The EmSite model for high resolution emissions from machinery in construction sites

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TITLE

The EmSite model for high resolution emissions from machinery in construction sites

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ABSTRACT

The report describes the EmSite model developed to estimate exhaust and non-exhaust emissions from non-road mobile machinery (NRMM) used in building and construction. The model is based on a complete national database of the exact location of construction and building activity, machine registries and variables that affect emissions (ground conditions, meteorology, type of ground material). EmSite model allows us to determine, i) the location, area and time of construction projects at fine resolution; ii) energy demand for NRMM; and iii) fuel consumption, air pollutants and GHGs emissions. For exhaust emissions, specific dynamic emission factors for NRMMs were developed. For non-exhaust emissions, an approach based on the Tier 1 (EMEP/EEA Guidebook, 2019) was chosen. EmSite allows for bottom-up estimates for NRMM employed in construction, and the results are comparable with official air pollutant and GHGs emissions.

NORWEGIAN TITLE

EmSite-modellen for høyoppløselige ustlipp fra anleggsmaskiner

KEYWORDS

High-resolution emissions
Building and Construction
Bottom-up emissions

ABSTRACT (in Norwegian)

Denne rapporten beskriver den nyutviklede EmSite modellen. En modell for å beregne både eksos og diffuse utslipp fra bygg og anleggsmaskiner i Norge. Modellen er basert på matrikkeldata som dekker den nøyaktige posisjonen til alle bygningsarbeider. Den benytter seg i tillegg av en detaljert maskinpark-database, meteorologi og geoteknisk informasjon om grunnforhold. Basert på dette blir energibehovet beregnet innen forskjellige bygningsfaser og maskintyper. Vi presenterer utslipp for 2009-2020 hvor det for hvert år er tatt hensyn til endringer innen aktivitet, meteorologi og utslippsfaktorer. Dette er, oss bekjent, den første modellen i verden av sitt slag som beregner utslipp fra byggeaktivitet på denne måten og med denne graden av detaljer.

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Preface

This technical report is the final report of the 2nd phase of the EmSite project “Metodikkutvikling for finskala utslippsberegninger fra anleggsarbeid” (In English: Method development to estimate high resolution emissions from building and construction). The project is funded by the Norwegian Environment Agency. Its 2nd phase started in March 2021.

During a 1st phase of the project, the work focused on mapping out and evaluating available input data to define emissions from building and construction at high resolution (Lopez-Aparicio and Grythe, 2021). The 2nd phase of the EmSite project has aimed at developing a model, namely the EmSite model, to estimate emissions from construction activity based on bottom-up principles; from the individual construction site to municipal and national levels. This report describes the input data and principles behind the newly developed EmSite model.

The work has been carried out by Henrik Grythe and Susana Lopez-Aparicio, who has also led the project. We thank Scott Randall from the Norwegian Environment Agency (NEA) for his support, help and cooperation during the project. We would like to thank Thomas Astrup, Roy Lund, and Line Borgö from CRAMO AS, for their support and sharing the machine park database.

The quality control at NILU has been carried out by Claudia Hak. The report has benefited from the feedback and comments from Tomas Seim, Thea Johnsen and Scott Randall from the Norwegian Environment Agency.

Contents

Summary

The interest in off-road emissions, and specifically non-road mobile machinery (NRMM), has been increasing over time. At urban scale, NRMM associated with building and construction may constitute a significant source of air pollutants, both non-exhaust and exhaust, and greenhouse gas (GHG) emissions. Building and construction activity is a very defragmented and heterogeneous sector, with large variability in space and time and, compared to other sectors, virtually unquantified. In this study, we present the EmSite model, a new bottom-up methodology to estimate emissions from NRMM employed in construction.

The EmSite model is based on a complete national database of exact location of construction and building activity, as well as machine registries, and takes into account variables that affect emissions, e.g., ground conditions, meteorology, type of ground material. The model is set up to provide emissions from i) Building construction; ii) Building demolition and iii) Road construction.

The principle behind the EmSite model is the combination of different data-sets that allows us to determine:

i) the location, area and time of construction projects at fine resolution;
ii) energy demand for NRMM at the different phases of the construction project; and
iii) fuel consumption, and air pollutants and GHGs emissions.

For the spatio-temporal distribution of building activity, we processed data on building construction permits from 2010 to 2020 and combined with the other variables that influence emissions, i.e., soil data for the silt content, and ground conditions together with the size and type of building work, as it determines the energy demand for machinery. A specific parametrization to determine the different building phases (i.e., ground work, heating, building work) and duration of construction projects was developed based on real building permit data. The construction (or demolition) activity results are expressed in m^2. The energy demand for NRMM is then established taking into account the large NRMM, heaters/generators and small NRMM that are employed in the ground work, heating and building work, respectively. Specific energy demands expressed in $kWh \cdot m^{-2}$ are used for the different construction phases to obtain energy demand (kWh) for NRMM in construction and/or demolition.

To calculate exhaust emissions, specific dynamic emission factors for large and small diesel NRMM, and liquefied petroleum gas (LPG) and diesel heaters/generators, were developed based on information on the current machine park in Norway, continuous introduction of machines over time, the machine population per power class in Europe and basic emission factors from EMEP/EEA Guidebook (2019). For non-exhaust emissions, an approach based on the Tier 1 methodology by EMEP/EEA Guidebook (2019) was chosen as the basis. Particulate matter (PM) is emitted during the building and demolition phase. The approach takes into account not only the activity, but also meteorological factors and properties of the surface layer material. Most PM-emissions, therefore, occur under dry conditions and at places with intense activity.

The detailed data processing allows for bottom-up emissions estimates for NRMM employed in construction, and the results are comparable with official air pollutant and GHGs emissions submitted to the CLRTAP and UNFCCC, respectively. The heating of unfinished buildings in Norway is the most energy intensive activity within building construction, contributing up to 66% of the total energy demand, although there is known uncertainty here, which needs to be investigated further.

The EmSite model for high resolution emissions from machinery in construction sites

1 Introduction

The interest in off-road transport, and specifically non-road mobile machinery (NRMM), is growing. In the urban environment, NRMM associated with building and construction may constitute a significant source of air pollutants, both exhaust and non-exhaust, and greenhouse gases (GHG) emissions. Building and construction activity is a very defragmented and heterogeneous sector, with large variability in space and time and, compared to other sectors, virtually unquantified. In this study, we present a new methodology to estimate emissions from NRMM at building and construction sites. Hereby we refer to "building and construction" as any physical activity that involves the demolition and/or erection of buildings (residential and non-residential), roads and / or infrastructure (e.g., water system, bridges, tunnels). The methodology is based on a national database of exact location of building activity, machine registries, soil information, meteorological and ground conditions to calculate the NRMM energy need at the different phases of the construction process.

Emissions from NRMM contribute to 18% and 16% of total NO_x in the United States and European Union, respectively, of which 46% and 25% are associated with construction activity (Dallmann and Menon, 2016). These shares represent the total regional emissions, but in the urban environment, where most construction occurs, the share of NRMM emissions will be much higher. In Oslo, emissions from construction are estimated to contribute to 7% of city total GHGs emissions, without accounting for emissions associated with the transport of people and material to/from the construction sites[1], and in Trondheim emissions reach 13% of city total GHGs emissions[2]. Therefore, several measures are in place to reduce emissions, from the requirement to use biofuels in municipal construction projects to focusing on the transition to electric construction technologies supported by public procurements, incentives for investing, and closer cooperation with the construction industry. **In order to evaluate these measures, high quality methodologies need to be in place to estimate emissions for building activity at local resolution, and that allow for time series evaluation,** and up to now existing methods involve high levels of uncertainty.

Historically, the displacement of industrial pollution sources away from urban areas led to a change in the configuration of the main contributing sources to urban emissions and air pollution. Where heavy industries once were the main contributors to urban pollution, the most important sectors at local scale are currently considered to be on-road transport and residential heating. Both sectors have received increasing attention from a regulative perspective, and in the last decade, are experiencing significant emissions reductions. On-road transport and residential heating have also received more attention from the point of view of method development, and therefore their emissions are better quantified.

Accurate emission inventories are an essential part of monitoring and for planning purposes of mitigating air pollution and GHG emissions in a cost-effective way. To achieve this, emission estimates need to be developed taking the emission processes into account. It also requires high spatial and temporal resolution in order to monitor the progress set at local level. However, the development of such detailed emission estimates poses important challenges, especially regarding data availability. The needed input data commonly exist, however, under the responsibility of different data holders and/or decentralised. This is true both for an individual source and for the sector's accumulated emissions. The different datasets need to be combined and evaluated to assess that the emission

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[1] https://www.c40knowledgehub.org/s/article/How-Oslo-is-driving-a-transition-to-clean-construction?language=en_US

[2] Utslippsfrie bygge- og anleggsplasser. Innovative anskaffelser. Nasjonalt program for leverandørutvikling. Leverandørkonferanse, 2017.

process is properly represented, and it allows for the characterization also down to local scale. This challenge commonly requires the collaboration between different experts and data holders, as emission assessment typically requires input from both authorities and the private sector. The magnitude of this challenge varies from sector to sector. Hereby, traditionally well-studied sectors, such as on-road traffic, often pose less challenges than sectors that have received less attention.

In Norway, some studies have addressed GHG emissions from construction activity at specific construction sites or municipality level. Fufa et al. (2019) estimated embodied construction emissions from a zero-emission building construction site, and they estimated that around 47% of the embodied GHGs construction emissions is from the operation of construction machinery, thus constituting the largest single contributor. In a similar example, Fufa (2018) estimated GHG emissions from the construction phase of a kindergarten according to a Life Cycle Assessment (LCA) and concluded that construction machinery operation is the second largest contributor after transport of building materials. DNV (2018) estimated emissions for building activity in Oslo municipality based on the energy demand per square metre and the annual building and construction activity reported by Statistics Norway. The study concluded that 40.6 kt and 0.54 kt of CO_2 and NO_x, respectively, are emitted on an annual basis for building activity, and 39.6% of the total emissions are associated with the heating during the building (i.e., concrete setting, façade heating, internal heating).

The development of accurate and updated emission inventory for NRMM in construction has so far been a challenge. Viaene et al. (2016) stated that "*Compared to road traffic, the off-road traffic and machinery fleet is often more heterogeneous with more variable emissions. As the movement of the vehicles and sales of fuels are not comprehensively monitored at a local level and the activities are often outside the road networks, the estimation of the activity and emissions is challenging for off-road transport and machinery*". EmSite constitutes a significant step forward on the quantification of construction activities and emissions associated with. As this report shows, the availability and quality of input data is a crucial key factor on the estimate of emissions from building and construction.

