlandet, Agder and Rogaland, Vestlandet, Trøndelag, and Nord-Norge.

Figure 2 shows CWC emissions obtained by MetCab v.0. Whereas RWC emissions are exclusively located in areas with residential buildings and are thus more centralized, CWC emissions are spread over larger areas and only show a few hotspots in locations with a high density of cabins, e.g., at the coast. MetCab v.0 gave extremely high emissions at the coast, where this high density of coastal, mainly summer cabins exists. This is probably not where the highest emissions are, as these cabins are more used in summer and thus require less heating. Determining the cabin usage distribution is therefore crucial. This is in turn determined by the properties and facilities of and around the cabin. We try to correct in the new updated version how each cabin is weighted, with data and methods as described in the following sections.

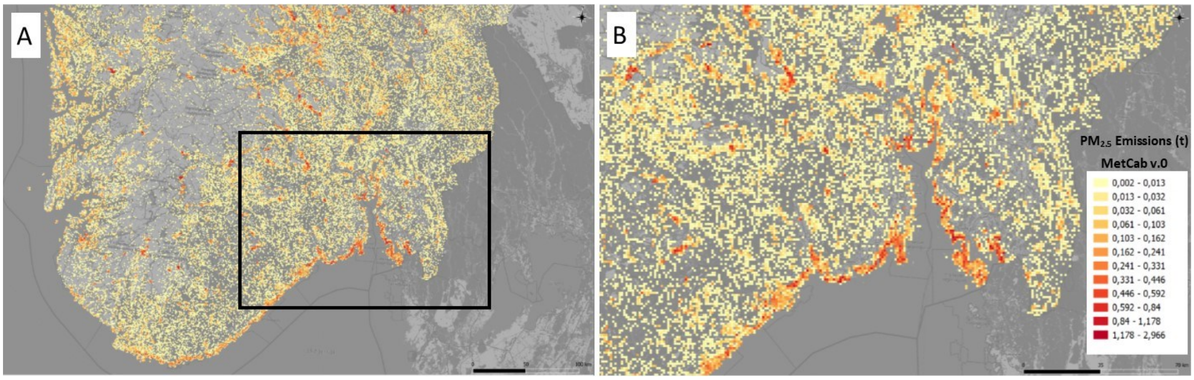

Figure 2: PM$_{2.5}$ emissions (t) from CWC (2016) estimated with MetCab module before updates. Grid resolution: 1 km. The area in figure A represents the zoom in B.

3.2 New Input data

The update of the MetCab module includes updated input data and improved parametrizations to overcome the perceived flawed results identified in the preceding iterations of MetCab. The basic input data to estimate emissions from CWC are wood consumption, emission factors and the spatial distribution of cabins in Norway.

The number and location of cabins was obtained from the georeferenced building statistics (SSB 2020a). These statistics are now available at 250 m resolution, thus increasing the resolution of the emission results from the earlier version. Wood consumption at cabins and holiday houses (“*bui2hol:*

Fritidsbolig" and "*bui2hut Koie, seterhus og lignende*" in the input database) was obtained from the officially reported information from Statistics Norway. MetCab uses the wood consumption for cabins for the available years. As in previous versions, the wood consumption data represent the total amount split in regional divisions Oslo and Akershus, Hedmark and Oppland, Sør-Østlandet, Agder and Rogaland, Vestlandet, Trøndelag, and Nord-Norge.

Wood consumption per technology in cabins in only available at national level, and for county level is only available as total wood consumption. In this study, we use a constant split of wood consumption consistent with that reported at national level by Statistics Norway. In 2019, national wood consumption in cabins is reported to be 51%, 37% and 12% in old stoves, new stoves and open fireplaces, respectively (SSB, 2020d). Although the average consumption in fireplaces and old and new stoves may have differences, there exist additional data from the Fire and Rescue agency on the split of wood burning technologies for cabins. Hereby, 26% of the wood installations are classified as clean in the Fire and Rescue agency dataset, which are taken as new stoves. Of the remaining, and classified as non-clean technology, 61% are old stoves, and 13% are open fireplaces. These data are generally in line with the wood consumption split, and there is not much indicating any strong regional dependency. However, only around 23 000 of about 800 000 buildings were classified as cabins in the Fire and Rescue agency data, as many municipalities only have partial or no description of the building the stove is in. Of these, 5 400 cabins have the type of technology reported and differentiate clean and other technologies. The same emission factors for RWC are used for each technology here for CWC (Chapter 2.1).

Cabins are spread out over most of Norway (Figure 3). They have a variety of properties that often relates to their geographical location. By international standards, Scandinavia has the highest frequency of second home ownership in the world (Hall, 2014). Both at the coast and in the mountains, a cabin or second home is preferred over hotels and lodges (Flognfeldt and Tjørve, 2013). According to Farstad et al., (2008), the average usage of a cabin in Norway is about 31 nights, but this is highly variable (Farstad et al., 2011). The same authors conclude that 36% of the households in Norway own a cabin, and the ownership is rather evenly distributed throughout Norway. In addition, there is no determinable difference between the usage of cabins whether it is owned by urban or rural populations. The distance to and from the residence to the cabin is a strong indicator for the frequency of visits and total nights spent at a cabin. The vast majority of the cabins are located within 3-hour drive from owners' residence.

Figure 3: The distribution of alpine (blue) and coastal (red) cabins in Norway according to the definitions applied (see text for details). The data contain 529 000 cabins of which 38% are defined to be coastal.

Regarding wood burning installations in Norway, there are an estimated 810 000 wood stoves in Norwegian cabins according to Norsk Varme. The Statistics Norway georeferenced file (SSB 2020a) includes 467 374 vacation homes (*bui2hol*) and 47 652 huts (*bui2hut*), which gives an estimated average of 1.6 installations per cabin. According to Norsk Varme, an estimated 65% of these stoves were produced before 1998 in 2016. Considering that 13% of the wood burning installations in cabins are open fireplaces according to the data from the Fire and Rescue Agencies, there are approximately 67 000 open fireplaces in addition to the wood stoves.

Along with the number of nights/days spent at cabins, the consumption of wood is determined, like for residences, by the physical properties of the cabin; the need of heating and availability of other heating sources. The need of heating is determined by the buildings heat efficiency and the difference between desired indoor temperature and the ambient outdoor temperature. This is to a large extent determined by at what time during the year the cabin is used, as obviously wood-based heating requires the presence of people.

To account for differences in each cabin's emissions, MetCab now combines physical geographical information to place each cabin (grid) into a category defined here as alpine or coastal cabin (Figure 3). This approach constitutes an advance regarding other methods available in the literature. For instance, Plejdrup et al., (2016) distinguish between single family houses, apartment and holiday houses in their emission model for RWC in Denmark. Different weighting factors are used for the different dwelling; however, they do not distinguish between holiday houses mainly used in summer or winter. As it occurs with previous versions (MetCab v.0), Plejdrup et al. (2016) obtained high emissions along the coastline where many holiday houses are located similar to those obtained by MetCab v0. In order to improve this, we classified cabins as alpine or coastal based on 4 attributes that were assigned to each cabin grid in the new MetCab module (Figure 4);

1) The distance to the coast.
2) The distance to a city/urban centre.
3) The altitude of the cabin grid.
4) The mean annual temperature of the grid.

