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Article

HIGH-RESOLUTION EMISSIONS FROM WOOD BURNING IN NORWAY - THE EFFECT OF CABIN EMISSIONS

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Abstract: Emissions from wood burning for heating in secondary homes or cabins is an important aspect for the development of high-resolution emission inventories in specific areas. Norway is used as case study as the national wood consumption for heating in cabins is around 20% of the total. Our study shows first a method to estimate emissions from cabins based on traffic data to derive cabin occupancy, which combined with heating need allows for the spatial and temporal distribution of emissions. The combination of residential (RWC) and cabin wood combustion (CWC) emissions shows large spatial and temporal differences, and a temporally "cabin population" can in areas be orders of magnitude larger than the registered population. While RWC emissions have been steadily reduced, CWC have kept relatively constant or even increased, which results on an increase in the cabin share to total heating emissions up to 25-35%. When comparing with regional emissions inventories, our study shows that the gradient between rural and urban areas is not well represented in regional emissions inventories, which resembles a population-based distribution and does not allocate emissions in cabin municipalities. At last, our study shows that CWC emissions may become an increasing environmental concern as higher densification trends in mountain areas are observed.

Keywords: residential wood combustion; emission modelling; MetVed model; cabin heating; cabin development; mountain areas

1. Introduction

Residential Wood Combustion (RWC) is a myriad of individual periodic point emission sources, which are statistically treated as a diffuse source. In Norway, with a population of approximately 5.4 million inhabitants, there are over 2.5 million wood burning stoves, and over half of them are used regularly. This high number of wood burning stoves also occurs in other countries (e.g., other Nordic countries, United Kingdoms, New Zealand) and in mountain regions (e.g., Alpine region). RWC is a valuable and important energy source for heating but is also one of the largest contributors to particle emissions, and the responsible of recurrent pollution episodes in Europe and other countries (e.g. [1–5]). Therefore, the understanding of RWC emissions, including the spatial and temporal distribution, is crucial for air quality management and the implementation of cost-effective measures to reduce air pollution. In order to evaluate policy scenarios and their effectiveness, emission inventories need to represent as close as possible the emission process, including accurate knowledge on where and when emissions occur. However, the distribution of residential emissions both in space and time poses important challenges. Knowledge and data concerning the amount of consumed wood and the type of technology are not usually available with much geographical or temporal detail. In addition, there are several influencing factors that largely affect emissions, such as variable weather and human behaviour. With regards to the latter, the way the wood stove is operated will have a strong effect on emissions, and can even be more important for emissions than the type of stove, as a clean stove operated in partial load have significantly higher emissions than an old stove operated with nominal load [6]. Moreover, heating by wood is commonly one out of several available

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heating options and thus, the share of energy sources will further vary with prices and the availability of the different energy options, such as gas and electricity.

The challenges concerning the estimation of RWC emissions and their spatio-temporal distribution have brought the need of continuous evaluation of existing emission inventories and proxies to improve these emissions. One commonly used approach for the spatial distribution of emissions has been proxies-based downscaling national emissions reported by Member States to the Convention of Long-Range Transboundary Air Pollution (CLRTAP), where RWC is included in NFR (Nomenclature for Reporting) Sector Residential: Stationary (NFR Code: 1A4bi). For instance, in CAMS regional emissions, the spatial distribution of emissions from the residential sector is done by using total population for light or medium fuels, rural population for coal and heavy liquid fuel, and wood use maps based on population density and wood demand and supply functions for biomass [7]. The use of population as ancillary data has been intensively discussed in the literature, as emissions may be overallocated in densely populated areas (e.g., [8,9]). In addition, studies highlight that spatial proxies typically used to place RWC in one area or region are hardly transferable to other areas than those where they were generated for, or they are highly inaccurate over large areas (e.g., [8,10,11]).

Local knowledge is essential to understanding emissions and developing the most accurate proxies for their spatio-temporal distribution, in a way that they resemble as close as possible a pure bottom-up approaches, where emissions are calculated at the individual source level and, therefore, have precisely defined the spatial allocation. In the last decades, several studies have focused on the development and analysis of RWC emissions for specific countries. For instance, [9] analyse the spatial distribution of RWC emissions in Nordic countries. Even thought one would expect that Sweden, Denmark, Norway and Finland to hold many similarities concerning wood burning activity, important differences concerning the predominant wood burning technology (boilers vs wood stoves) and even the location (main distribution in suburbs vs activity in urban areas) make the most suitable proxies for these Nordic countries different. One of the most challenging aspect for developing spatial proxies for residential emissions is to predict the fuel mix. In Norway, electricity is the main source of heating followed by wood, and other fuels only represent a minor part of the energy mix. In Poland, for instance, the main energy source for space and water heating is hard coal followed by natural gas, wood and other minor sources. The identification of the different energy sources for heating at high-resolution represents one of the biggest challenges in these countries. [12] developed a high-resolution spatial emission inventory for greenhouse gas emissions in Poland, and in the case of residential emissions they use population data along with data on access to energy sources, percentage of area equipped with central heating and data on the amount of heat energy provided to households. Similarly, [13] developed also an air pollutant emission inventory for RWC in Poland based on building data including characteristics that define their insulation factor, energy demand based on the heating degree day, the fuel mix, gas usage for heating, heat distribution network and access to heat distribution network.

In this study, we consider one aspect beyond the spatial and temporal distribution of emissions from RWC, which is the use of wood burning for heating in secondary homes or cabins (cabin wood combustion; CWC, in this study), and discuss the relevance for regional emission inventories. CWC emissions are also included within the NFR Sector Residential: Stationary (1A4bi), although they are not commonly treated separately in regional emission inventories. We use Norway as case study as Norwegians spend less than 2% of their time at cabins but, according to the national statistics [14], over 20% of the total wood consumed occur there. Cabins are spread out over most of Norway, and they have a variety of properties that often relate to their geographical location. By international standards, Scandinavia has the highest frequency of second home ownership in the world [15]. Both at the coast and in the mountains, a cabin is perceived as preferred over hotels and lodges [16]. According to [17], the average usage of a cabin in Norway is about 31 nights, but this is highly variable [18]. The same authors conclude that 36% of the households in Norway have access to a cabin, and the ownership is rather evenly distributed throughout the country. The distance to and from the primary residence to the cabin is a strong indicator for the frequency of visits and the total nights spent at a cabin, and the vast majority are located within 3-hour drive from the owners' residence.