2 Officially reported estimates for Norway

In Norway, air pollutants and GHGs emissions are reported to the CLRTAP[3] and to the UNFCCC[4], respectively. Emissions are reported per sector, and exhaust from NRMM in construction are included as part of the subsector "*Mobile Combustion in manufacturing industries and construction*" (NFR[5] sector 1A2gvii), within the sector Energy Combustion (1A). Non-exhaust emissions in building and construction are reported in sub sector "Construction and Demolition" (NFR subsector 2A5b).

2.1 Exhaust emissions

Based on the Informative Inventory Report (IIR) and the National Inventory Report (NIR) by the Norwegian Environment Agency (NEA, 2019a; 2019b), exhaust emissions are calculated from fuel consumption. The fuel consumption is, for both CLRTAP and UNFCCC reporting, estimated following IPCC guidelines (IPCC, 2006), and thus based on the fuel sales, i.e., sales of petroleum products reported by Statistics Norway.

Exhaust emissions from NRMM are in Norway denoted as "motorized equipment", which comprises all mobile combustion sources except on-road, maritime, aviation and railways. Within the motorized equipment category, construction machinery is together with farming equipment the two main emitting sources, and several other smaller sources included such as machinery used in mines and quarries, forestry, snow scooters, household equipment and recreational boats. Emissions from NRMM are thus split in the following subcategories in the official reporting of emissions;

- Manufacturing and construction (1A2g-vii);
- Commercial and institutional (1A4a-ii);
- Households (1A4b-ii);
- Agriculture/forestry/fishing (1A4c-ii);
- Military (1A5b).

Motorized equipment fuels include gasoline, bioethanol and LPG, but are dominated by tax-free auto-diesel. The latter one is exempt from a road tax, and is, therefore, only allowed to be used in NRMM. This makes the distinction from the diesel used in road vehicles simple and straightforward. This separation of tax-free diesel has been in place since 1994.

The spatio-temporal distribution of air pollutants and GHGs emissions in Norway is not part of the official annual reporting. Even though they are not annually reported, gridded emissions are available at the Centre on Emission Inventories and Projections[6]. For both GHGs and air pollutants, a higher resolution than national level is required to evaluate individual mitigation measures and to evaluate the progress towards local emission targets. For air pollutants, high resolution emissions are also crucial to the assessment of local air quality and human exposure. In Norway, there are limited spatio-temporally resolved emission inventories for NRMM, and none that details construction activities. Regional or global emission inventories such as CAMS-REG-AP (Granier et al., 2019) are relatively coarse and inaccurate and they cannot be used to model air quality at urban scale.

Another source of spatial information is the accounting of GHGs emissions at municipality level by the Norwegian Environment Agency[7]. In this case, emissions from construction activity, which is included in "motorized equipment", are produced by Statistics Norway based on the same methodology used

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[3] CLRTAP: Convention of Long-Range Transboundary Air Pollution

[4] UNFCCC: United Nations Framework Convention on Climate Change

[5] NFR: Nomenclature for Reporting

[6] https://www.ceip.at/the-emep-grid/gridded-emissions

[7] https://www.miljodirektoratet.no/tjenester/klimagassutslipp-kommuner/?area=618&sector=-2

for the official reporting of emissions. National emissions from NRMM are distributed to municipality level based on a distribution key described in NEA (2020)[8]. The distribution of emission is performed based on the delivery address of tax-free auto-diesel sales. When the delivery address is not available, the organization number of the fuel buyer is used and linked to the address of the company in the Business and Enterprise Registry. In the case the organization number is not available, emissions are estimated at county level and distributed at municipality level based on population. The fuel sales without i) delivery address; ii) organization number or iii) county information, are not included in the GHGs emission accounting at municipality level. In many cases, the registered petroleum products sales are not to an end user but to redistribution companies that receive large quantities. The share sold to large distributors has been between 40 and 60% of total sales between 2009 and 2019. For large fuel distributors, the location of pumping stations for tax exempt diesel is used to place the sale, along with information on the distribution area of the company and population at the municipality level, to further distribute the fuel sales and therefore emissions. Thus, fuel is distributed based on several proxies, but not all of them are indicative of where the fuel was actually consumed.

2.2 Non-exhaust emissions

Non-exhaust emission estimates from "construction and building" activity are described in the Norwegian official emission informative inventory report (IIR 2019; section 4.2.5, NFR2A5B; NEA, 2019a) as "*Construction and building include a lot of different activities that will generate particle emissions. Building of roads, railways, tunnels and demolition of buildings are also a source of particle emissions, but no emission factors are found in literature, and therefore such emissions are not included in the inventory. The activity data used is the annual area of completed buildings from the building statistics at Statistics Norway* " (NEA 2019a). This implies that there is no national account of non-exhaust emissions other than from the construction of buildings. Furthermore, as the IIR acknowledges, it does not take into account factors that affect non-exhaust emissions, such as meteorology, soil conditions, silt content or factors in the types, sizes and locations of the built area. The emission factors used are those from the EEA/EMEP Guidebook (2019) recommended for Tier 1 methodology (Table 1). However, it is apparent that the Norwegian official reported emissions do not use them as were originally intended. The emission factors (EF) are part of the equation that also includes additional factors that affect non-exhaust emissions:

$$EM_{PM_{10}} = EF_{PM_{10}} \times A \times D \times (1 - CE) \times \frac{24}{PE} \times \frac{S}{9\%} \qquad \text{Equation 1}$$

Where annual emissions (EM in g) are given as a function of the EF ($g \cdot m^{-2} \cdot yr^{-1}$), the building duration (D in yr), the area affected (A in m^2), the control measures' effectiveness in reducing emissions (CE; 0-1, unitless), the precipitation evaporation index (PE) as given by Thornthwaite (1948) and "S", which is the silt content of the soil. At the same time, EFs are a function of the type of building or construction project (Table 1). As the Norwegian national emissions can be reproduced by a simple product of the built area and the EF suggested by EEA/EMEP Guidebook, it is indicative of emissions produced by the suggested equation for tier 1 methodology, ignoring most parts of Equation 1. We further question the use of the emission factors in such a way as silt content and PE largely varies and their terms generally $\neq 1$. **Over all, the use of a part of an equation to calculate emissions is questionable.** There is therefore no proper data from Norway to evaluate non-exhaust emissions obtained by means of the EmSite model against.

For the other parts of Equation 1, EEA/EMEP Guidebook suggests values, when this information is not available, for the duration of each building project (D) and the area affected (A). The area affected is dependent on the footprint area of the building and a factor, that ranges between 1.5 and 2, is

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[8] The methodology to distribute emissions at municipality level was modified in 2022. Therefore, this report refers to the previous methodology (NEA, 2020).

suggested dependent on building type. For duration, the suggested values are 0.5 -1 year, and again varying with the type of building.

Table 1: Tier 1 emission factor for uncontrolled fugitive emissions for construction and demolition (Source: EMEP/EEA Guidebook, 2019)

	EF (kg . m^{-2} . yr^{-1})	Type of Construction
TSP	0.29	House
PM_{10}	0.086	House
$PM_{2.5}$	0.0086	House
TSP	1	Apartment Building
PM_{10}	0.3	Apartment Building
$PM_{2.5}$	0.03	Apartment Building
TSP	3.3	Non-residential
PM_{10}	1	Non-residential
$PM_{2.5}$	0.1	Non-residential
TSP	7.7	Road
PM_{10}	2.3	Road
$PM_{2.5}$	0.23	Road

3 Principles behind EmSite model and Input data

In the EmSite model, we follow a process that goes from the location of building and construction activity, thereafter allocation of energy demand for NRMM and finally estimation of emissions based on the energy demand. One of the aspects considered for **exhaust emissions** is that the energy demand and therefore emissions are split across phases of the building process and the main type of machines employed. Figure 1 shows the type of machines used in the processing of exhaust emissions and the description of the processes where they are mainly involved as part of a building and construction work.

Large NRMM: mainly used in the ground work, preparation of the site, removal and / or replacement of material, and the beginning of the construction. Exhaust emissions are mainly associated with diesel fueled machines.

Heaters / Generators: used in different phases of the construction process, from concrete setting, interior heating, ground casting to façade heating. Exhaust emissions are associated with the combustion of LPG and/or diesel.

Small NRMM: used mainly in the activities over the foundation and during the sealing and finishing of the building. Exhaust emissions are associated with the combustion of diesel and/or gasoline.

Figure 1: Non-road mobile machinery used in building and construction (large, small, and heaters) and distributed per phase within the building process.

Concerning **non-exhaust emissions**, the Tier 1 methodology suggested by EEA/EMEP Guidebook (2019) (i.e., Equation 1) is very coarse, but presumably includes implicitly all governing factors of emissions. Tier 1 methodology also implies a linear relationship between emissions and the duration and size of the construction project. On a construction site, there are several distinct processes that can be a source of PM emissions. In Figure 2, we have split the different processes that influence non-exhaust emissions as those associated with i) wind, ii) mechanical upheaval, iii) tyre and traffic and iv) freight. Exhaust particles are excluded from these calculations as it is part of the combustion process and shown in Figure 1. Aside from that, it is not clear which of the non-exhaust processes the Equation 1 is meant to include. However, by the parameters included in the equation, it is possible that only wind (i) and mechanical upheaval (ii) are considered. The remaining parameters in the equation are about the physical properties of the place where the construction process occurs.

Surface wetness efficiently prevents suspension. Thus, the drier the masses on construction sites are the more mass can be suspended. For all of the above processes the Thornthwaite equation for evapotranspiration can be said to encompass the meteorological conditions which makes them have a potential for suspension. The silt content of the soil is often used to describe the efficiency of aeolian processes. Between 0.002 and 0.05 mm, silt particles themselves can be larger than suspendable particles in the atmosphere, as their gravitational settling is too fast for them to travel significant distances if emitted near the surface. However, silt particles are too large to form the electrostatic bonds of smaller particles (e.g., clay), thus the fine particles are most easily moved by winds. Therefore, silt content is of special interest as high silt content masses can produce suspended dust. Tier 1 methodology (Equation 1) has duration and size of the project as proxies for the dust generating activities. The scope in time of the equation is annual emissions, whereas within the EmSite model hourly emissions are desired. Equation 1 has, therefore, been modified to accommodate more detailed activity data and achieve the desired higher temporal resolution. Details on these adaptations and following implementation in the EmSite model are given in Section 4.5.

Wind: Amost all construction activity involves turning or marking the topsoil, which makes it exposed to the atmosphere. Under strong wind conditions, the exposed material will be a source of aeolian dust, getting its name from the Greek god of winds, Aeolus.