The distance to the coast is calculated for each grid as the shortest distance to the coastline, which was a geographical file taken from Høgaas et al., (2012). Figure 4 shows the cabin grids classified according to their distance to the coastline. In a similar way, the distance of a cabin grid to a city centre was calculated as the shortest straight line between each grid and the closest city centre. In this case, we took the centroid of the 773 urban centres ("*sentrumssoner*") in Norway in 2019 obtained from Statistics Norway (SSB, 2020a). The distance is static for all years as the location of the city centres changes very little over time on this timescale.

Temperature is based on the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis fields at a 0.1° x 0.1° resolution. This resolution is probably too coarse for some locations (~10 x 6km) in order to pick up, for instance, fjords, valley and other local effects, nevertheless it gives a good overall description of the climatic features of each grid. For cabin altitude, MetCab also relies on ECMWF data to calculate surface elevation in a grid. This is based on surface geopotential (m s^{-2}) and divided by the gravitational constant, then both altitude (m) and temperature (°C) is re-gridded (bilinearly) and then the two fields are added to the cabin grid. The distribution of all cabin properties in Norway is, along with cabin density, shown in Figure 4. The way in which these assigned properties were used to estimate wood consumption and emissions is described in section 3.3.

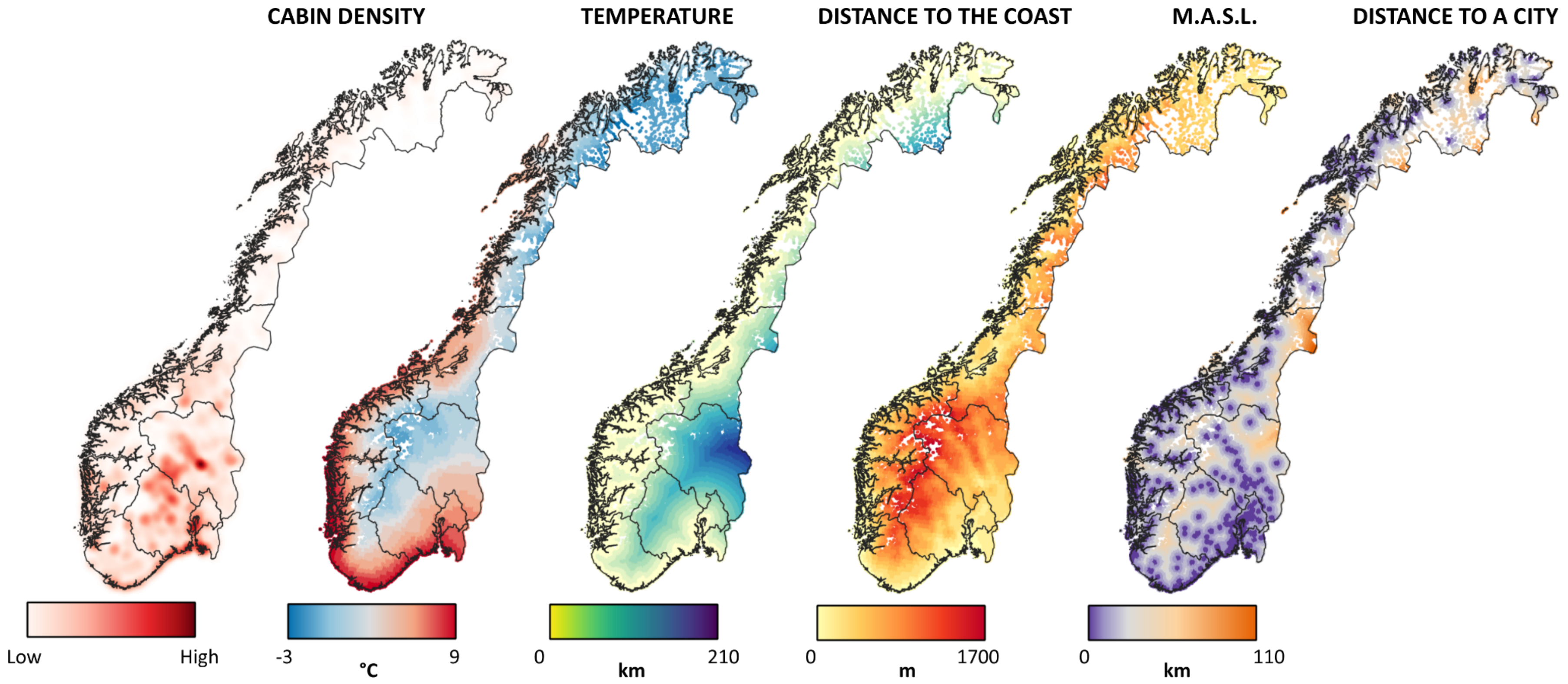

Figure 4: MetVed's assigned properties are shown in figures from left to right: CABIN DENSITY. As there are numerous points covering most of Norway, the map shows in darker colours where the density is higher. TEMPERATURE: The annual average 2 m temperature. DISTANCE TO THE COAST: Shortest straight-line distance from the cabin to the closest point on the coastline. M.A.S.L.: Elevation of terrain where the cabin is located. DISTANCE TO A CITY: Shortest straight-line distance of each cabin to the closest city centre. There are about 700 city centres quantified in the data and they appear as blue circles in the data.

Both the total wood consumption and its temporal distribution are to a large extent determined by the usage of the cabin at a given time. There are no known data sources that directly describe this "*cabin occupancy*" on a given day and so proxies are used. In combination with temperature, the daily consumption is determined by the level of occupancy of cabins.

The relative amount of people in an area generate local traffic, therefore, traffic counting data was taken as a proxy to define cabin activity or occupancy. More than 90% of people visiting their cabin go by car, and an increase in traffic counts has previously been applied to determine the amount of people going to cabins (Hjorthoel et al., 2014; Dybedal and Farstad, 2012). Two traffic counting stations were carefully selected from The Norwegian Public Roads Administration (NPRA) database. They were selected based on their locations, which are characterized by high a density of cabins and the lack of transitional traffic on the specific roads of the counting. While these two sites may not represent sufficiently all areas in Norway and that very few suited traffic counting sites were found. The two selected stations for our analysis are in Hvaler, at the Bukkholmen bridge leading to and from the Hvaler archipelago, and Kirkebrua in Trysil. Both sites do not have much transitional traffic and have a very high ratio of cabins to residential buildings, and Hvaler, for instance, has the highest cabin density in Norway (SSB, 2020c).

For these two counting stations, we use hourly data for two-directional traffic of vehicles shorter than 5.6 m for 2019. For each weekday, the daily "*excess traffic*" was determined as the traffic volume above the 25th percentile (Figure 5), and subsequently weekly excess traffic was calculated. Combined with the Norwegian Holiday calendar, the traffic volume increase associated with each holiday was calculated. Each day with a holiday before and after was then treated as a full holiday, whereas the days where either the day before or after was not a holiday was treated as half holiday. On a normal weekend, Saturdays are treated as holidays and Sundays and Fridays are half holidays. This is due to the fact that traffic increases happen mainly on Fridays and Sundays and people are at the cabins mainly on Saturdays, leaving the other two days as travelling days.