In Norway, RWC emissions are estimated with the MetVed model, which is based on several high-resolution data-sets including dwelling number and type, wood and energy consumption, available heating technology, location of RWC chimneys and meteorology [19]. However, the proxies used for the distribution of RWC emissions are not directly transferable to emissions from CWC as, in the latter, emissions from a temporal "cabin population" needs to be determined for the different types of cabins, which usage largely varies across locations and seasons. Other available models to distribute emissions from residential wood combustion use a weighting factor for wood combustion per building group, and in the case of holiday house they assigned 0.2, assuming to be occupied only part of the year and mostly during warmer periods [20]. In this study, we present a novel method to estimate CWC, where both the method for spatial and temporal distribution largely differ from RWC. The estimation of the "cabin population" is based on determining the excess traffic in areas characterised by high density of cabins. Both RWC and CWC emissions are compared and benchmarked with CAMS regional emission inventory for residential heating to analyse the implications of a high share of CWC for total and urban emissions. Moreover, whilst, in the past, cabins were predominantly made up of simple structures, with wood as the sole heating source, and largely dispersed, our study shows how new cabin development involve the creation of large cabin settlements. The share of CWC for heating has steadily increased compared with RWC, and we use available data to examine the reasons for this increase. The methods and results presented in this study are especially relevant for other countries and regions (e.g., Alpine regions) with intense wood burning activity and a high share of cabins. For instance, in the Nordic countries, where the cabin stock is estimated to be around 75 per 1000 inhabitants. Moreover, the proxies can be used for other activities that entail a significant flow of population from their residence, such as energy consumption during holidays or associated with tourism activities.

2. Methodology

In this section we present and analyse the input data used to estimate emissions and distribute them at high spatio-temporal resolution, along with the proxies to determine cabin occupancy and heating needs to, thereafter, estimate emissions. As the methodology to estimate high-resolution emissions from RWC is described in detail in [19], this section has a stronger focus on the methodological aspects concerning high-resolution emissions from CWC.

2.1. Wood consumption for heating

In Norway, the amount of wood consumed each year is estimated based on the responses to the Travel and Holiday Surveys run by Statistics Norway on a quarterly basis, where each survey covers the preceding 12 months. The annual wood consumption for heating is then obtained by the average of five consecutive quarterly surveys [14]. The sampling of the survey is drawn at a nationwide level and is considered representative for all 11 counties. The sampling error is estimated to be 3% on national scale, and there are separate questions for primary and secondary properties, [for details, see 19]. As there is no other available source of wood consumption for heating in residences or cabins at national scale, this represents the main input data to estimate wood combustion for heating. However, annual total number of heating degree days (HDD) were found to explain ($r2 = 0.8$) the inter-annual variations in consumption between 2005 and 2018, indicating that wintertime temperatures can also be a good indicator for RWC [19].

Wood consumption for residential and cabin heating are available on a yearly basis and split in consumption in old stoves (produced before 1998), new stoves (produced after 1998) and open fireplaces. While for residential heating, wood combustion per technology

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is provided at county level, in the case of cabin heating, the wood consumption is reported for 5 regions, where each region contains several counties, and the split in technology is only available at national level (for more detail see 2.2).

The trend of wood consumption for residential and cabin heating have been analysed for the period between 2005 and 2021 (Figure 1), and a declining trend in RWC is found from 2005 to 2019. This decline is related to more energy efficient buildings, lower shares of wood as a heating source and more efficient stoves, despite more and larger residential buildings. In 2020, the decline was interrupted when, even experiencing the warmest winter season, COVID19 and the imposed lockdowns affected human activity and increased time at residences, which is related to higher residential wood burning activity. The increase in 2021 regarding preceding years may resemble the still higher activity at residences due to COVID19 (e.g., home office), in addition to the increase in electricity prices from September 2021. Conversely to RWC, wood consumption in cabins experiences few changes over time or even a slight increase from 2014 (Figure 1).

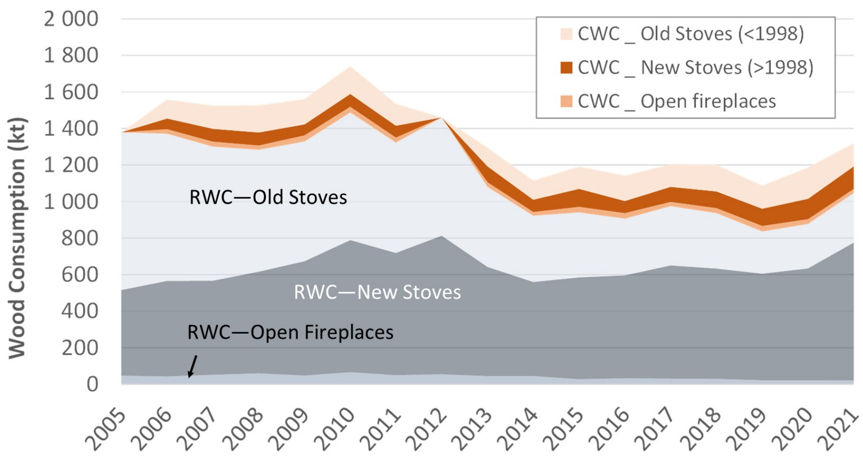

Figure 1. Wood combustion (*kt*) for residential (grey tones) and cabin heating (orange tones) split per technology in old stoves (produced before 1998), new stoves (produced after 1998) and open fireplaces.

2.2. Cabin stoves

There are an estimated 820 000 stoves in the roughly 450 000 cabins in Norway according to *Norsk Varme*, an association of wood burning stove producers. Due to the type of input data available, the stove technology is linked to the wood consumption as it is reported per technology class installation. In the case of CWC, we use a constant split of wood consumption per technology in cabins across regions that is consistent with that reported at national level by Statistics Norway. For instance, in 2019, national wood consumption in cabins was reported to be 51%, 37% and 12% in old stoves, new stoves and open fireplaces, respectively [14]. Although the average consumption in the different technologies may have geographical differences, additional available data can support this assumption. The MetVed emission model includes additionally data from the Fire and Rescue agencies, which are responsible for inspecting and assessing all firing installations. This data-set contains the complete information from around 100 municipalities, covering 1 million of the 2.5 million dwellings in Norway. Within those buildings classified as cabins, 26% of the wood installations are classified as clean, which are taken as new stoves. Of the remaining 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 in the data that indicate a strong regional difference. The Fire and Rescue agencies data-set also confirms the number of wood stoves in cabins in Norway (i.e., 820 000 stoves), where, even for coastal cabins, over 1.5 installations per cabin are estimated.