Mechanical Upheaval: The movement of mass is essential for all construction activity. This is performed by heavy NRMM by scraping, loading, crushing and/or transporting the material. These processes can be a source of PM.

Traffic and tyres: Mud, sand and other materials readily available at construction sites attach to the tyres of road vehicles. The material may be dragged onto surrounding roads and pavement. This can become airborne from suspension, either from wind or traffic.

Freight: the transport of material on open road heavy duty vehicle can be a source of PM. As mass is brought or removed from a construction site or desired materials are moved to the site, movement and speed induced wind may cause a suspension of PM.

Figure 2: Processes that influence non-exhaust emissions.

The EmSite model is based on a combination of different input data sets. Table 2 shows the main input data used in EmSite, data sources and, in addition, includes other potential sources that can be used both in EmSite or as part of specific studies at local or construction site resolution. The description of the data processing to define emission processes is included in the following sections.

Table 2: Overview of EmSite input data and sources.

INPUT DATA	DATA SOURCE
Input Data used in EmSite v.1	
Emission Grid (500 m)	Map and Geodata – Statistics Norway
Matrikkelen	Norwegian Mapping Authorities
Road Construction	NVDB – Norwegian Public Road Administration
FKB-Tiltak	GeoNorge
FKB-Bygning	GeoNorge
Daily mean temperature	Norwegian Centre for Climate Services (Met.no)
Daily mean precipitation	Norwegian Centre for Climate Services (Met.no)
Soil data	NGU - GeoNorge
Basic Emission factors	EMEP/EEA Guidebook 2019
Machine park composition	CRAMO database
Engine size used in NRMM	Dallmann and Menon (2016)
European equipment population	Dallmann and Menon (2016)
Other input data with potential applications in the future versions	
Road Construction	Regional/Municipal data sources
FKB-Veg	GeoNorge
FKB-Tiltak	GeoNorge
FKB-Bygning	GeoNorge
Road / Infrastructure activity	ledningsportalen.no

4 The EmSite Model

EmSite is built as a bottom-up model to evaluate different aspects concerning construction site activity, such as location, duration, energy consumption, heating demand and, exhaust and non-exhaust emissions in Norway. The model is based on the processing of a spatially distributed set of input data that represents construction or demolition activity and variables that affect emissions, such as meteorological conditions. The latter is relevant as both heating demand and non-exhaust emissions rely on meteorological factors for each individual building site. The combination of different datasets allows us to determine i) the location, area and time of construction projects at fine resolution; ii) energy demand for NRMM and iii) air pollutants and GHGs emissions.

4.1 Pre-Processing input data

The matching of input data takes up the bulk of the computation time in the model and is an important part of it, though it is dominated by stand-alone processes. EmSite has 5 geospatial datasets that need to be matched, and most of this can be done to the data without other input. Processing is done to obtain annual files of activity data, with all relevant details of other variables. For construction and demolition of buildings, most projects span over 1 calendar year and thus, those construction activities are present in more than one annual dataset file. To each building site, properties relevant for activity and/or emissions are given from the other spatial datasets. For instance, soil data for the silt content, as it will affect non-exhaust emissions, and ground conditions, together with the size and type of construction (or demolition) work, as they will determine the energy demand for machinery. The EmSite model has a module to pre-process 3 types of activities; 1) Building construction; 2) Building demolition and 3) Work on roads and infrastructure.

Each of these modules attaches the activity data to the meteorological fields, to obtain daily temperature and precipitation for each site. It also attaches ground and groundwater data to each site. In addition, the altitude and daily solar insolation is adjoined to each site by spatial matching. Finally, municipality data is overwritten over the *matrikkelen* data based on spatial matching with current (2020 - 356) municipalities administrative divisions. The output is annual files with points containing all required information to calculate emissions.

For both construction and demolition this pre-process is similar and relatively straight forward. For road construction, the activity data has not been successfully made complete, and only some current projects are available.

4.2 Time, location and volume of construction activity

For the spatio-temporal distribution of **building and construction** activity, we processed data on building construction permits from 2010 to 2020 provided by the Norwegian Mapping Authorities (i.e., *matrikkeldata*; Table 2; namely *matrikkelen* in this report). The aim of using *matrikkelen* is to establish which buildings have been ongoing work over the last 10 years. The received excerpt from *matrikkelen* contains all buildings in Norway with a status change since January 1st 2010. The change of building status is the key parameter, as a change in the legal status is required before construction can start, the building is taken into use, or it is demolished. Thus, a change in the building status represents all building or removal of building mass that changes the building. This data is also used by Statistics Norway (SSB) as the basis for their built and demolished area reporting. Through the legal/administrative framework, *matrikkelen* establishes both a geographical reference and a timeline for where active construction has occurred or is ongoing. In addition, the dataset contains information about the type of construction work (e.g., apartment building, school, detached house) and the size. As *matrikkelen* is only a registry of buildings, it does not cover the totality of the construction sector. For other important construction projects, such as roads and infrastructures, the data regarding their construction sites will therefore come from other sources. There is, however, no single data source that covers this type of activity. Therefore, data on this must be patched together from several sources.

The **demolition** of buildings has the same data source and structure as building construction (i.e., *matrikkelen*). Therefore, the demolition data is treated the same as the construction data with the exception that there is only one phase (i.e., ground work). Demolished buildings have significantly more variability between the time of registration dates. This is probably a cause of less accurate data, which again may come from weaker incentives to follow a fixed application routine. Several (also large projects) have the same date registered for “allowed to demolish” as they have for “demolished”. Similarly, many entries have the difference in dates by 3 years, which is the expiry time of a permit allowing demolition. Therefore, the timeline of demolition projects may be significantly more uncertain than that for construction.

Roads in Norway can have private, municipal, county, or national ownership. Depending on the ownership of the finished road, different applications, planning, and registration are required. Therefore, there is not 1 single database for road construction but several different databases. The National Road Network database from the Norwegian Road Administration (NVDB) primarily provides data on ongoing national road construction projects. The NVDB data is, for the most part, limited to national roads, namely Europe standard roads (E) and *riksveg* (R). While these are most of Norway's largest and most trafficked roads, it is currently not possible to extract historical data.

In a similar fashion to NVDB, databases exist for ongoing work on municipal roads. A permit is required before digging in public surfaces (e.g., ledningsportalen.no), and thus both roads and digging for laying water, electric or other underground cables are covered. For some municipalities, ongoing or planned permits are publicly accessible (e.g., oslo.gravearbeider.no; lillestrøm.gravearbeider.no), either in map or in table format. No method has, however, been found to extract historical data from these. For historical and not currently ongoing road construction, a possible data source was *FKB_veg*. Several attempts were used to find dates or times in the available *FKB_veg* dataset in order to see if it was possible to get historic data, but so far it does not seem possible. This will add uncertainties to the estimates of national emissions from the construction sector, as the building of roads has been highlighted as one of the most relevant activities for emissions from construction (US EPA, 1999). However, at urban scale, where most of the road construction affects minor roads, or entails maintenance, the most significant source of emissions would be the building construction.

Whereas the timeline of the construction leaves room for interpretation, the geographical location is generally very precise. We compared the construction area obtained from *matrikkelen* at county level to that reported by Statistics Norway for buildings completed/initiated. These are data from the same source (i.e., *matrikkelen*) and the total area should be very similar. Some differences were found, which are probably related to the data included in the extraction from *matrikkelen*. This is made probable because the difference is only notable in non-residential buildings. A more detailed assessment is included in Section 5.

For the **timeline of the construction of buildings**, matrikkelen dataset has 4 types of data;

i) there is a well-defined time period for when construction started and ended;
ii) there is a start date but not an end date;
iii) there is an end date but not a start date; and
iv) there are both start and end dates but not well constrained.

Moreover, the timeline does not represent the actual date when the work did take place, but the administrative/legal procedure (“Construction application process” in Figure 3). Therefore, and in order to make a best estimate of the real duration of the construction project, a parameterization of how the physical timeline compares with the legal procedure was established based on real data. This was done over each construction project in *matrikkelen* and to also distinguish the relevant construction phases for emissions (i.e., ground work, heating, building work). Based on construction projects analysed by Mjøsund (2017), we established that, on average, 15% of the initial time is destined to contract and administration work, 5% to ground work, 7% to foundation, 30% to activities over the foundation and 43% for the finalization and sealing of the building (Figure 3). These average values were used to establish the duration of the building construction phases that results in emissions from NRMM. Hereby, during ground work, heating and building work phases, large machines, heaters/generators and small machines, respectively, are dominating. These parametrizations were implemented to each single construction project, and the final result is construction activity per year and grid expressed as m^2 as a result of the sum up of daily activity.

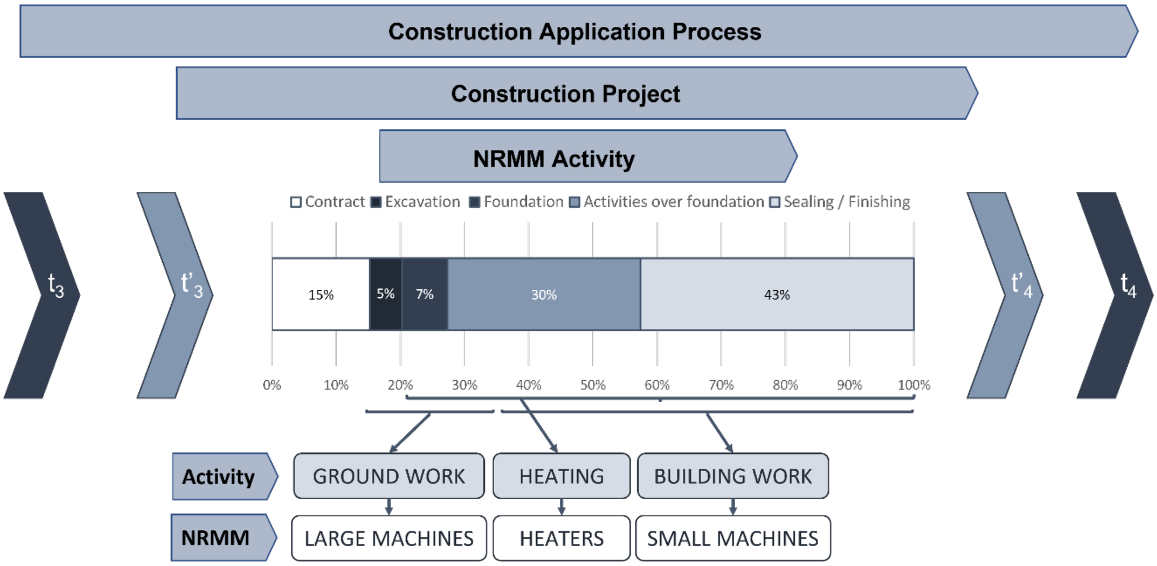

Figure 3: Scheme comparing the legal procedure (Construction Application Process) with the duration of the Construction Project, and the activity that results in emissions (ground work, heating, building work) with the corresponding main distribution of NRMM (large machines, heaters, small machines). The % represents the average time of the different phases of the construction project based on data from Mjøsund (2017).