Based on the two-way traffic counting of NPRA, the excess traffic was calculated as the increase in traffic on holidays relative to this benchmark for a road of that size. From this, we calculated a relative excess to the expected traffic on a travel to or from holiday day of 5.4 times with regards to non-holidays, which was used to set the usage ratio between holidays and working days for both types of cabins. For practical calculation purposes, Christmas Eve and New Year’s Eve were treated as full holidays for every year in MetVed.

The resulting fit of weekly and day of the week weights for 2019 are shown in Figure 5, where the usage rates of the two different cabin areas show different properties. The coastal cabins (defined by the Hvaler traffic counting station) show a much clearer seasonal pattern that the alpine cabin (defined by the Trysil traffic counting station). The usage of coastal cabins is negligible from November to March, whereas Easter is the first high peak of the year in cabin usage. The coastal cabin usage is dominated by the 4 weeks of July and weekends around this time, with a very small peak during the week of Autumn holidays (Figure 5). For the cabin area located the low mountains around Trysil, namely an alpine cabin, a much more evenly distributed usage is seen throughout the year, with the most marked peaks around Winter, Easter, Autumn holiday weeks and Christmas / New Year.

Holidays vary across the calendar year and thus, in order to apply this method for any year a parameterisation was made by adjusting the raw fit to the data. It consists of a csv file with a weekly weight, a function to calculate the day of Easter and other school and bank holidays, along with weights for cabin usage increase for each movable holiday. It also has the possibility to set the winter and autumn holiday week for different weeks for different regions. The improved holiday calendar is incorporated also in both residential and cabin calculations of the MetVed model.

The above parametrization provides the daily cabin usage. The parameterization has 2 components and calculate the relative usage as:

*Daily Cabin Usage = WeekW*HolidayC*

Where *Cabin Usage day* should be interpreted as the relative probability that a cabin is in use on a given day. *WeekW* is the weekly weight unique for alpine and coastal cabins and *HolidayC* is from MetVed holiday calendar, where daily weights for both holidays, transition half holidays and weekends are given. Thus, in order to obtain hourly wood consumption at cabins, the daily cabin usage (Figure 5) is multiplied with the HDD (see Grythe et al., 2019) and then with the hourly weight average reported activity during weekends (Haakonsen and Kvingedal, 2001):

*Time Variation (h) = Daily Cabin Usage(d) * HDD(d) * Hourly weight (h)*

The resulting hourly time variation is shown in Figure 5. As for RWC emissions, outdoor temperature is taken as the daily average temperature currently taken from observations from the closest meteorological station from the about 500 measuring stations in Norway, although it can also be sourced from a model field (2m temperature) if desired.

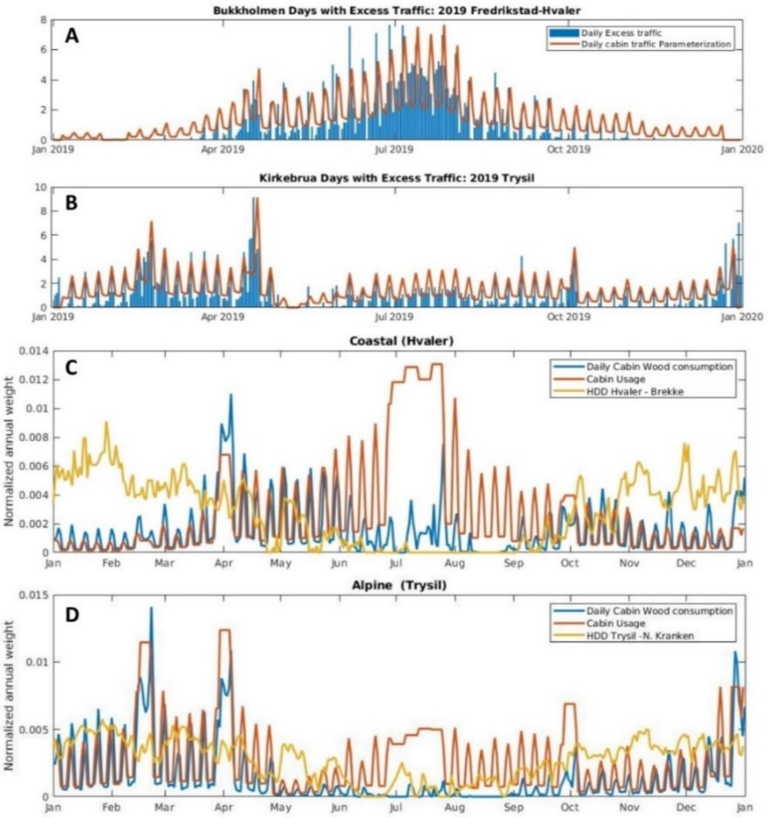

Figure 5: A and B: Daily excess traffic and daily cabin traffic parametrization at Hvaler and Trysil, respectively. C and D: Daily wood consumption, cabin usage and HDD_{15} at Hvaler and Trysil. All data are normalized.

3.3 Method to estimate cabin wood consumption and emissions

Following the method applied in MetVed for RWC emissions, national wood consumption at cabins should equal to the official total wood consumption reported by Statistics Norway. According to our assessments in the previous section, the daily weight can be determined as a function of the **cabin occupancy** and **heating demand from wood**. Both factors have several dependences, however, there are no known direct data to establish them. Where possible, we have derived relationships between ancillary data and established these dependencies.

Heating demand
The specific heating demand from wood stoves and open fireplaces depends on the availability of other heating sources and the total need for heating, which is largely determined by the outdoor temperature (t2m). We follow the same approach as that in the RWC sector and relate heating demand to wood consumption through the concept of HDD (see Grythe et al 2019 for details).

Most of the 519 000 (in 2019) cabins in Norway will have wood burning installation, but most will also have other means of heating such as electricity. Statistics Norway reported that 251.1 kt of wood was consumed for CWC in 2019. Assuming an average of 31 days use of all cabins (Farstad et al., 2008), this gives approximately 16 million cabin-days (total days with 1 or more person in them) for all the Norwegian cabins, which equal to 15.7 kg of wood per cabin-day. Considering a rough half of these days have very limited heating demand, this is equivalent to around 2 x 60 litres bags of wood used per day during the heating season.

The total annual wood consumption of a cabin will depend on the season when the cabin is used, and especially for coastal cabins, which has shown a strong cabin usage seasonality (Figure 5). This is an important factor as Statistics Norway reports wood consumption at regional level and generally, regions include both coastal and alpine cabins, as there is up to 2 000 km distance within a region. It is important to differentiate these as they have different facilities, climates, properties and hence usage rates and times. Therefore, we used the properties of each cabin grid to classify them as either “alpine” or “coastal” cabins. A cabin is classified as alpine if it is located above 400 m.a.s.l.[1], more than 15 km from the coast (as shortest distance) or the grid annual average temperature is below 2°C. These thresholds were set based on visual inspection and analysis of the cabin grid distributions using different settings of the parameters. As these are not official classifications and there exists no exact data a more detailed method would be preferable but was not found. The wood burning installation number was set to 1.2 for coastal and 1.8 for alpine cabins, thus implying the alpine cabins have on average a higher reliance of wood for heating, and that there are more wood burning devices per alpine cabin.