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2.3. Emission factors

The emissions factors (EFs) used in MetVed are the same than those used for the official reporting of emissions to the CLRTAP [21], and are used to calculate emissions from both RWC and CWC. The EFs per technology 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 formed condensable matter [6]. These EFs also take in account that there are differences in emissions depending on operating conditions. In that way, EFs are given for part-load and nominal-load operating conditions for each type of stove. In our case, we follow 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, respectively, for new stoves [6]. The EFs for $PM_{2.5}$ are 7.85, 20.86 and 16.40 gkg^{-1} of dried wood, for new stoves, old stoves and open fireplaces, respectively. The emission factor for $PM_{2.5}$ emissions from RWC in Norway is steadily going down due to renewal of stoves [22]. However, the reduction is slower for CWC (for more detail see 3).

2.4. Location and classification of cabins

The number of all buildings in Norway, including residential and cabins, are openly available from Statistics Norway on a 250, 1000 and 2000 m grid since 2008 to 2021. This information represents the basis for the distribution of emissions. Cabins are geographically distributed to serve several purposes, and the highest density of cabins is along the coast (Fig. 2). Coastal leisure activities are for the most part limited to summer, whereas cabins in the mountains are considered more of a full year destination. In order to estimate emissions, the consumption of wood needs to be determined by the physical properties of the cabin, such as the heating need 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 again to a large extent determined by at what time during the year the cabin is used. To differentiate cabin types we made a set of parameters to classify each cabin (grid) as either "alpine" or "coastal", as the occupancy of these cabins will have very different seasonal profiles (see section 2.5) and presumably different qualities. This approach represents an advancement regarding other methods available in the literature. For instance, [20] distinguish between single family houses, apartment and holiday houses in their RWC emission model for Denmark, and different weighting factors are used for the different dwelling. However, they do not distinguish between holiday houses mainly used in summer or winter as is necessary in Norway.

We assigned different attributes to each cabin grid in the emission model to classify type/usage of cabins. These attributes are i) The distance to the coast; ii) The distance to a city/urban centre; iii) The altitude of the cabin grid; and iv) The mean annual temperature of the grid. The distance to the coast is calculated for each grid as the shortest distance to the coastline, and in a similar way, the distance of a cabin grid to the nearest urban centre was calculated as the shortest straight line (Fig. 2). In the latter case, we took the centroid of the 773 urban centres in Norway. The distance is static for all years as the location of the city centres changes very little over time on this timescale. The mean annual temperature of the grid (Fig. 2) is based on the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis fields at a 0.1°x 0.1° resolution. This resolution (approx. 10 x 6 km) is probably too coarse for some locations to pick up, for instance, fjords, valleys and other local effects, nevertheless, it gives a good overall description of the climatic features of each grid. For cabin altitude, the model also relies on ECMWF data to calculate surface elevation in each grid. This is based on the surface average geopotential (ms^{-2}) and divided by the gravitational constant, then both altitude (m) and temperature (° C) is re-gridded (bilinearly) to the cabin grid and added to the cabin properties. Together, these cabin properties provide the necessary additional information to classify each cabin. The distribution of all cabin properties in Norway is, along with cabin density, shown in Figure 2.

In order to classify the cabins in the two categories as coastal or alpine, different thresholds were evaluated based on visual inspection and analysis of the grid distribution. In our study, a cabin is classified as alpine if it is located above 400 *m* above sea level, more than 15 *km* from the coast (as shortest distance), or the grid annual average temperature is below 2° C. The latter criteria is only relevant in Northern Norway.

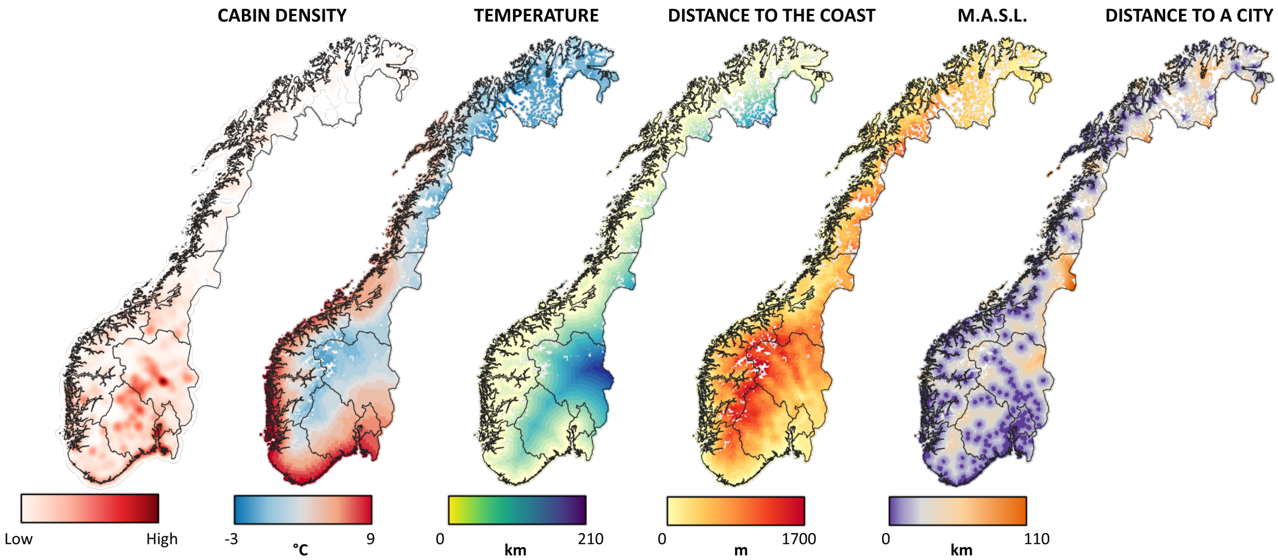

Figure 2. Properties assigned for cabin classification. From left to right; Cabin density as heatmap, darker colours represent higher density. Temperature: the annual average 2 *m* temperature. Distance to the coast: shortest straight-line distance from the cabin grid to the closest point on the coastline. M.A.S.L.: *m* above sea level as elevation of terrain where the cabin is located. Distance to a city: shortest straight-line distance of each cabin to the closest city centre (773 city centres represented by purple circles).