Daily activity is assumed to follow the Norwegian holiday calendar and therefore, activity is allocated to working days. Normal working activity is assumed on weekdays and a lower activity on weekends and holidays (Figure 4). Hourly activity is assumed to ramp up from 06:00 and wind down around 17:00. Hourly emissions are adjusted to UTC +1, Norwegian wintertime.

Construction Activity has a strong diurnal variation following working hours, this also gives a dip in activity in months with fewer working days. **Suspension Potential** in Figure 4 represents the meteorological parameters that influence dust emissions, which have a strong monthly variability with a peak in summer, but as it uses daily data, no diurnal variability (additional information on the suspension potential is included in Section 4.5). The **heating demand** for setting concrete and indoor heating is dependent on the outdoor temperature and thus peaks in winter. Depending on the type of emission, more than one of the time-variations are employed.

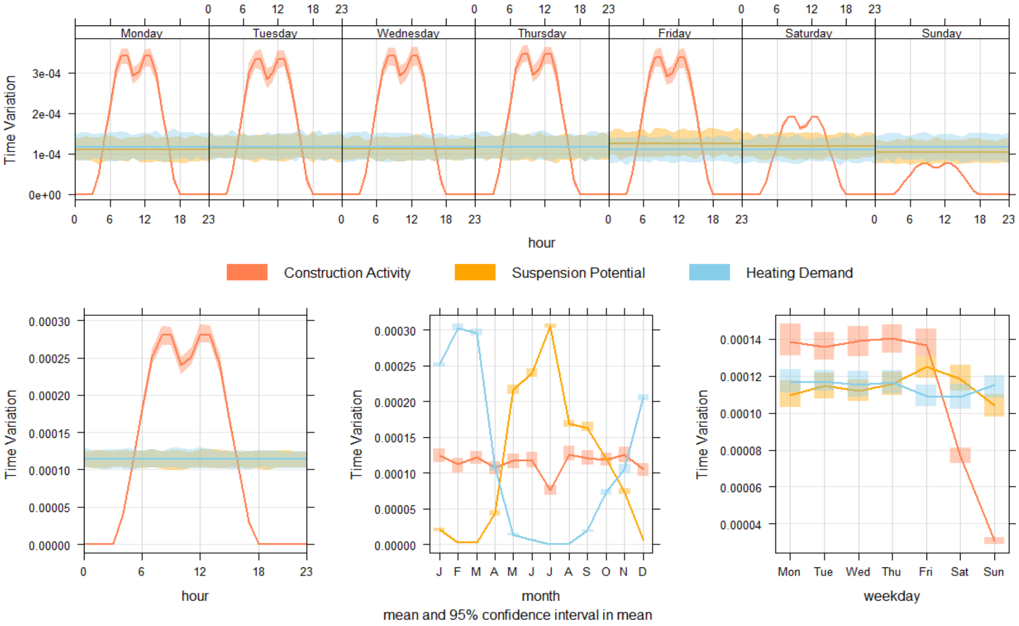

Figure 4: Time variations employed in the EmSite model averaged over Norway for 2019.

4.3 Machine use, Energy and Fuel demand of each construction site

The outcome from the processing described in the previous section is building and construction activity expressed in m^2. Based on the energy demand per m^2 established by DNV (2018), EmSite estimates energy demand for machinery in each building and construction site. The energy demand depends on the phase of the building and construction process, hereby ground work, heating and building work. Table 3 shows an overview of the energy demand values ($kWh \cdot m^{-2}$) used by EmSite for each construction activity, type of machinery and building type when relevant. In the case of demolition, and due to the lack of specific data, we assume that the average energy demand for demolition equals the energy demand per area in ground work, as demolition requires large NRMM.

Table 3: Energy demand per m^2 for ground work, heating and building work (Source: DNV, 2018). N/R: Not relevant. Non-residential: commercial and administrative buildings.

Activity	Ground Conditions	Type of Building	EmSite NRMM	Energy demand ($kWh \cdot m^{-2}$)
Ground Work	Simple		Large NRMM	30
Ground Work	Difficult		Large NRMM	45
Heating	N/R		Heaters/Generator	47
Building Work	N/R	Apartment, non-residential	Small NRMM	2.8
Building Work	N/R	House	Small NRMM	0.53

For ground work, the **energy demand for large NRMM** also depends on the ground conditions as they will affect the need for crashing ground material, and soil removal or replacement. In our study, we established simple and difficult ground conditions based on the soil type at each construction site (Table 2). For instance, thick sedimentary deposits are classified as simple ground conditions, whereas thin layers over bedrock or exposed bedrock are classified as difficult ground conditions. Table 3 shows the energy demand for large NRMM performing ground work under simple and difficult ground conditions. EmSite employs these values due to the lack of more detailed information. Based on the Caterpillar Performance Handbook (2018), the amount of fuel consumed and thus climate emissions increase up to 2-4 times for heavy duty works, when compared with light duty applications for the same equipment. The values suggested by DNV (2018) for simple and difficult work conditions do not reflect such large differences, and it may, therefore, underestimate emissions. For specific applications (or construction sites) more detailed information is needed. Other variables that may affect energy demand of NRMM are altitude and weather, such as severe weather conditions and cold winters. Under these conditions, NRMMs consume more fuel and increase emissions due to the underperformance of the engine, and longer engine start up and warm up to reach efficient working conditions (Fan 2017).

The **energy demand for heating** buildings under construction is calculated based on the assumption that heating is only required during periods with low daily temperatures. EmSite uses the daily temperature at each building site from the met.no reanalysis temperature grid (Lussana et al., 2019). In DNV (2018) an average heating demand of 47 kW·m^{-2} is reported (Table 3). This is split between concrete setting (8 kWh·m^{-2}), interior heating (34 kWh·m^{-2}), 4 kWh m^{-2} for concrete setting and ground casting, and 1 kWh·m^{-2} for façade heating. With 2015 as reference year and a threshold temperature of 5 degree Celsius, EmSite calculates the number of heating degree days (HDD) for each site in each month in that year (for more detail on the HDD concept, see Grythe et al., 2019). In a similar fashion as the MetVed model (Grythe et al., 2019), the EmSite model calculates the demand for heating in each building construction site as a relationship between HDD and kWh. The results of the HDD is a monthly need for heating at each active building site, expressed in kWh. Active sites for heating are buildings that are beyond the phase “ground work” (Figure 4). The energy demand for interior heating is assumed for the latest phase in the construction, i.e., “sealed/finishing building”, and the remaining is used during “foundation” and “activities over the foundations” (Figure 4).

DNV (2018) established that the energy demand for small NRMM used in the construction of an apartment building and a kindergarten is around 2.8 and 0.53 kWh·m^{-2}, respectively. EmSite uses 2.8 kWh·m^{-2} for apartment building, administrative building and industrial commercial buildings, whereas 0.53 kWh·m^{-2} is used for houses (Table 3).

The annual energy demand for large NRMM, small NRMM and heating is provided in the accompanying EmSite output data sets to this report. For 2019, the energy demand for large NRMM, small NRMM and heating is estimated to be 33%, 2% and 66%, respectively, of the total energy demand for NRMM in building and construction. The fuel split per machinery is based on the information from the machinery fleet composition database. Large NRMMs run exclusively on diesel, whereas small NRMM use a mix of diesel and gasoline, and generators and heaters run on diesel and LPG. The EmSite model applies a fuel split of 80% diesel and 20% LPG. As no information is available on electric machines, the use of electricity has not been currently considered, although is suggested as further need.

4.4 Emission Factors

Most of the NRMM used in building and construction are diesel fuelled machines. However, other fuels, such as LPG and petrol can also be used in heaters and small machineries, respectively. This section describes the EF developed for the EmSite model and associated with combustion processes. EF will largely differ across the different NRMM sub-operating conditions such as idling, digging, swinging, dumping or hauling (Heidari and Marr, 2015). The EmSite EF represents, however, an average over the entire “operating conditions” during each phase of the construction work.

4.4.1 Diesel Machines

Specific dynamic EF for GHGs and air pollutants have been defined for the three NRMM categories defined in EmSite; i) large NRMM, ii) small NRMM and iii) heaters or generators, all running on diesel. These EFs cover emissions from combustion sources, whereas EF for PM associated with non-combustion activities, non-exhaust emissions, are addressed in the next section. Based on the range of engine sizes used in NRMM (Figure 5) for the construction sector, we have defined large NRMM as those with power class above 75 kW, and small NRMM as those with power class below 75 kW, whereas diesel generators or heaters cover all power class ranges.

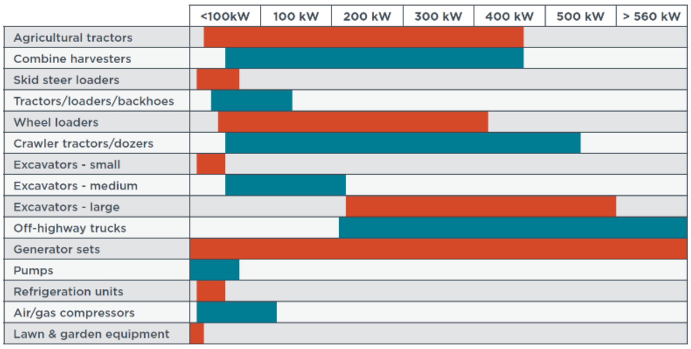

Figure 5: Range of engine sizes used in NRMM (Source: Dallmann and Menon, 2016).

To define dynamic EF, knowledge of the NRMM fleet composition over time and within the three categories is essential. This will reflect the technological changes and improvement due to the introduction of European emission standards for engines used in NRMM. Over the years, new and more stringent tiers have been introduced (i.e., Stage I, II, IIIA, IIIB, IV and V) as specified in the EU Directive 97/68/EC (EU 1997) and amending directives adopted from 2002 to 2012 (EU 2002, 2004, 2010, 2012). In the EmSite project, fleet composition and evolution over time have been designed for the three NRMM categories based on information about the current machine park of one of the biggest machinery rental companies in Norway, and assuming a continuous introduction of new NRMM over time. The NRMM park database contains over 2000 entries covering machines and equipment, and information of the type of fuel they run on, manufacture year and, in some cases, the Stage standard. The NRMM fleet composition results and their evolution over time are shown in Figure 6 for large NRMM (top left), small NRMM (top right) and heaters/generators (bottom).