As usage is a key factor in determining the total heating demand of a cabin, we based the heating demand on differences between the two selected locations, i.e., Hvaler and Trysil. This only affects the fundamental parameters and allows for variations between cabins in other places. To establish heating demand, we connect HDD to annual average temperature. As heating demand is also dependent on usage rate, the HDD is only calculated considering the period when the cabin is in use (Figure 5). This is done for both Hvaler and Trysil and the difference in HDD in 2019 between both is roughly a factor of **2** (Hvaler, 2 600 HDD_{15}; Trysil 5 300 HDD_{15}), where subscript 15 is the heating threshold for using firewood, and is at 15 the same as for residential heating. This threshold has been examined for MetVed in different locations, from Tromsø to Lillehammer and Stavanger and regional differences in the threshold were found to be minor (Weydahl et al. 2019 Grythe et al. 2019). Then, the difference in annual average temperature of 3.2 was used to make the relationship between annual temperature and HDD of 0.62 HDD $°C^{-1}$. Ignoring all other influences, this relationship predicts a heating demand

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[1] m.a.s.l.: meters above sea level

difference of 2 by taking the annual average temperature at alpine versus coastal cabins, which fits with the Hvaler – Trysil relationship and thus provides some evidence of the representativeness of these two places.
A key point is that when considering usage difference among both types of cabins, this factor increases to 6.4 in 2019. The reason for this is that with the usage times applied in MetCab the usage of alpine cabins is enhanced in colder periods, whereas the usage of the coastal cabins is heavily enhanced in the warmer months. However, it must also be considered that alpine cabins are on average better isolated and require less heating than coastal, as they are constructed to be used to a larger degree during winter.

Evidence for the better isolation in alpine cabins can be observed by comparing different regions. The warmest average cabin temperature is found to be in Agder and Rogaland at 7.0 °C. These regions have about the same average wood consumption per cabin as the two coldest regions, i.e., Northern and Inland Norway, with annual mean temperature at 2.2 °C. Assuming that these data are accurate, similar average usage of cabins in these regions implies that cabins are built for the environment they are located in, and in addition, that there is a weaker than linear relationship between HDD and heating demand.

As the average cabin grid temperature in a region has very little predictive power to how much wood is consumed in an average cabin in that region, the temperature in each region was normalized. This normalization also reduces the potential border effects that would arise between regions. In addition, a limiting weighting factor was applied to dampen the effects temperature has on consumption:

*HDD weight = W * regional temperature z-score, W = 0.2.*

Where W positive number and is the amplitude by which the normalized temperature data is multiplied.

Cabin usage

The number of nights a cabin is used varies from virtually unused to essentially residential (Farstad et al., 2008). The only available data to suggest the potential use of a cabin is the distance from the owner's residence. Systemic differences in the use of a cabin type were therefore set by the distance from a city centre. Rather than applying this as an individual feature of each grid, the average distance from a city centre was used for the two classes: coastal and alpine cabin. As there are no data on where each cabin owner actually lives, this is an approximation, as it is unlikely that most owners live in the closest city. As alpine cabins are by this definition more remote by approximately 12 km on average from a city centre, we set the usage rate for alpine cabins to 20% less than for coastal cabins.

Usage weight = 1.2 coastal and 1 for alpine.

Wood Potential

The wood potential of a cabin is determined in relation to the other cabins of each region. The wood potential is then used as distribution key to distribute the total consumption in a geographical region. For each grid the wood potential is given by:

*Wood Potential = Number of Cabins *Cabin type weight * HDD weight*

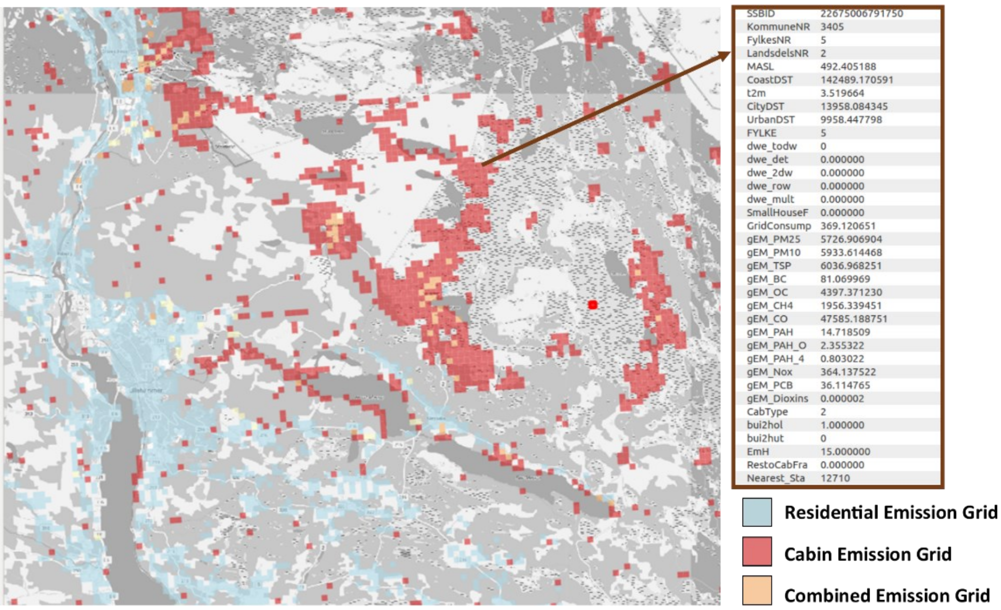
To arrive at consumption in a grid the normalized wood potential is multiplied with the total consumption in the geographical area. The consumption is then multiplied with the local emission factor to arrive at annual emissions.

Emission Height

Emission height for cabins are set to 15 m, the same as the height for detached houses. Arguably cabins are somewhat lower than detached houses on average and with proper documentation of this could be adjusted.

4 MetVed Output

MetVed has 4 primary output files, 3 annual emission files and a time variation file. The annual emission files are ESRI shape files, one for RWC, one for CWC and one combined (ALL) file. Each of these files contain all grids with corresponding emissions and all information about the grid that is used by the model. Each grid is in the reference Statistics Norway grid, containing the assigned ID by Kartverket, and is in the UTM 33N coordinate system. Much of the data is dynamically assigned in the model and can vary somewhat with different years. The model is also set up with a number of options that can change the output if desired. The fields in the total emissions file are shown in Figure 6.



SSBID	22675006791750
KommuneNR	3405
FylkesNR	5
LandsdelsNR	2
MASL	492.405188
CoastDST	142489.170591
t2m	3.519664
CityDST	13958.084345
UrbanDST	9958.447798
FYLKE	5
dwe_todw	0
dwe_det	0.000000
dwe_2dw	0.000000
dwe_row	0.000000
dwe_mult	0.000000
SmallHouseF	0.000000
GridConsump	369.120651
gEM_PM25	5726.906904
gEM_PM10	5933.614468
gEM_TSP	6036.968251
gEM_BC	81.069969
gEM_OC	4397.371230
gEM_CH4	1956.339451
gEM_CO	47585.188751
gEM_PAH	14.718509
gEM_PAH_O	2.355322
gEM_PAH_4	0.803022
gEM_Nox	364.137522
gEM_PCB	36.114765
gEM_Dioxins	0.000002
CabType	2
bui2hol	1.000000
bui2hut	0
EmH	15.000000
RestoCabFra	0.000000
Nearest_Sta	12710

Figure 6: A close up of Lillehammer and the area to the east of it. The window on the right displays the variables in the output ALL_Emissions_2019. These fields include emissions in grams and ancillary data defined at each grid.