2.5. Cabin occupancy

In addition to having a stove installed, heating by wood requires the presence of people to start and feed the fire. Therefore, the residence time or occupancy of cabins needs to be determined to spatially and temporally resolve wood consumption in cabins. Even though cabins are mainly used for leisure activities or holidays, information on the time spent in privately owned cabins is not reported or documented in the way international travel and stays in commercial institutions are. It is, therefore, much less data to base calculations on, and a parametrization based on hourly traffic counts was developed to determine cabin usage.

Based on previous analysis of national travel surveys and additional documentations (e.g., 36% of Norwegians have access to a cabin), people who owned a cabin spends on average 30 nights per year distributed over 12.5 trips [23]. Other investigations has also shown that longer time is spent on the cabin if the cabin is closer to the place of residence. The primary assumption for our parametrization is that the relative amount of people in an area generate local traffic. This is supported by the fact that more than 90% of people visit their cabin by car, and the cabin population would have a car available. An increase in traffic counts has previously been suggested as data source to determine the amount of people going to cabins [24,25]. Therefore, an ancillary data source that represent when people are at cabins is the additional road traffic created by them.

The Norwegian Public Roads Administration (NPRA) database is available through an API of approximately 12 000 automatic traffic loops. The NRPA has national responsibilities and cover national roads, whereas regional and local roads are administrated by local authorities, as a consequence, most of the counting points are on main roads. To get a clear signal of the traffic activity associated with cabin visits, two automatic traffic counting

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stations were carefully selected from the database. They were selected based on their locations, which are characterised by a high 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, very few suited traffic counting sites were found for this analysis. The two selected stations are in Hvaler, at the Bukkholmen bridge leading to and from the Hvaler archipelago (a dead end), and Kirkebrua in Trysil. They share that they do not have much transitional traffic and have a very high ratio of cabins to residential buildings. Trysil is located in the mountains, has a skiing resort and is the municipality in Norway with the second highest number of cabins [14] (i.e., 6 530 cabins). Hvaler archipelago is south east in Norway, in the top ten municipalities in Norway concerning number of cabins (i.e., 4 310 cabins), which are commonly used in summer.

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 (Fig. 3 A, for coastal cabin and B for alpine cabin), 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 were treated as half holiday. In that way, for a 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, travelling days, and people are at the cabins mainly on Saturdays. For longer holidays the travelling day is the day before the holiday and the last day of holiday.

Based on the two-way traffic counting of NPRA, the excess traffic was calculated as the increase in traffic on holidays relative to the 25 percentile 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. As holidays vary across the calendar year, 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 comma separated values (.csv) file with a weekly weight, a function to calculate the Easter days 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 school holiday weeks differently for different regions in Norway.

The resulting fit of weekly and day of the week weights for 2019 are shown in Figure 3, where the usage rates of the two different cabin areas (C and D, coastal and alpine cabin, respectively, Fig. 3) show different properties. The coastal cabins (defined by the Hvaler traffic counting station; C in Fig. 3) show a much clearer seasonal pattern than the alpine cabin (defined by the Trysil traffic counting station; D in Fig. 3). 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 (Fig. 3). For the cabin area located in the low mountains around Trysil (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 (D in Fig. 3). The traffic variability is combined with the number of nights on average spent in cabins to get an occupancy fraction throughout the year.

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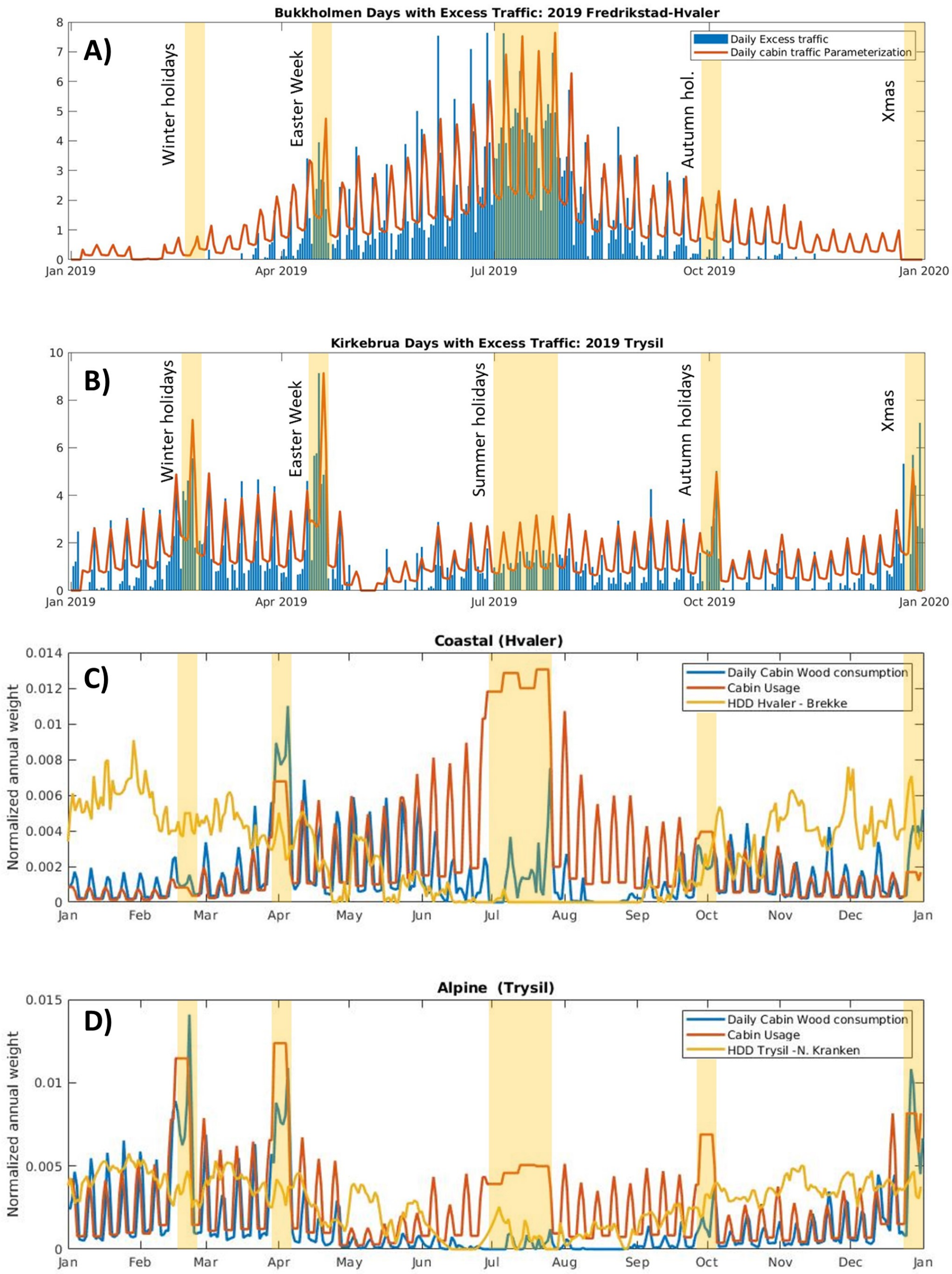

Figure 3. A and B: daily excess traffic and daily cabin traffic parametrization at Hvaler and Trysil, respectively. C and D: cabin usage, daily wood consumption and HDD15 at Hvaler and Trysil, respectively. See text for more details.