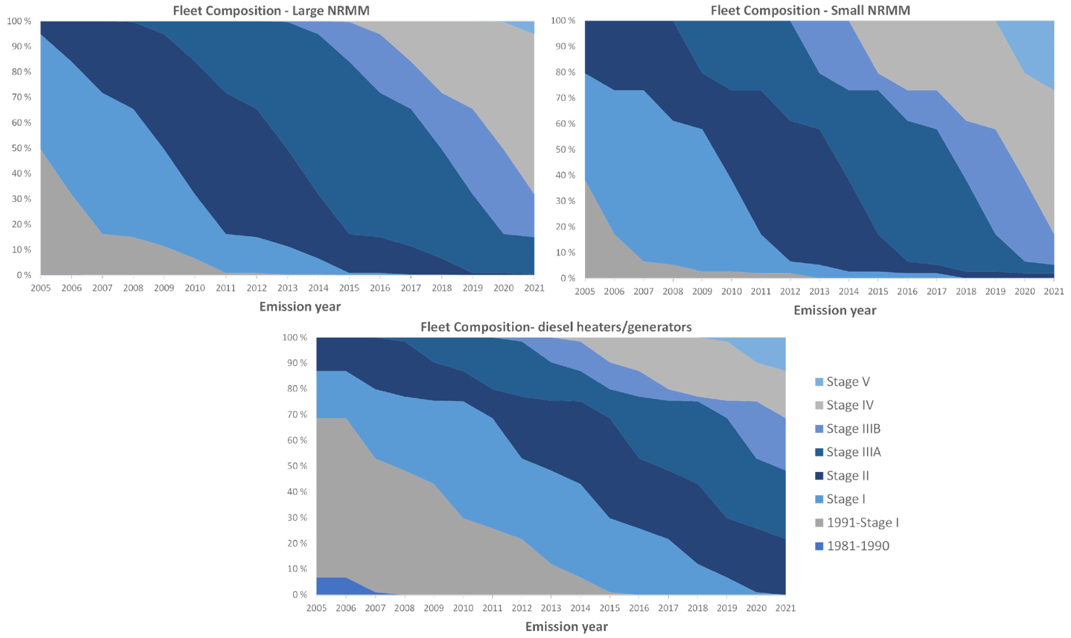

Figure 6: Fleet composition based on European engine standards (i.e. Stages) for large NRMM (top left), small NRMM (top right) and heaters/generators (bottom) for different years for machines in construction in Norway.

Dynamic weighted EF for i) large NRMM, ii) small NRMM and iii) heaters or generators were estimated combining the yearly NRMM fleet composition with basic emission factors. As each EmSite category includes different types of NRMM with different power class (kW), basic weighted EF were developed based on the EFs for Tier 3 methodology from EEA/EMEP Guidebook (2019) for diesel machinery within different power class and engine technology pre-1991, 1991-Stage I, Stage II, Stage IIIA, Stage IIIB, Stage IV and Stage V, and the machine population per power class used in Europe within construction (Dallmann and Menon, 2016). Figure 7 shows the machine population where NRMM with 56-75 kW engine power is the most abundant (34%), followed by small machines below 19 kW (23%), machines with 19-37 (16%) and 37-56 (14%) kW engine power, and large machines with 75-130 kW (7%), 130-560 kW (5%) and above 560 kW (1%) engine power (Dallmann and Menon, 2016).

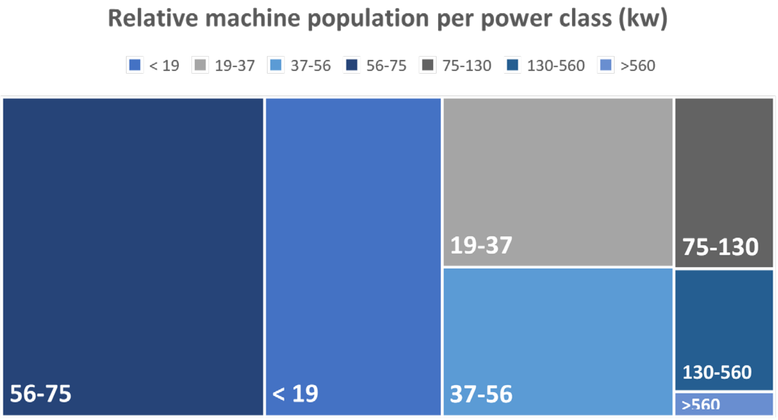

Figure 7: Power class distribution for non-road vehicles and equipment used in construction in the European Union (Data Source: Dallmann and Menon, 2016).

The resulting EmSite dynamic EFs per component for large NRMM, small NRMM and heaters/generators running on diesel are shown in Table A 1 - Table A 3 in Appendix A. The EmSite EF_{NOX} time series have been compared with those used by Norway for the official reporting of emissions as documented in the Informative Inventory Report (NEA, 2021). Figure 8 shows this comparison; EmSite EF_{NOX} are higher for the three categories than the weighted EF_{NOX} used in Norway for the general NRMM sector and specific for the sector 230100 – 230210, which represent NRMM used in agriculture, forestry and construction. The lack of detailed information in the IIR regarding what these EFs represent and the basis for the yearly weight does not allow us to determine the basis for these differences. We have similarly compared with the EF_{NOx} used in the assessment of external cost associated with construction machinery and provided by the Norwegian Environment Agency. This comparison is shown in Figure 9, where EFs per power class and Stage engine technology (III, IV and V) used in the aforementioned study are shown along with EmSite EF_{NOX} for the three categories (large NRMM, Small NRMM and Heaters/Generators). EmSite EF_{NOX} are similar to those for NRMM with engine power below 56 kW and all Stage engine categories, and similar to large machines with Stage engine III. Based on the machine park of the Norwegian machine rental company that NILU had access to, 50% of large NRMM belong to Stage IIIA and 13% to Stage IIIB, whereas 6 and 9% belong to Stage IV and V, respectively (22% of the entries do not provide Stage engine classification). Information about the Stage engine of small machines is not available in the dataset, and 92% of the available information about heaters/generators belong to Stage IIIA. Based on the available information, we can assume that our EF may be representative of the Norwegian machine park.

In the case of CO_2 emissions, our estimates are based on fuel consumption (FC), which is calculated based on the fuel consumption reported in Appendix A as $g{\cdot}kWh^{-1}$, and considering 3.17 t CO_2 t^{-1} of fuel (NEA, 2019a).

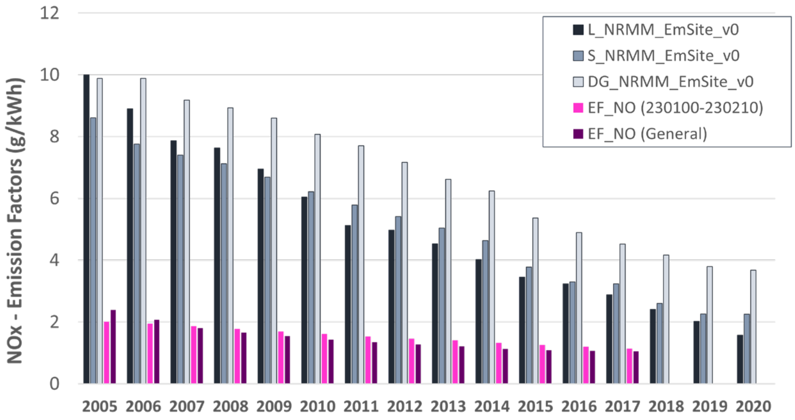

Figure 8: *Comparison of EmSite EF_{NOx} time series and used for the official reporting of emissions specific for NRMM in agriculture, forestry and construction (230100-230210) and general for NRMM (NEA, 2021).*

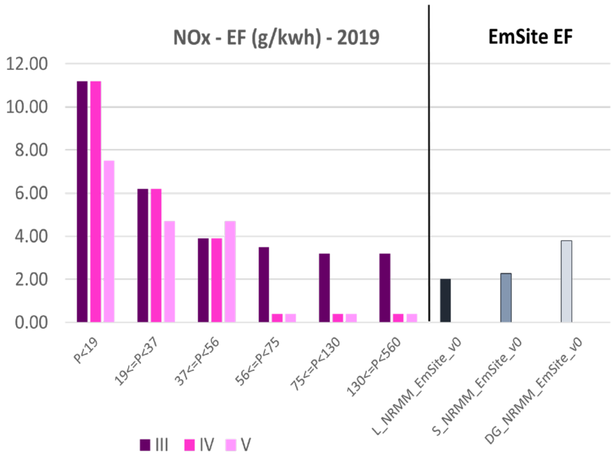

Figure 9: Comparison of EnSite EF_{NOX} ($g{\cdot}kWh^{-1}$) with EF_{NOX} used in the assessment of external cost associated with construction machinery (Source: NEA). L_NRMM: Large NRMM. S_NRMM: small NRMM. DG_NRMM: diesel heaters and generators.

4.4.2 LPG machines

LPG is a commonly used fuel for heaters employed in building and construction activity. Around 15% of the total number of machines available in the machine park dataset run on LPG, and all of them are classified as heaters or generators. Within the category heaters and generators, 51% of the machines run on diesel, around 42% on LPG and the remaining 7% of the NRMM run on gasoline.

Table 4 shows the EF used in EmSite for LPG NRMM. Due to the lack of information on the development of the machine park over time, we use these emission factors for all emission years. CO_2 emissions are estimated based on the fuel consumption defined in Table 4 in g kWh^{-1} and EF_{CO2} = 3 t CO_2 t^{-1} of fuel (NEA, 2019a).

Table 4: Emission factors for NRMM running on LPG ($g{\cdot}kWh^{-1}$) based on Tier 3 methodology from EEA/EMEP Guidebook.

NO_x	VOC	CH_4	CO	N_2O	NH_3	N2O	TSP	BC	FC
10	2.2	0.11	1.5	0.05	0.003	0.05	0.07	0.01	311

4.4.3 Gasoline

We have less information on the use of gasoline NRMM for building and construction. Based on the machine fleet available, around 16% of the machines run on gasoline. The dataset does not include detailed information concerning the EU Stage engine category of gasoline NRMM. These NRMMs are mostly small machines (14%) and a small amount is classified as heaters or generators (2%).