The time variation is an ascii text csv file. This file contains the normalized time variation either of the temperature measurement stations or from the gridded temperature. The latter was considered too large and is not a part of the standard output as it adds very little compared to how cumbersome it is to apply. The column header is a Norwegian meteorological office station id, proceeded by a letter A, C or R, representing alpine, coastal and residential time variation respectively. As the two types of cabins have different usage rates (Figure 5) and the residential have its own, each meteorological station produce 3 time variations. The first column is the Norwegian wintertime hour, and each data point is the hourly weight to multiply annual emissions by in order to obtain hourly emissions for the following hour.

5 Assessment of updates to emissions from RWC and CWC

In this chapter we present an assessment of the updates and improvements done over the MetVed emission model. We have selected some of the most determining factors that have been updated, such as the emission factors (section 5.1), and the spatial (section 5.2) and temporal (section 5.3) distribution of emissions from CWC. In general, the updates and improvements done involve a more comprehensive inventory due to the inclusion of the improved emissions parametrization for cabins. We also foresee improvements due to a better parametrization of the time variation of emissions and the inclusion of a dynamic system that consider the building statistics that correspond to the emission year. The spatial distribution of emissions follows the same principles than in MetVed v1. Therefore, significant differences in the spatial distribution of emissions are not foreseen. Potential differences in the spatial distribution of emissions between v.2 and v.1 could be associated with the differences in the building stocks per year, and this could be evaluated in the future, specially concerning the time series of emissions.

The best way to validate the updated emissions both from the RWC and CWC subsectors is against measured atmospheric concentrations. To do this, there is the need to perform atmospheric dispersion modelling where updated MetVed emissions are used as input data and compare the results with observations. However, especially in the rural areas with high cabin density there exists very few measurements of for instance PM, and for most compounds, there is none. Therefore, validation is primarily done by assessing other relevant data on distribution, consumption and emissions.

There exists very limited direct data regarding the usage of cabins, or indeed the actual difference between the frequency of wood burning installations in cabins at varying locations or their isolation. As for RWC, the usage of a wood burning installation must also be assumed to vary greatly between individual households. Therefore, a conservative approach was used in setting a parameter for differentiating consumption in cabins.

5.1. Emission factors update

Emissions factor is one of the critical aspects defining the accuracy of emissions from wood burning from residential heating. The EFs employed in MetVed v.1 from Seljeskog et al., (2013) were the factors previously used for the official reporting of emissions to the CLRTAP. As in MetVed v.2, the emission factors have been updated also in the official reporting of emissions, and Seljeskog et al., (2017) are currently being used (Norwegian Environment Agency, 2020). Several studies in the literature (e.g., Denier van der Gon et al., 2015; Grythe et al., 2019), pointed out about the uncertainties in emissions factors for $PM_{2.5}$ and on the possibility that those previously used (Seljeskog et al., 2013) may involve an overestimation of emissions from RWC. The updated emission factors (Seljeskog et al., 2017) are much higher emissions for old stoves, but lower for new stoves, and will today act to reduce emissions, but only from new stoves. With the update it is implied that the decline in emissions is faster than previously assumed, higher back in time and lower in most recent years. Such a reduction should be evident over time. However, in a case study for Oslo, an approach based on winter and firing time observations of $PM_{2.5}$ levels found no evidence that the reduction trend in $PM_{2.5}$ levels is underestimated with the 2013 emission factors (López-Aparicio and Grythe, 2020). Based on these findings, it is hard to conclude that the emission reduction is attributed to new stoves, and to ascertain that the update overall gives a better presentation of actual emissions.

Figure 7 shows $PM_{2.5}$ emissions from sector 1.A.4.b.i (Small Combustion: Residential Stationary) submitted to the CLRTAP by Norway. In addition, we have included $PM_{2.5}$ emissions in Norway estimated by MetVed v.1 and MetVed v.2 based on EFs developed by Seljeskog et al., (2013) and Seljeskog et al., (2017), respectively. From 2013 to 2018, $PM_{2.5}$ emissions from both versions of the

MetVed model agree well with the $PM_{2.5}$ official emissions from the residential stationary sector, although emissions produced by MetVed v.1 are slightly higher in the most recent years.
The biggest discrepancies are observed from 2006 to 2012. In the early years, from 2006 to 2010, emissions produced by MetVed v.2 seem to be at the same level as those officially reported, whereas emissions produced by MetVed v.1 are lower. MetVed emissions represent exclusively those associated with wood fuel, whereas the official emissions include in addition those associated with gaseous, liquid and solid fuels (Figure 7). Therefore, emissions from MetVed should be at a lower level than those officially reported as it does not include activity data regarding other fuels. The difference should be also more noticeable in the early years, due to the more prominent presence of other solid fuels, before its disappearance in 2008, and the reduction in liquid fuels over time (Figure 7).

Based on the data published by Statistics Norway regarding the average energy used per household, the use of oil and paraffin has been reduced by an average of 3% per year since 1993 to 2012, whereas electricity and other fuels (i.e., wood, coal and coke) show an average reduction of 1% per year. The time series data from Statistics Norway SSB regarding energy used per household was discontinued in 2012. Fuel sales statistics in Norway (Drivkraft Norge, 2020) show that since 1973 to 2017 the sales of kerosene, paraffin, heavy distillate and heavy oil for residential heating have been reduced by an average of 2% per year, also after temperature correction. The difference between the MetVed estimate for RWC and CWC emissions and the officially reported emissions for combustion in the residential sector should, therefore, decrease over time. With the EFs from Seljeskog et al., (2017), MetVed total emissions seem to be exactly at the same level or slightly higher than the total emissions from combustion in the residential sector also back in 2006, where other fuel sources should have a stronger effect on total emissions. That the emissions are at the same level in early years is unclear for us, whereas slightly higher in more recent years can be explained by the share of wood consumption per technology in cabins, which differs to the share reported by Statistics Norway.