2.6. Heating needs

In Norway, almost all cabins have a stove or fireplace, and the need to heat the cabin is linked to the outdoor temperature. 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 (Fig. 3). A common method to describe the heating needs is the heating degree day (HDD). Thus, the heating need and the daily consumption are determined by the level of occupancy of cabins. 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,

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which is applied for both coastal and alpine locations (Fig. 3). The difference in total HDD in 2019 between both locations was estimated to be a factor of 2, i.e., Hvaler, 2 600 HDD_{15}; Trysil 5 300 HDD_{15}, where subscript 15 is the heating threshold for using firewood, and is established at 15°C, the same as the one use for residential heating [19]. Considering that the difference in annual average temperature between Hvaler and Trysil in 2019 was estimated to be about 3.2, the relationship between annual temperature and HDD was establish at 0.62 HDD $^\circ$ C^{-1}. Ignoring all other influences, this relationship predicts a heating demand 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. When considering usage difference among both types of cabins, this factor increases to 6.4 in 2019, as the usage of alpine cabins is enhanced in colder periods, and therefore in heating season, whereas the usage of the coastal cabins is heavily enhanced in the warmer months.

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 normalised. This normalisation also reduces the potential border effects that would arise between regions. In addition, a limiting weighting factor of 0.8 was applied to dampen the effects temperature has on consumption.

2.7. Emissions from wood combustion in cabins

In order to determine the spatial and temporal distribution of emissions from CWC, cabin occupancy and wood burning potential from cabins were used as distribution key. The wood burning potential of a cabin is determined in relation to the other cabins of each region. The wood burning potential is then used as distribution key to distribute the total consumption in a geographical region. For each grid (g) the wood burning potential (WP) is given by the number of cabins in the grid (C), the cabin type weight (CT_w) and HDD weight (HDD_w) as:

$$WP_g = C \times CT_w \times HDD_w \tag{1}$$

where the HDD_w is defined to dampen the effects temperature has on consumption by multiplying the regional temperature z-score by 0.2. 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.

3. Results

3.1. Residential wood combustion emissions trends

Figure 4 shows total $PM_{2.5}$ emissions from residential heating, including both RWC and CWC since 2006 to 2021, along with mean temperature and total heating needs. The mean temperature represents the average over all dwellings, where temperature is given as the value from the geographically closest measurement station with valid observations. The total heating need is estimated as the total number of HDD_{15} averaged over all dwellings in Norway.

Whilst total emissions show a clear downwards trend up to 2019, the trend is reversed in the last two years. Whereas, emissions from RWC have been reduced (from 2006 to 2019), CWC emissions has been kept constant or even slightly increased (Fig. 4). This opposite trend implies that cabin emissions shares to total emissions increase overtime from around 12% in 2006 up to 25-35% in the last years.

The reduction in emissions from residential heating has been mainly driven by a reduced trend in the consumption of wood, but also by a shift to newer and cleaner stoves. The stove replacement to cleaner installations has mainly been observed in residential buildings, whereas this process is slower in cabins. The reason behind may be linked to regulation of emissions from RWC, which policy instruments have a stronger focus on urban residential areas [5]. The technology replacement mainly acts to reduce EFs, i.e.,

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the emissions per consumed dry wood, but also newer stoves are reported to be more efficient, producing more heat from the same amount of wood. The long-term decline in consumption has previously been studied [19], and influencing factors were found to be; i) increased share of other heating technologies, especially heat pumps and district heating; ii) more energy efficient buildings; and iii) lower winter outdoor temperature reducing the demand for heating.

While 2020 was the warmest year on record, and the total heating need dropped from 2019 by 12% (Fig. 4), emissions increased. There are diverse reason for the reversal of the trend, which shows increased emissions over to 2021. There is a probable influence on wood burning emissions by the COVID19 pandemic. The most two most prominent COVID effects are: i) time spent at home increased, especially during lockdowns, and ii) travel restrictions affect the time spent on Norwegian cabins. Both of these changes in activity act to a net increase in consumption and subsequently emissions. Similarly, increased usage of cabins increases the expected consumption there. The latter, in addition, has the overall effect that it acts to increase the average age of stoves, and thus the emission factor, as cabins have significantly older stoves than those in residencies. Our results are in line with reported changes in emissions due to COVID19 pandemic, where a slight increase in $PM_{2.5}$ emissions from residential wood combustion at European level was reported [26]. Opposite to 2020, 2021 was the coldest year since 2013, and thus the total heating need increased from the previous year (Fig. 4), driving wood consumption up. In addition, still COVID restrictions and higher flexibility of home office can possibly explain the increase in wood burning emissions. Moreover, since September 2021 a marked increase in electricity prices in Norway occurred, which resulted in record sales of wood.