Basic EFs are available from the EMEP/EEA Guidebook (2019) for gasoline NRMM with 2 or 4 stroke combustion engines. We do not have information on the type of combustion engines, however, considering that 2-stroke engines are typically found in smaller applications (e.g., remote-controlled cars, lawn tools, chainsaws, boat motors), we have assumed that most of the machinery used in construction activities are 4-strokes. EFs for Tier 3 methodology from EMEP/EEA Guidebook (2019) for gasoline machinery with engine technology pre-1991, 1991-Stage I, Stage II, and Stage V were combined with a gasoline machine park composition developed based on the introduction of new technologies from diesel small NRMM. In this case, we assume a similar introduction of gasoline machines than that one for diesel machines.

In the case of particulate matter, EMEP/EEA Guidebook (2019) provides EF for total suspended particulate matter (TSP), and it does not provide specific information on the size fraction. We have assumed that, as most of the TSP is associated with combustion, they belong to the fine fraction ($PM_{2.5}$). Figure 10 shows the designed fleet composition for gasoline NRMM, and the resulting dynamic EFs for gasoline NRMM are shown in Appendix A. CO_2 emissions are estimated based on the fuel consumption defined in Appendix A as g kWh^{-1} and EF_{CO2} = 3.13 t $CO_2 \cdot t^{-1}$ fuel.

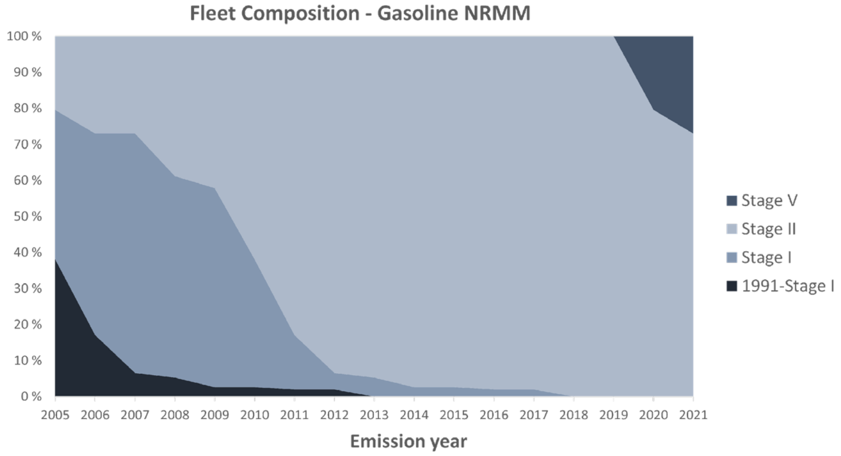

Figure 10: Fleet composition based on European engine standards (i.e., Stages) for gasoline NRMM.

4.5 Non-exhaust emissions

The EmSite model first calculates annual non-exhaust emissions based on Tier 1 methodology suggested by EEA/EMEP Guidebook (2019; Equation 1). The EEA/EMEP EFs are specific for building type as 1) residential houses 2) apartment buildings 3) all other buildings and 4) road construction, and EFs are given for $PM_{2.5}$, PM_{10} and TSP (Table 1). EmSite uses the attribute *Bygningstypekode* (building type) to classify a construction project as 1, 2 or 3 for all buildings in the dataset, thus it uses the corresponding building type based EF. For road construction, EmSite uses the corresponding EF for roads (Table 1).

In addition, the area influenced by construction activity is dependent on the footprint of the building and a factor that depends on the building type. The footprint of the building is not part of the input data but rather “usable area”. As an approximation, the usable area is used without a factor. As the factor suggested by EMEP/EEA Guidebook (2019) is larger for taller buildings, this seemed a feasible approach. The PE index (Thornthwaite 1948) is used as given in EMEP/EEA Guidebook (2019):

$$PE_{index} = 3.16 \sum_{i=0}^{12} \left(\frac{P_i}{1.8T_i+22}\right)^{\frac{10}{9}}$$

Equation 2

where P_i is the monthly precipitation and T_i is the mean monthly temperature. To calculate the PE_{index}, the meteorological 2 m temperature and precipitation of the meteorological grid of the centre point of each building is used. When used over a year like this, the PE_{index} is dominated by the months with cold temperatures. The PE_{index} was originally developed, and is still used, for climate zone classification of the global land surface as wet (128+), humid (127-64), sub-humid (63-32), semi-arid (31-16), arid (16-6) and desert (-6). However, the Equation 2 is not well suited for low temperatures as occurs in Norway, where many months have average temperatures below 0. Therefore, sub-zero temperatures were replaced by 0 as is commonly done. For Germany, for instance, an average PE_{index} of 100 was applied to the whole country reported emissions. Equation 2 only works when precipitation is greater than 0, and therefore, it is not suited for higher temporal resolution than annual emissions. Still, a similar equation for potential evapotranspiration is also presented by Thornthwaite for both monthly and daily evapotranspiration (PET_d) potential. This is meant to represent what the transpiration would be in the case of an infinite source of water at the surface:

$$PET_d = 16\left(\frac{L_m}{12}\right)\left(\frac{N_m}{30}\right)\left(\frac{10T_d}{I}\right)^{\alpha}$$

Equation 3

$$I = \left(\frac{T}{5}\right)^{1.514}$$

Equation 4

$$\alpha = (6.75 \times 10^{-7})I^3 - (7.71 \times 10^{-5})I^2 + (1.792 \times 10^{-2})I + 0.49239$$

Equation 5

where L_m is the average of sunlight hours in a day of the month m, N_m is the number of days in the month, T_d is the daily temperature (°C), I is a heat index (Equation 4) and α a dampening factor in Equation 5, typically = 0.5-0.8 in Norway. Equation 3 does not include precipitation but simply describes the potential for evapotranspiration. For Equation 3, negative temperatures are replaced by zeros based on the recommendations of Thornthwaite. There exist more advanced functions that take more detailed data into account, however, this would require significantly more meteorological input data. Consideration was given to use an energy balance model to model surface moisture. This involves several additional input data and considerable work, and was deemed too resource demanding for this project. These previously presented equations are meant as simple approximations to the dryness of each worksite and thus describe the daily suspendability of the soil in the area. Hourly emissions are then calculated based on the hourly activity, the total emissions assumed and the potential for suspension on that day.

$$EM_h = hourly\ activity\ \times EP \times EF$$

Equation 6

Where EF is a property of building activity speed (m^2 day^{-1}), building phase (day) and type of building, and has the soil properties as a component factor. The daily dust emission potential (EP) depends on the daily insolation, temperature, and precipitation. The relationship is in EmSite described as a change in surface moisture from time i-1 to i:

$$EP_i = \frac{1}{WET_i}$$

Equation 7

$$WET_i = max(0, WET_{i-1} \times s^{PETd_{i-1}}) - (PETd_i - rr_i)$$

Equation 8

where PET_d is from Equation 3 and rr is the daily precipitation, s is a constant (=0.9) describing how long precipitation is retained after rainfall. WET_i is the surface wetness on day i. Both PET_d and rr are given in mm day^{-1}. The results for Norway and for some selected city regions are shown in Figure 11. Based on the equations above, there is a strong seasonality in 2019 emissions. Regions with lower potential for dust emissions are in central and western Norway with down to 50 days. In the drier south eastern Norway, there are more days with dust emissions potential. In northern Norway, the lack of sunlight and cold temperatures during winter inhibit much suspension as the surface remains frozen and snow covered for several months. The pattern observed in 2019 is generally similar for most years across Norway (not shown in Figure 11).

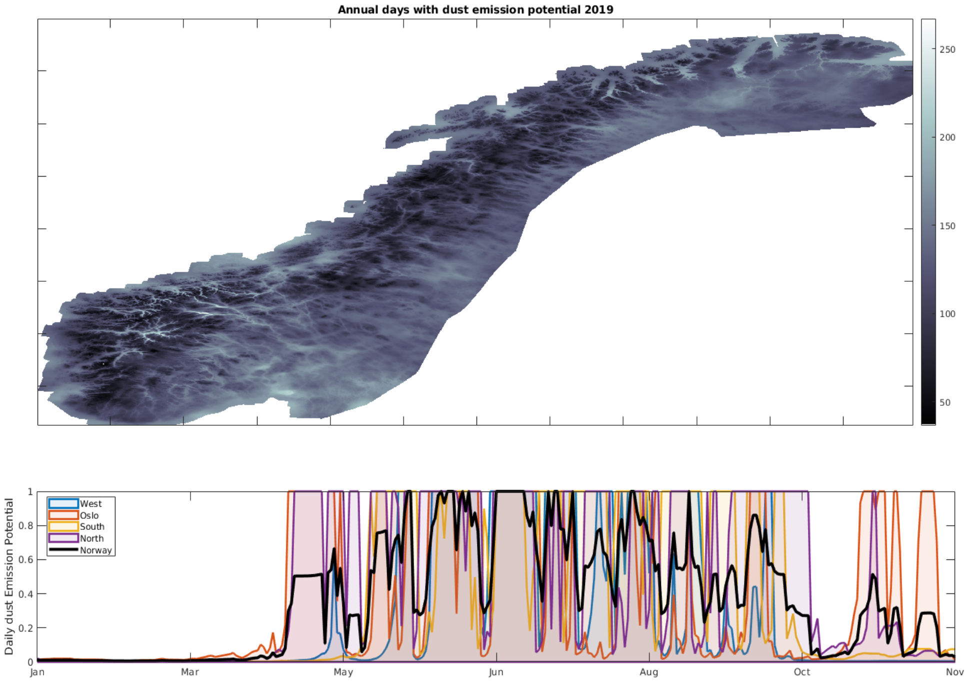

Figure 11: Number of annual days when dust has the potential to be emitted during building and construction. Top: days with potential for non-exhaust emissions in Norway (2019). Bottom: daily emission potential as averages over some regions in Norway and at national level.

5 EmSite Results and Assessment

The EmSite model has a good coverage of activity that involves both the construction and demolition of buildings. The spatio-temporal distribution of building activity over time must be considered robust as unregistered building activities can be considered minor compared to registered. For work on roads and infrastructure, there is, however, no national database for when, where and how much activity was/is ongoing that we could rely on, and only partial results can be obtained. This shows both the weakness and strength of a bottom-up approach such as it is used in EmSite. With good and available input data, it is possible to produce output with high accuracy and detail, but it is hard to have a complete picture when this is lacking. Emissions from the construction sector are also complex from a top-down perspective, and thus the EmSite model fills an important knowledge gap. At the current stage, the EmSite model includes the subroutines to estimate emissions from road construction. However, due to the lack of road construction data, and with sufficient coverage, the results presented in this section include only building construction and demolition.