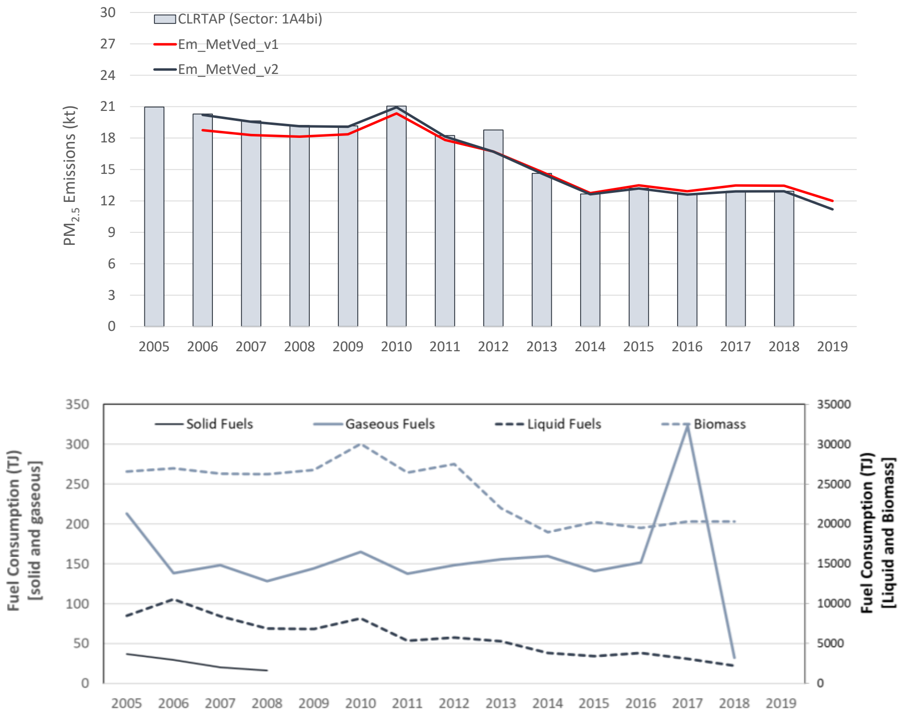


Figure 7: Top; $PM_{2.5}$ emissions from residential heating (Sector 1A4bi: Residential: Stationary) submitted to the CLRTAP by Norway (Grey bars; Source: https://www.ceip.at/) and emissions estimated by the MetVed model based on EF from Seljeskog et al., (2013) (Red line: Em_MetVed_v1) and Seljeskog et al., (2017) (Black line: Em_MetVed v2.0). Bottom: Trends of fuel consumption in the residential heating sector in Norway (Sector 1A4bi: Residential: Stationary; Source: https://www.ceip.at/).

The comparison between MetVed and official emissions reported to the CLRTAP and UNFCCC have also been assessed for the other compounds emitted from RWC and CWC. Table 1 shows the comparison for all emitted compounds. Except CO_2, NO_x and SO_2, all species show similar deviations as $PM_{2.5}$, that MetVed produces slightly higher emissions (in 2018) than those officially reported and for the same reason as for $PM_{2.5}$. The exceptions of NO_x and SO_2 can be explained by the fact that other fuels used in residential heating have a stronger influence on emissions of these compounds. For instance, the EF_{SO2} for heavy fuel oil for residential heating is 17.94 kg/t versus 0.35 kg/t in the case of fuel wood. In the case of NO_x, the EF_{NOX} for kerosene for residential heating in small stoves is 2.3 kg/t, whereas for fuel wood is 0.97 kg/t. For CO_2, the reported amount excepts emissions from biofuels (IPCC, 2006).

Northern Scandinavia is the place in Europe that has shown the highest reduction in HDD and this trend is predicted to continue under all IPCC RCP's with a reduction of more than 25% in 2100 relative to 1980 (Spinoni et al., 2018). Alone, this trend indicates a decline in residential energy consumption of about 0.24% per year. In Grythe et al. (2019), the decline in wood fuel consumption was investigated and in part attributed outdoor temperature and several house effects; oven efficiency, changes in preferred indoor temperature, residential house size and insulation changes, lower share of total heating from wood, in all predicting a decline of 2.3% per year in wood consumption. In addition to the decline in consumption, Lopez-Aparicio and Grythe (2020) found an annual reduction of emission factors of 0.73% per year between 2005-2018 in Norway, resulting in a predicted decline of ~3% per year in emissions. This should predict that the observed long-term decline in RWC emissions is ongoing and should continue also in the future.

*Table 1: Comparison between national emissions estimated by MetVed v.2 (2018 and 2019) and reported by Norway to the CLRTAP and UNFCCC (2018) (Sector 1.A.4.b.i: Small Combustion: Residential Stationary) for air pollutants and GHGs, respectively. n.r.: compounds are not reported. n.a.: emissions for these compounds are not available. * CO_2 from biomass burning is considered zero in the official reports to UNFCCC according to IPCC guidelines (IPCC, 2006).*

Compound	**CLRTAP and UNFCCC (2018)**	**MetVed v.2 (2018)**	**MetVed v.2 (2019)**
CO (t)	92 623	92 480	83 107
CH_4 (t)	8 460	8 911	7 716
PM_{10} (t)	14 055	14 569	12 741
$PM_{2.5}$ (t)	12 931	13 371	11 708
BC (t)	830	832	740
PAH_{TOTAL} (t)	n.r.	22	18
PAH-4 (t)	1.2	1	1
N_2O (t)	30	31	28
NO_x (t)	1 105	966	873
CO_2 (t)	161.60*	1 573 013	1 426 367
NMVOC (t)	17 278	17 590	15 747
OC (t)	n.r.	8 138	7 109
SO_2 (t)	376	338	306

5.2. Spatial distribution of emissions

Figure 8 illustrate the spatial distribution of emissions from RWC and CWC. As it is expected RWC is mainly allocated to densely populated areas, whereas CWC is more spread out in terms of its geographical location (Figure 8). For the estimate of emissions, we have chosen to use the geographically resolved consumption data from Statistics Norway. As a consequence, there is less uncertainty in where the consumption takes place, but it also displays some of the features of the data. For cabins we saw that there is little to no dependence on the average temperature of the cabins in that part of the country and the wood consumption. Still we selected to use temperature as a determining factor for consumption for cabins. This is due to the fact that each of the 7 regions spans over relatively much larger geographical areas. In the case of RWC, wood consumption is available at county level and so the area covered by each county is smaller. Table 3 and Table 4 show the regional and county data on cabins and residential buildings, respectively, along with statistics on the wood consumption per cabin type or highest/lowest wood consumption per household. In the case of RWC, it is correct to assume that the lowest wood consumption in each county correspond to that in apartments.

At the grid and in several areas, we have detailed data, down to fireplace type and chimneys. However, this data is limited, and as individual usage is unknown, it is more accurate to treat it statistically as such a large fraction all types of houses have installations. The statistical treatment of the gridded data also reduces the uncertainties associated with the errors and flaws identified in the different datasets, such as missing information or misplaced fireplaces.