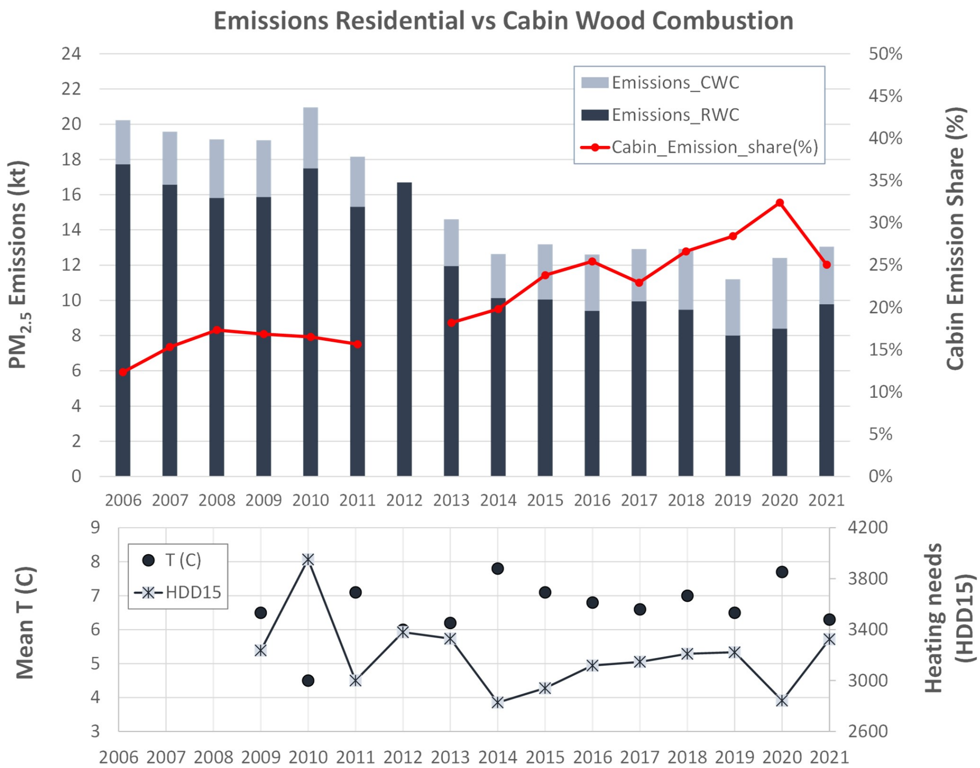

Figure 4. Top: Annual $PM_{2.5}$ emissions from residential (RWC) and cabin (CWC) wood combustion for heating in Norway and the share of cabin emissions to the total emissions (%). Bottom: Annual mean temperature (° C) and heating need (HDD15), both averaged over all dwellings in Norway.

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3.2. Spatial and temporal distribution of emissions

Heating activity occurs differently in space and time in residences and cabins, based on where cabins and residences are located and when they are vacant. To highlight the difference, Figure 5 shows as a heat map emissions produced for residential (left) and cabin (right) $PM_{2.5}$ wood combustion for heating. The largest hotspot of emissions from RWC occurs in and around the main cities in Norway, and most pronounced around Oslo. Hotspots of CWC are found in central Norway, mostly in areas with cabin agglomerations around ski resorts. While much of the cabin are along the coast (Fig. 2), these areas are not identified as areas of high emissions. This is a result of the proxies applied in our study to account for differences in occupancy between alpine and coastal cabins, which gives the time spent in coastal cabins, mainly summer, a very low heating demand compared to alpine cabins.

This also results in a different temporal distribution of emissions between residencies, alpine and and coastal cabins. Occupancy of cabins, and consequently use of wood stoves, varies strongly throughout the year and week. Fig.6 shows the time variation of emissions for RWC (Residential) and CWC (coastal and alpine cabins). RWC emissions occurs mainly during the winter months, at weekends and during the evenings. The monthly variation shows the "U-shape" characteristic of residential heating with a minimum during summer. While the same heating demand influences time variation of emissions from CWC, their emissions follow more strongly their occupancy during the year. Coastal cabins have the highest peak in spring due to the combination of occupancy and HDD. There is also an emission peak in July, when coastal cabin has their peak occupancy, mainly evident in colder parts of the country.

Alpine cabins have their highest activity in the holidays in winter and spring, which results on emission peaks due to the substantial heating demand in this period. Whereas Christmas and Easter is the same all over Norway, the week of autumn and winter holiday varies across the country, and the national emissions peaks are therefore less pronounced. Furthermore, Easter day, which determines the holidays of Easter, can make the holiday fall in either March or April from year to year.

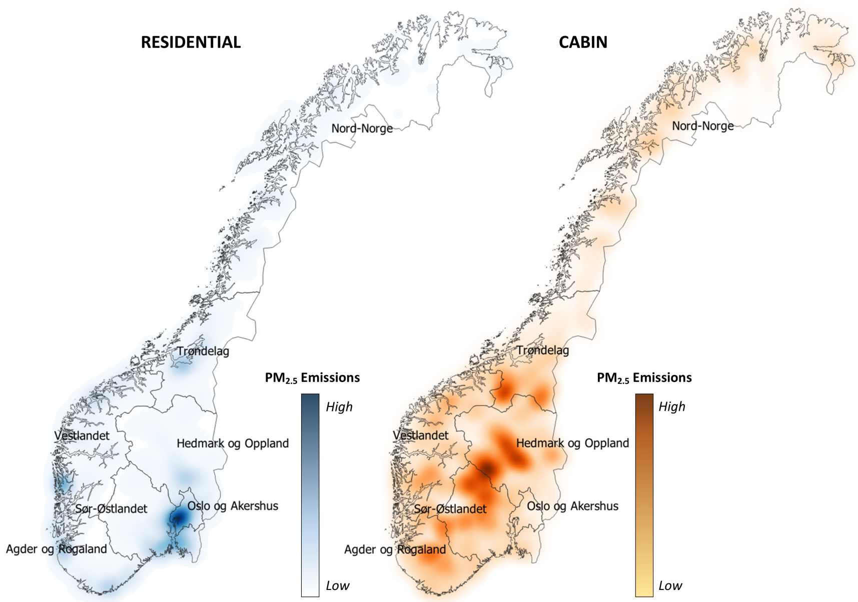

Figure 5. Spatial distribution of emissions from residential and cabin wood combustion for heating. Note that the colourbar has a different scale for cabins and residential.

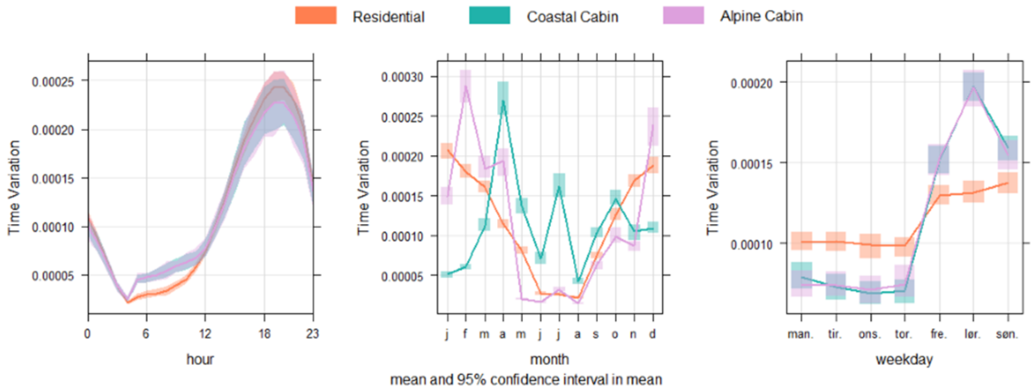

Figure 6. Time variation of emissions from residential and cabins wood combustion. The time variation of emissions from cabins is split in coastal and alpine cabins. Unit: hourly weight.