EmSite has been run to produce emissions for the years 2010 to 2020, the time span for which input data was available for Norway. Accompanying EmSite output data sets to this report are produced as annual emissions supplemented by daily and hourly time variation files. The annual emissions produced by the EmSite model are gridded at 250 metre resolution on the standard Norwegian grid provided by Statistics Norway (SSB, 2021), but the output files can be in any predefined grid covering Norway. In the gridding process, each building construction (or demolition) site is given an influence radius, which is determined by the size of the building being constructed. The size of a building is given by the “usable square metres'' (BRA) of the building. Emissions are assumed to occur uniformly in this polygon of influence and are mapped onto the output grid by area. The output data produced for this report is the irregular 250 m UTM33N grid (SSB, 2021), where only grids with emissions are included for each year. In order to determine daily or hourly emissions the annual data should be combined with one (or more) of the time variations functions in the supplementary data. The time variation files add to 1 so that hourly emissions can be calculated by simple multiplication. In addition to the annual gridded emissions, EmSite provides emissions per municipality, county and annual level by aggregating the gridded emissions to the corresponding administrative geographical levels. The output files separate the source of emissions in kWh (Large NRMM, small NRMM and heater / generators), and the fuel consumption (diesel, petrol or LPG), along with the emissions.

5.1. National EmSite emissions

There are good statistics on the number and area of buildings completed each year. Building activity in Norway has kept relatively steady in the past decade (Figure 12). The square metres of buildings started on specific years are for most of the years very similar in EmSite and in the Statistics Norway database. Considering they have the same data source, i.e., *matrikkelen*, the pronounced difference in 2010 and 2011, is probably related to how the data was extracted. The difference is more pronounced for completed buildings, where EmSite for nearly all years has more square metres being completed. This is probably an artefact of data extraction, where also buildings that were never actually built are included in this EmSite statistics, and probably also due to slow updates of the database, as the data was extracted for this study in late November 2020. As buildings never built are later removed in the process, this does not affect emissions. As EmSite tracks individual building sites, it is possible to define the number and square metres of all ongoing building projects. This shows low activity in 2010, consistent with the economic downturn, and similarly in 2020 (Figure 12). Although there is some year to year variability, there is no discernible significant trend in the data. The active construction sites in Norway steadily cover 22-25 million square metres that are in the process of being constructed. They cover various phases of the building process from the completion, or near completion, planning and waiting to start. Thus, many of these sites will have little or no activity at any given time.

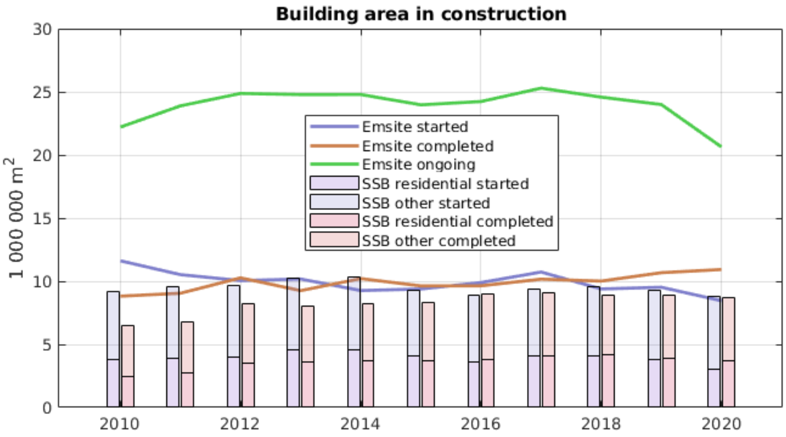

Figure 12: Area of initiated (blue line), completed (red line) and ongoing (green line) residential and other than residential building projects in EmSite. SSB: Area reported in Statistics Norway (SSB Table 05939 and 05940).

Annual fuel consumption closely follows the building activity. Neither the square metres of ongoing work nor the completed/initiated square metres give an accurate picture of the actual construction being done in the model or in the real world. Therefore, there is not a direct connection between the amount of work being carried out and the ongoing building sites, as the activity can be idle. Out of the fuels used, about 90% is diesel, 9% is LPG for heating and less than 1% is gasoline used in some small machines. Other influencing factors on the fuel use are the amount of ground work required for construction in a given year, the building types and the heating demand.

EmSite exhaust emissions show a decreasing trend for the main air pollutants NO_x and PM (Figure 13 and Figure 14), whereas the decline is less prominent for CO_2 emissions (Figure 15). As building and construction activity has not been reduced over time, the main reason for such a decline is the reduction in EF as a consequence of the technological changes and improvement with the introduction of European emission standards for engines used in NRMM (i.e., Stages). Emissions are also dependent on the amount of heating required, and thus have a climatic component. Annual variability of CO_2 emitted closely follows the need for heating (*Heating* and *CO_2* in Figure 13), which affects the use of diesel and LPG. The reduction in NO_x and PM emissions is mainly due to filters and catalysts, whereas CO_2 reductions are due to increasingly efficient engines. Thus, the reduction in EF_{NOX} and EF_{PM} is stronger, similar to what is seen in on-road exhaust emissions.

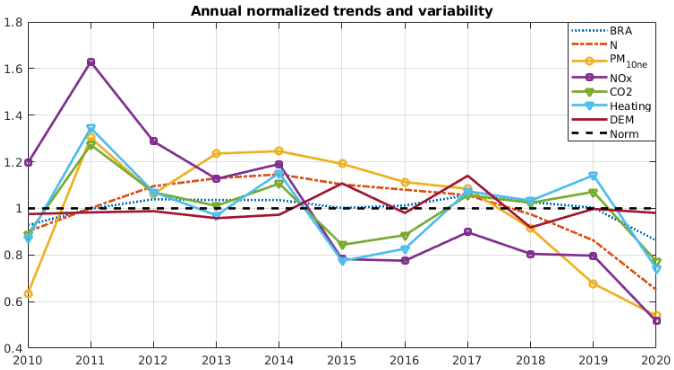

Figure 13: Normalized annual emissions for the main components in EmSite. N is the number of ongoing constructions and BRA their combined size. PM_{10ne}: non-exhaust PM_{10} emission.

Non-exhaust emissions depend on several factors. The overall construction activity and the soil and surface dryness where the construction is ongoing are the most important parameters. While generally quite steady, the overall construction activity has gone somewhat down since the peak in 2017 (*BRA* in Figure 13). The peak year of non-exhaust emissions was 2014 and has since then, somewhat declined. The reason for this can be a shift in locations and/or type of buildings that are being built, or climate. Climatic conditions are defined in EmSite based on temperature and precipitation. A trend in the location of building sites across regions can also be part of determining the emission changes.

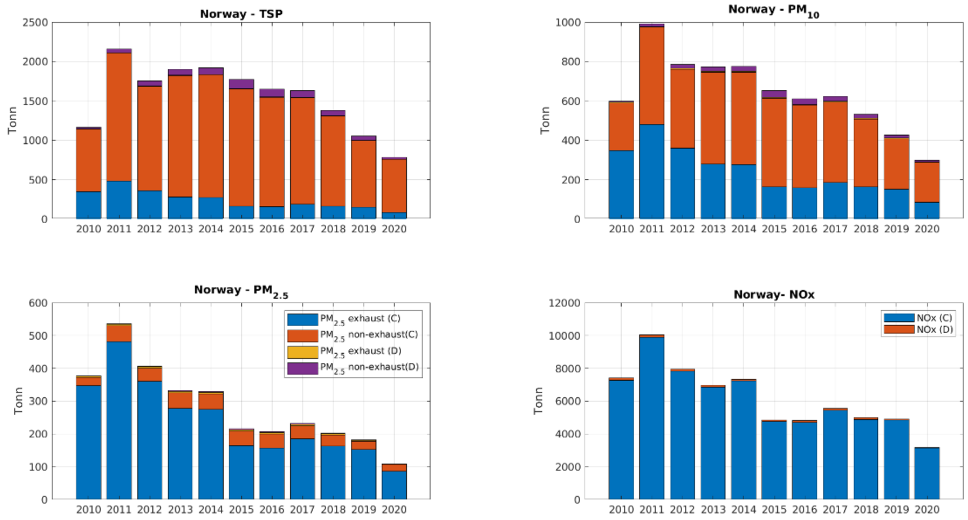

Figure 14: Exhaust and non-exhaust emissions by activity related to construction (C) and demolition (D) of buildings in Norway from 2010 to 2020. Similar figures for some Norwegian municipalities are included in the Appendix B and data at national level in Appendix C.

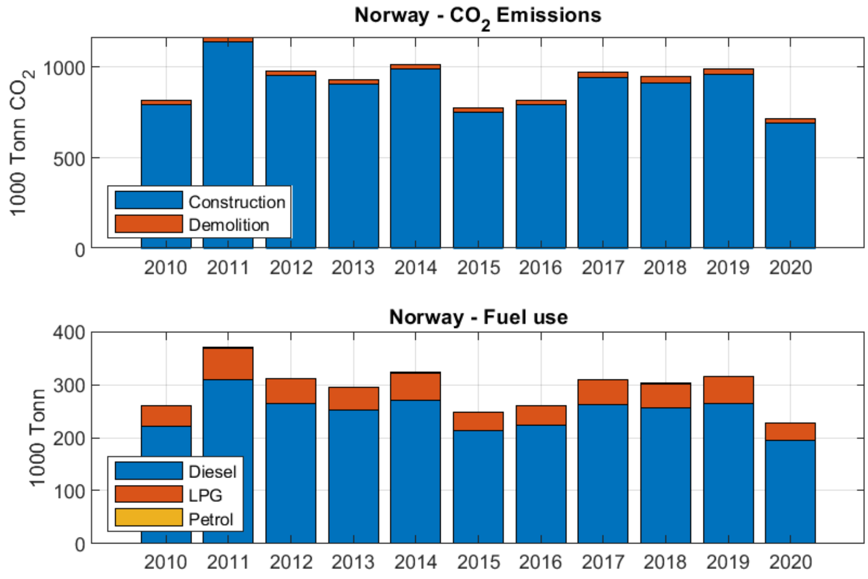

Figure 15: CO_2 emissions by activity related to construction and demolition (top) and fuel (bottom). Similar figures for some Norwegian municipalities are included in the Appendix B and data at national level in Appendix C.

5.2. Comparison with officially reported emissions

National Non-exhaust emissions

For non-exhaust emissions, we have argued that there is very little to nothing to compare emissions with, not even at national level. The Norwegian reported emissions (sector 2A5b; “Construction and Demolition”) only represent a partial picture of non-exhaust emissions, and thus have limited value as a benchmark. Figure 2 shows the different processes where non exhaust material can be suspended. The term in the Tier 1 methodology (Equation 1) contains aspects of duration, size of the construction site, soil and building type, but it is not clear which of the 4 processes it represents, or if these are considered separately. Out of the 4 processes, it is clear that only the mechanical upheaval activity is included. Wind suspension, and most probably the 2 emission processes that do not occur on site (i.e., traffic and tyres, and freight), but rather on roads, should be considered more carefully as they are probably not included by Tier 1 methodology by EMEP/EEA Guidebook (2019). The EmSite non-exhaust emissions by construction sites should, therefore, be considered as a very conservative estimate, as it does not provide an overall picture of all the non-exhaust emissions associated with building and construction.