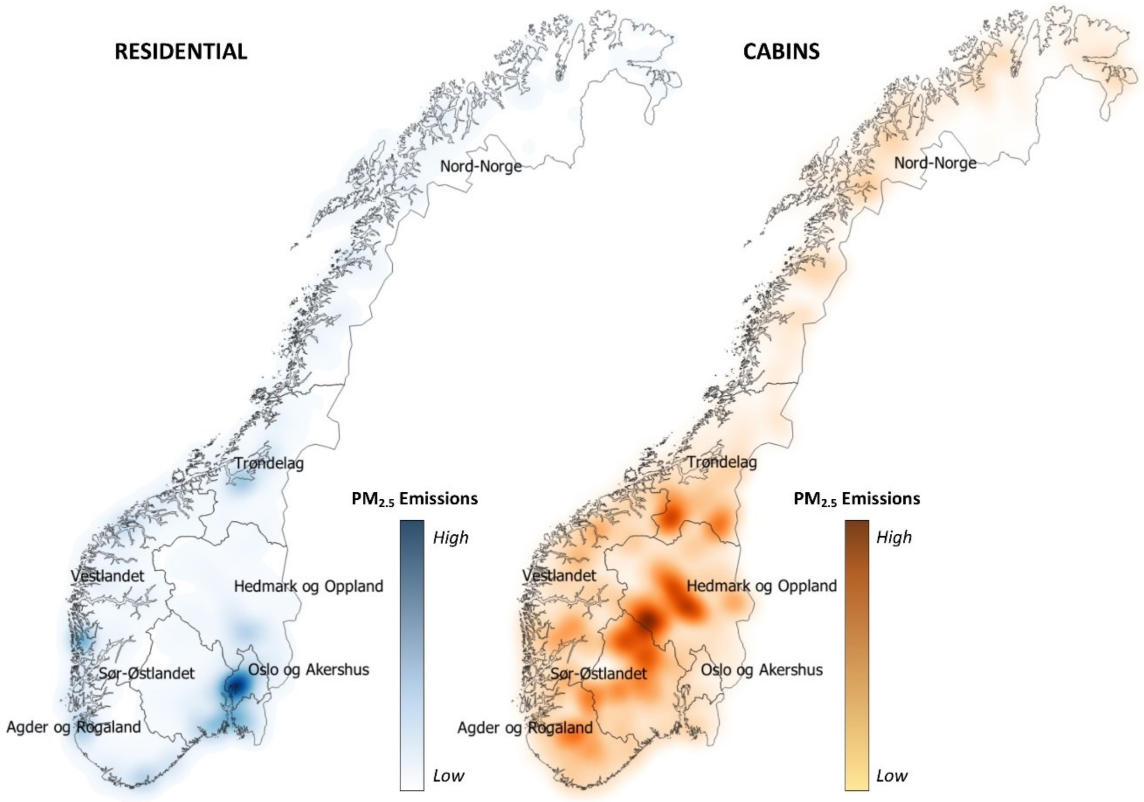


Figure 8: 2019 Annual emission density map for residential (left) and cabins (Right). For illustration purposes emissions are shown as heatmaps of emissions. The two figures have different scales, the residential is roughly an order of magnitude higher.

Table 2: Regional data on cabins and the distribution of wood consumption, and the ratio of alpine to coastal wood consumption in cabins.

Region	Total Cabins	WC (kt) (dry)	Average WC (kg)	Alpine Cabins (%)	Average WC Alpine (kg)	Average WC Coastal (kg)	(WC_{Alpine}/ $WC_{Coastal}$)
Oslo and Akershus	17 369	1.70	99.14	36	172.79	56.84	3.04
Hedmark and Oppland	106 200	45.70	430.08	100	430.08	-	-
Sør-Østlandet	123 328	37.60	305.19	64	414.85	107.17	3.87
Agder and Rogaland	64 637	26.20	405.96	40	707.17	205.86	3.44
Vestlandet	80 373	36.00	447.89	42	747.15	229.67	3.25
Trøndelag	56 781	27.10	478.01	54	710.26	206.87	3.43
Nord-Norge	66 338	31.60	475.90	49	740.92	222.19	3.33

Table 3: Regional data on residences and their wood consumption per household.

Fylke	Total Residences	Average distance to City (km)	Average WC (kg)	Highest WC per Residence (kg)	Lowest WC per Residence (kg)
Østfold	131 732	2.99	339.46	509.28	28.96
Akershus	251 404	2.30	303.76	525.47	29.22
Oslo	322 624	0.74	66.71	376.19	21.17
Hedmark	97 962	7.07	423.48	533.47	35.41
Oppland	93 494	6.18	366.79	449.64	32.31
Buskerud	127 505	4.65	215.11	317.62	14.86
Vestfold	110 512	2.91	330.37	485.18	29.55
Telemark	83 194	4.20	328.79	429.10	33.19
Aust-Agder	54 490	4.41	323.79	401.84	28.96
Vest-Agder	82 759	3.65	407.23	625.06	36.07
Rogaland	205 130	3.05	217.06	339.84	10.85
Hordaland	244 671	3.87	241.46	435.21	18.26
Sogn and Fjordane	54 041	10.71	492.76	606.39	24.25
Møre and Romsdal	125 521	6.50	359.16	502.12	31.49
Sør-Trøndelag	154 107	5.47	286.08	557.78	22.56
Nord-Trøndelag	63 955	10.34	502.26	652.48	41.67
Nordland	120 922	8.82	361.60	482.66	35.23
Troms	83 115	8.50	201.76	285.56	15.02
Finnmark	37 280	13.74	307.58	403.38	51.64

5.3. Time variation of emissions

The use of cabin occupancy is necessary due to the requirement of the presence of people to operate stoves and fireplaces and its strong variance throughout the year and week. There exists very little data on when cabins are occupied, and what determines when people use firewood for heating cabins. However, for outdoor temperature there exists good accurate data with good spatial resolution, and the relationship with heating demand has been investigated rigorously (e.g., Bands et al., 2013). Figure 9 shows the time variation of emissions from RWC and CWC, the latter one differentiated in coastal and alpine cabins. RWC emissions occurs mainly during the winter months, at weekends and during the evenings. The time variation of emissions from CWC shows clearly differences between coastal and alpine cabins due to their different occupancy during the year. While alpine cabins show higher activity in winter months, coastal cabin activity is more predominant in the Easter Week, July and Autumn holidays.