4. Discussion

The use of common proxies in the development of regional emission from heating, which are more representative of residential emissions, involve errors with consequences for modelling the transport and deposition of air pollutants, and assessing local and regional air quality plan. In this study, we show, with the example of Norway, the complexity of distributing at high spatial and temporal resolutions emissions from residential heating. Our study considers a factor that has not received significant attention in the literature, which is the distinction of primary and secondary homes. In Norway, about 20-30% of the residential wood combustion takes place in second homes or cabins (CWC), and considering that occupancy has been reported to be around 30 days per year, involves that CWC is 13 times more intense than wood combustion in permanent residential addresses (RWC). Moreover, as cabins can be classified as coastal and alpine, mainly used in summer and winter, respectively, wood burning will be even more intense due to the seasonal differences in heating needs.

Emissions obtained in our study have been compared for specific municipalities with emissions from residential heating (NRF Sector: Residential Stationary) available through Copernicus Atmosphere Monitoring Services (CAMs [27]). For our comparison, we selected the most populated urban municipalities, i.e., Oslo, Bergen, Thondheim, Stavanger and Drammen, representing around 24% of Norway's population. Moreover, we selected the five municipalities with the highest density of cabins, i.e. Ringsaker, Trysil, Hol, Vinje and Sigdal, representing around 7% of the cabins in Norway. Figure 7 shows the comparison of emissions produced in our study for the mentioned municipalities with the same sector from CAMS-REG-AP [7]. While our emissions produced for the two biggest municipalities (Oslo and Bergen) are much lower than those produced by CAMS-REG-AP, the proxies behind CAMS-REG-AP do not allocate emissions in most of the cabins municipalities showing a clear correlation with population. The reason is that the regional emission inventory distribute emissions from residential stationary as exclusively from residences, and does not consider a different proxies for the use of wood consumption for heating in cabins, which represents a large part of the emissions reported as residential stationary. As a consequence, the gradient in heating emissions from rural to urban is much larger in CAMS emissions than in our study. Considering that residential emissions produced in our study have been extensively validated for Norwegian cities by comparing modelling results with observations [19,28,29], the gradient obtained in our study better represents local emissions in rural and urban areas than those provided by CAMs.

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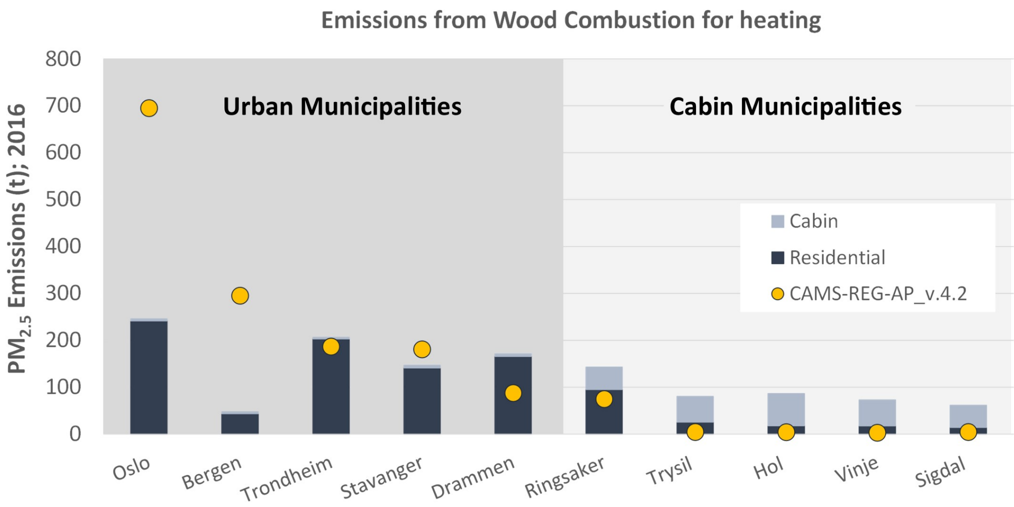

Figure 7. $PM_{2.5}$ Emissions from residential and cabin wood combustion estimated in out study (Bars) compared with CAMS-REG-AP emissions (NFR Sector: Residential: Stationary) for the residential sector (version 4.2) for urban municipalities and cabin municipalities.

Our study shows how considering the distinction between primary and secondary homes is highly relevant in Norway to avoid an overallocation of emissions in urban are underestimation in densely populated cabins areas. This aspect can be relevant for other countries, where having second homes is very extended, such as other Nordic countries, and partly explained by wealth and availability of space (e.g., [30]). For instance, in Finland, with a similar population than Norway, there are approximately 500 000 recreational houses, where wood is used for heating [31]. In Denmark, the total wood consumption in holidays houses, even thought assumed to be mostly used in summer, is approximately half of the consumption in permanent residences [20]. In the Alpine Region, second homes are estimated to be around 1 850 000, around 25% of the housing stock, and are expected to grow in the future [32]. Taking into account that the occupancy of holiday houses is much lower than that in primary houses, wood combustion for heating represents an intensive activity in short periods of time. In mountain areas for instance, and those affected by intense tourism activities, it represents the largest energy source for heating, which emissions, intensified by temperature inversions and topography, result in high pollution episodes and additional environmental impacts (e.g., [33–35]). Moreover, wood burning is one of the largest sources of black carbon [36], and its deposition in snow, along with dust, has been estimated to be responsible of advanced snowmelt of around 17 days on average in mountain areas such as the Alps and Pyrenees [37], with subsequent impact on mountain ecosystems, water resources and society.