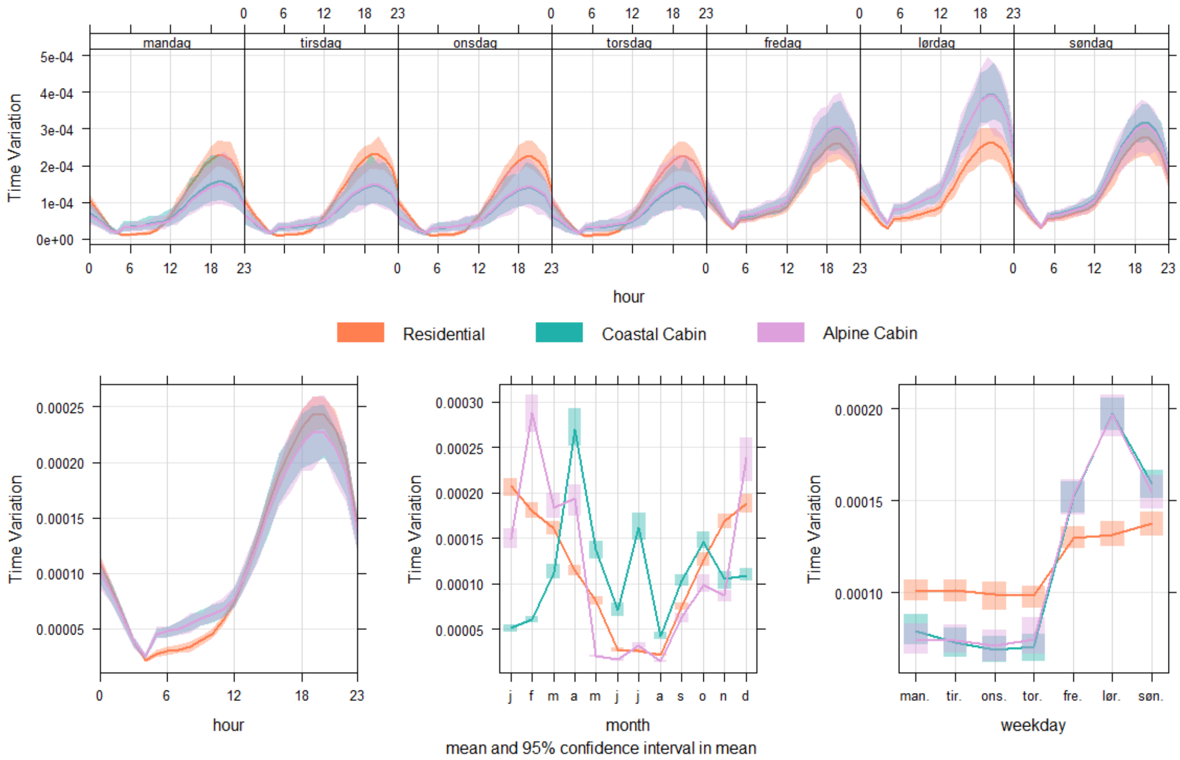


Figure 9: Time variation of emissions from RWC (Residential), CWC in coastal cabins and CWC in alpine cabins. The time variations are based on HDD at one meteorological station out of the approximately 500 stations available in 2019. Top: hourly time variation per weekday. Bottom left: Hourly time variation. Bottom middle: monthly time variation. Bottom right: Weekday time variation.

Possible data to cross reference or check the derived time variation based on the cabin occupancy were evaluated. Rental price variation at different times on sites like Airbnb or finn.no could offer some clues but this is indirect proxy data and is hard to quantify this in a meaningful way. Also travel and holiday surveys generally have too broad questions to capture detailed effects on weekends and moving holidays especially. One idea was to have retail volumes at sites generally influenced by the cabin population. This could be grocery stores at places like Oppdal, Hvaler, Sjusjøen or Kragerø, but in the end, we opted for traffic counting and a comparison with a holiday calendar to quantify the amount of activity at cabins. It offers reliable and objective data with low uncertainties. The main objection to these data is perhaps that it is not clear how much traffic are generated by people when they have first arrived at their cabin, and that suitable traffic counting stations were limited.

An emerging source of data is temperature information from microsensors. Originally designed to improve the effectiveness of chimney sweeping, and thereby reducing emissions, a temperature sensor (AirMont.no) installed inside individual chimneys offer real time hourly temperature data. When widely deployed, these data may offer the possibility to evaluate the time variation of emissions with very high levels of detail. Also measured temperature by microsensor does not have the same large uncertainties associated with it as other types of microsensors (e.g., air pollution low-cost sensors) and could give accurate and detailed information on the usage of wood burning installations. NILU is currently in dialogue with AirMont to evaluate potential collaborations in the use of these temperature data to improve the knowledge on wood burning emissions.

6 Maintenance and future updates

The code will be maintained and updated by NILU. Any changes to the code will be accessible through GitHub. This allows also to use old version of the code if updates are not wanted.

6.1 Yearly updates

The MetVed model as it stands now requires i) annual consumption data, ii) gridded dwelling and cabin input data and iii) temperature to be updated for the computation year. The model should need no further input data to simulate a new year, and this can and should be done every time the new data are available. This is typically:

- Wood consumption: the wood consumption data is published by Statistics Norway and the data for a specific year is available the year after. Based on our experience, there has been no consistency on the publication date of these datasets, and it can vary from late spring to late autumn.
- Gridded dwelling and building: these databases represent the buildings registered by the 1st January. Hereby, a database that represents 2019 contains the building stock registered by 1st January 2019. Based on our experience, gridded building information for a specific year is available in the same year that it represents, and it is possible to access in spring.
- Temperature: the temperature data (daily mean temperature) is currently retrieved from the Norwegian Meteorological Institute (eklima.no) based on observations. Each yearly dataset is therefore available on January 1st the year after.

Changes of administrative unit from 2020 involves new administrative borders. These modifications could require adjustments to the code to deal with such changes. For instance, the new administrative units involve changing from 19 to 11 counties, and some of them become much larger and more diverse. This may introduce strong border effects or have unexpected consequences that lead to further processing of the data or adaptations. These aspects need to be evaluated once the data, e.g., wood consumption at the new county level are available.

6.2 Further developments and improvements

There are a number of variables that could be improved. As far as possible we recommend that MetVed emissions are based on quantitative data where available. Below are some points (not in order of priority) for desirable improvements or updates. Though none of them seems critical, there are always room for more data to either improve parametrisations or to be used directly in the model.

Update of **other input data** beyond the annual data (i.e., wood consumption, gridded building number, temperature): this refers to ENOVA, webcrawled data and the databased from the fire and rescue agency at the municipalities. Updates, in these cases, should be considered when the data has increased in coverage or type of information, then re-processed to incorporate the improved or new information. The frequency this could be done is considered to be approximately 5 years for ENOVA and somewhat sooner for the webcrawled data as it was originally less complete. For the data from the fire and rescue agencies at municipalities, the prioritization should be given to contact those municipalities from which data is lacking in order to increase coverage. These are about 250 mainly small municipalities that did not respond to initial inquiries about data in connection to the MetVed project. As the ways municipalities have their data stored varies significantly and also the accuracy and update rate is extremely variable, it is hard to know exactly how much this would add to the model accuracy, unless complete national coverage is achieved.

Other residential heating source emissions. The current version of MetVed considers the availability of other heating sources other than wood as one of the parameters that determine the wood consumption. This data is currently available from statistically processed information based on the webcrawling database. However, the team see the need to investigate available georeferenced data that represent for instance the district heating network in Norway. We are aware of the current implementation of new district heating areas (e.g., Grunerløkka in Oslo), which can affect the distribution of emissions at local scale in the coming years.

Classification of cabins. The current version of the MetCab module distinguishes between coastal and alpine cabins in order to establish the differences in the usage and account for the time variation of emissions. The possibility of envisioning hybrid cabins or adding other types of cabins with individual properties also exists. Additional data to classify the cabins should also be considered.

Detachment from Statistics Norway wood consumption. By detaching MetVed from the annual wood consumption reported by SSB it would become a pure bottom up model. This has many implications that must be considered. The main implication is that it would predict annual wood consumption and emissions by itself, and thus not necessarily be equal to those reported by Statistics Norway to international conventions. However, the predictive power of energy trends and HDD in Grythe et al. (2019) was estimated to explain 80% of the variance in the Statistics Norway consumption, so the year to year difference between Statistics Norway and an estimate based on this is expected to be small. While this difference must be seen as a disadvantage, there are also advantages. A key advantage is that it would be more feasible to make forecasts and autonomously predict current and future emission with more confidence. It would also allow for a more detailed description of share of wood consumption per technology. This could be done by having either a separate version or module.

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