Wood burning for heating of secondary homes or cabins is an aspect that needs to be also considered for future assessments of cabin development plans in rural areas. We have analysed webcrawled data from the state market portal in Norway ([38]) in combination with the annual gridded building data, and the results indicate that new cabins are mostly built in areas with existing cabins, creating cabin settlements. Moreover, the share of newly built alpine cabins has increased over time from 60% in 2010 to 70% in 2021. Figure 8 shows the alpine cabin distribution based on the building year (x-axis) and the location where they are built based on number of existing cabins (km^{-2}; y-axis), along with the median (green line) and the 90th percentile (blue line). While in 2010 the median number of existing cabins per square kilometre for newly built alpine cabins was 12 km^{-2}, it increases to 40 km^{-2} by 2021, with a trend of 2.5 per year (Fig 8). Moreover, from 2015 to 2021, 10% of the new cabins are built in areas where there are already 100 or more existing alpine cabins. New cabins are being built at higher elevations, with median rising from

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630 *m* in 2010 to 730 *m* in 2021. The new cabin development is, therefore, resulting on the creation of cabin settlements and higher densification at high altitude. The strong periodicity in emissions, following the holiday calendar, further suggest this episodes of extreme emission intensity. This can also be exacerbated in 2022 due to the increase in electricity prices. Hereby, subsides are in place in Norway to support the high electricity prices that started in September 2021, and have continued upwards over 2022. However, the subsidies only apply to residential buildings, and second home are excluded, therefore incentives are to rely on alternative heating sources, mainly wood. Moreover, land use changes associated with cabin development has been highlighted along with the need for stricter land use and building regulation [39]. Second homes, such as cabins, and the tourism associated with are increasing worldwide [40,41]. Therefore, emissions from CWC may become an increasing concern, which needs to be capture in regional emission inventories to assess potential environmental implications, and avoid the allocation of such emissions in urban areas.

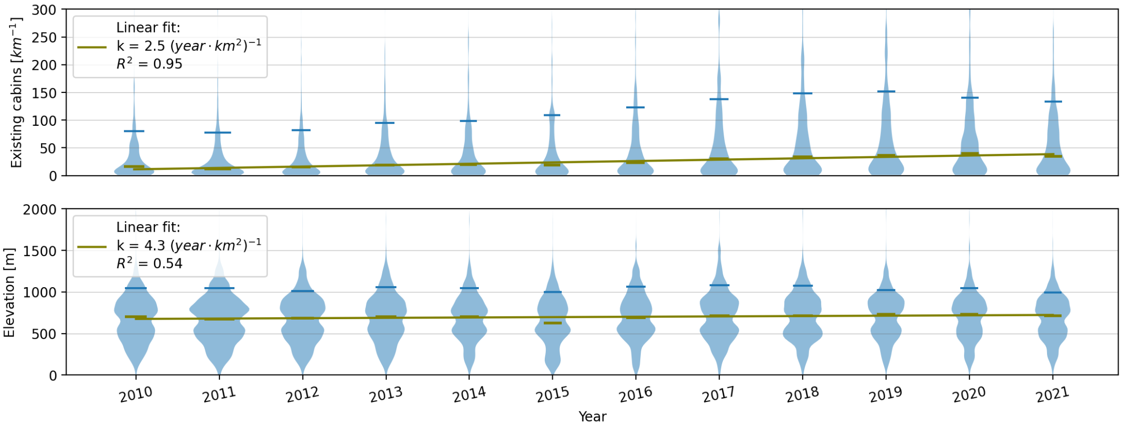

Figure 8. Distribution of alpine cabins built per year since 2010 to 2021 based on the location of existing cabins (km^{-1}) (top) and elevation *m* above sea level (bottom). Green lines: medians and the trend. Blue lines show 90th percentile.

5. Conclusions

High-resolution emissions are essential for air quality assessment and management. Our study takes into account an aspect beyond the spatial and temporal distribution of emissions, which is the use of wood burning for heating in secondary homes or cabins. Norway, with a population of around 5.5 millions, has approximately 450 000 cabins, and even thought we spend approximately 2% of the time at cabins, around 20% of the wood consumed and 30% of the emissions for heating occurs there. Our study has presented first a method to estimate emissions from cabins at high resolutions based on the analysis of traffic data and, thereafter, determining cabin occupancy for cabins classified as coastal and alpine. By combining wood burning emissions in permanent residences (RWC) and cabins (CWC), our results show that while emissions from RWC are distributed mainly around cities and townships in Norway, emissions from CWC is more spread in the geography with large hotspots in mountain areas with high density of cabins, even thought the highest cabin density is along the coast. When analysing the temporal variation of emissions, whilst RWC emissions show a characteristic "U-Shape" with high emissions in winter and low or zero emissions in summer, coastal cabins show high activity in Easter week, July and Autumn holidays, whereas alpine cabins show peak emissions in winter holidays and Christmas holidays. The spatial and temporal analysis indicates that a temporally "cabin population" can in areas be orders of magnitude larger than the registered population, and emissions are specially intense in holidays.

The emissions estimated in our study has been compared with a regional emission inventory commonly used to model transport and deposition of air pollutants (CAMS-

REG-AP). Our study shows large discrepancies between municipalities that contain the biggest cities in Norway, and municipalities with the highest density of cabins. While the regional emissions inventory does not allocate emissions in the cabin municipalities, much larger emissions are allocated in urban municipalities than those obtained in our study by the MetVed model. The spatial distribution from CAMS-REG-AP results in a stronger gradient in emissions from more rural to urban areas than that obtained in our study. This discrepancy can occur in other countries or regions than Norway also characterised by intense wood burning activity for heating and large share of second homes. Some of these regions are mountain areas, where additional temperature inversions, topography and the fact that heating is the prominent local emission sources, will involve large local pollution episodes, and for instance the deposition of black carbon with subsequent snowmelting effects.

Cabins are an increasingly important consumer of energy and wood is the primary heating source, which is not expected to change in the future. Our study shows an increasing trend in the cabin stock in Norway along with a higher densification specially in mountain areas. The nexus between cabin development, energy use and emissions needs to be considered in future assessments and in the context of rural development and building regulation in areas, such as mountain areas.

Author Contributions: The paper was conceptualized by S. L.-A. The MetVed model and additional module for cabin emissions have been developed by H.G. Input data collections and curation have been prepared by S.L.-A. and M.M. All authors have contributed to the data analysis and visualization of the results. Original draft prepared by S.L.-A, and H.G. and M.M. have read, reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The code for the MetVed model is available at git.nilu.no. MetVed emission results are available through https://utslippskartlegging.nilu.no and they can be retrieved in gridded format at https://www.miljodirektoratet.no/tjenester/luftforurensning-utslippssystem-og-database/. Data is also available upon request to the corresponding author.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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