The emissions of non-exhaust particles are primarily coarse particles. Therefore non-exhaust emissions dominate the TSP (total suspended particles) and are an important contributor to PM_{10}. $PM_{2.5}$ emissions, however, are dominated by combustion processes for all years (Figure 14 and Appendix B). The annual variability has primarily two drivers: i) the volume and number of construction sites; and ii) the days with emission potential (Figure 4). These are somewhat interconnected as the local conditions (suspension potential) from the various building sites may depend also on where the building sites are located, and their soil characteristics.

National Exhaust emissions

Norway reports emissions of air pollutants and GHGs from machinery used in building and construction to the CLRTAP and UNFCCC, respectively, as sector 1A2gvii (namely “Mobile Combustion in manufacturing industry and construction” and “off-road vehicles and other machinery”). Official emissions are estimated based on petroleum products sales statistics, and includes gasoline, bioethanol and tax-free auto-diesel; this latter is the most used fuel in NRMM.

Figure 16 shows the comparison between official NO_x and CO_2 emissions for 1A2gvii in Norway and that of EmSite. NO_x emissions in EmSite are larger than officially reported figures from 2009 to 2014, although consistent with or slightly higher from 2014 onwards. EmSite emissions represent lower activity levels than occurred in Norway, as the building and construction activity of other projects than building is lacking. Under lower activity levels, the generally higher EmSite NO_x results than official emissions indicate that the reason behind such differences is in the EF. As it was shown in section 4.4, EF developed for EmSite are higher than those employed in official estimates, although at the same level as those used by Norwegian Environment Agency in the assessment of external cost from construction machinery.

A similar difference as for NO_x emissions is not observed for CO_2 emissions when comparing EmSite emissions with officially reported figures (Figure 16). CO_2 emissions in EmSite are estimated based on the fuel consumption and corresponding EF for different types of NRMM and fuels. EmSite CO_2 emissions are for most years lower than officially reported emissions, and consistent with the lower activity level in the building construction sector, and the fact that construction only represents part of the 1A2gvii sector. An additional source of information in Norway is the accounting of GHGs at municipality level published by the Norwegian Environment Agency (NEA, 2020). In this accounting, NRMM used in building and construction does not appear as an individual sector, but is included in “diesel motorized equipment” along with other machines and equipment that use tax-free diesel. These machines are used in agriculture, forestry, military, and in private households. EmSite CO_2

emissions at national level are compared with the national aggregated emissions from "diesel motorized equipment" at municipality level[9] (*Utslippsregnskapet_MD* in Figure 16). EmSite CO_2 emissions, which includes diesel, LPG and petrol NRMM, represent approximately 50% of the total emissions from tax-free diesel motorized equipment.

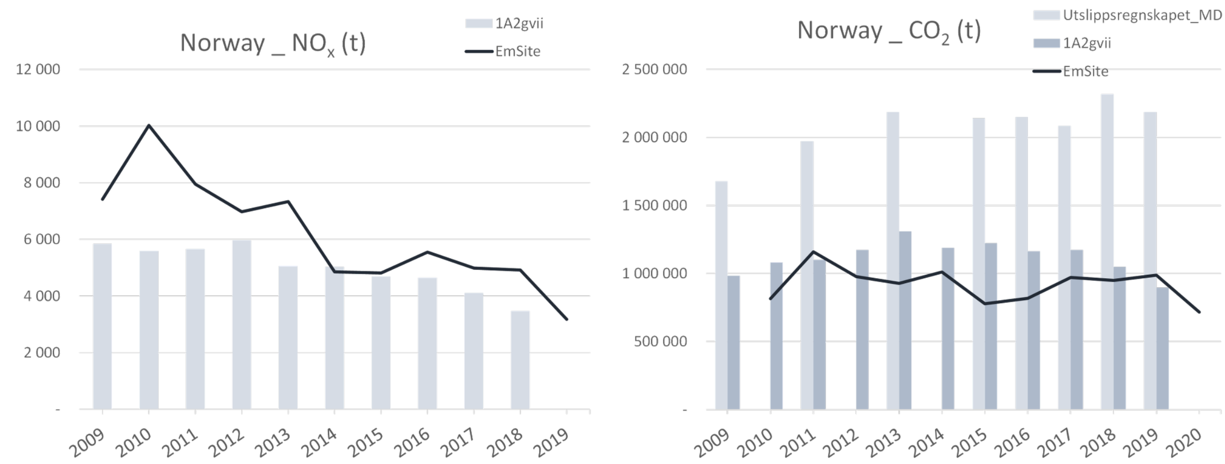

Figure 16: Comparison between EmSite and officially reported NO_x and CO_2 emissions. 1A2gvii: Mobile Combustion in manufacturing industries and construction, submitted to CLRTAP (NO_x), and off-road vehicles and other machinery, submitted to UNFCCC (CO_2). Utslippsregnskapet_MD is the sum of CO_2 emissions by diesel motorized equipment at municipality level.

CO_2 emissions at municipality level[9]

The accounting of emissions at municipality level is used to evaluate progress towards existing plans to reduce GHGs emissions at local level. The sector "diesel motorized equipment", which includes machines and equipment used in various sectors, poses important challenges for such evaluations. Some municipalities will have a higher intensity of activities within one specific sector, e.g., agriculture, whereas others will have a higher intensity in others, e.g., building and construction. A clear distinction of emissions from the different sub-sectors is, therefore, crucial for the municipalities. We have compared CO_2 emissions in EmSite for specific municipalities with CO_2 emitted by "diesel motorized equipment" reported by the GHGs accounting (Figure 17). In the latter, emissions at the municipality level are distributed according to the delivery address of tax-free auto-diesel sales, and when this one is not available, the organization number of the fuel buyer linked to the company address in the Business and Enterprise Registry is used. Given neither of them are available, emissions are estimated at county level and distributed at municipality level based on population. When the petroleum products sales occur to a distribution company that received large quantities (between 40-60% of total fuel sales for tax-free diesel), the location of pumping stations for machinery diesel is used, along with information on the distribution area of the company and population at the municipality level. As previously reported in Lopez-Aparicio and Grythe (2021), this distribution key may result in an over-allocation of emissions in certain municipalities combined with an under-allocation of emissions to others. Figure 17 shows the comparison between EmSite CO_2 emissions in Oslo, Lørenskog, Bergen and Askøy and CO_2 from the GHGs emissions accounting (*Utslippsregnskapet_MD*). Whilst in Oslo and Bergen, EmSite CO_2 emissions are lower than those reported from "diesel motorized equipment" in the GHGs emission accounting, in other municipalities, e.g., Lørenskog, EmSite emissions are much higher (Figure 17). Lørenskog municipality has experienced intensive building and construction activity

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[9] The methodology to distribute emissions at municipality level was modified in 2022. Therefore, this report refers to the previous methodology (NEA, 2020).

in the last years, which the GHGs emission accounting at municipality, and the distribution key behind, does not seem to capture.

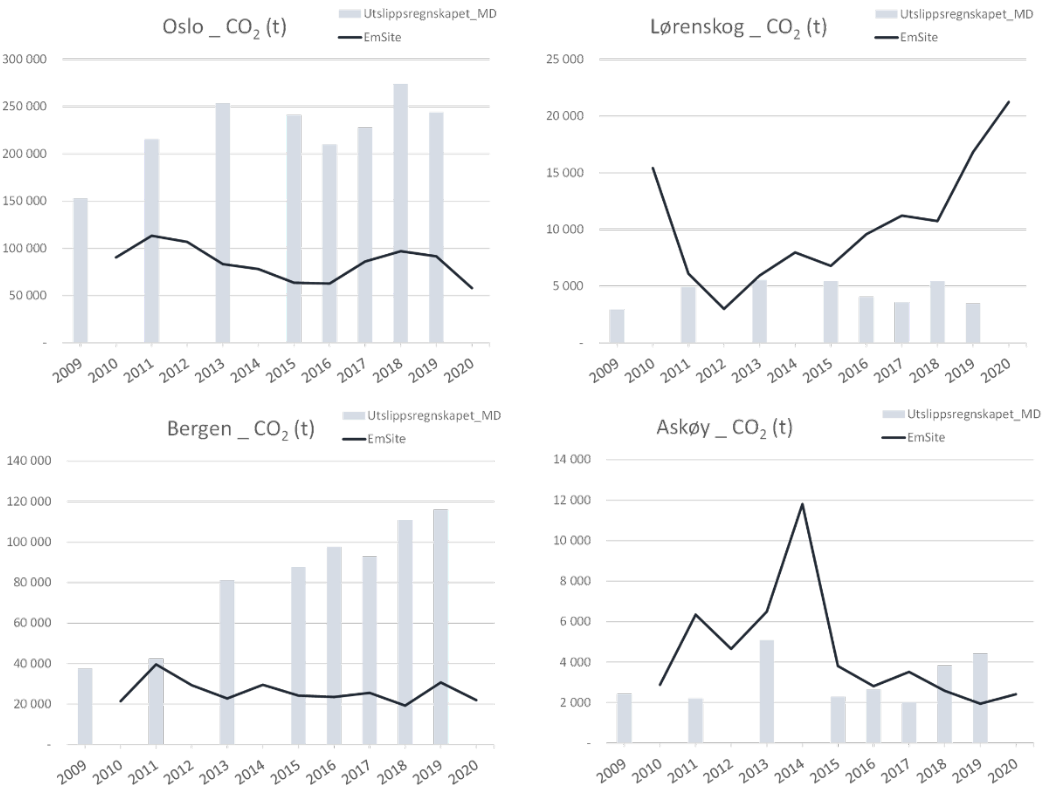

Figure 17: EmSite CO_2 emissions at municipality level compared with CO_2 emissions from "diesel motorized equipment" as published in the GHGs emissions accounting at municipality level (Utslippsregnskapet_MD).

Comparison with petroleum sales statistics

Diesel consumption was also calculated by EmSite and is shown in Figure 18 for 2019. Fuel consumption is compared with tax-free diesel from the petroleum sales statistics as reported by Statistics Norway distributed in business sectors, which is the input activity data of official emissions in Norway.

The sales of petroleum products are split in different business sectors based on the organization number of the buyer and, when the buyer is a private person or a housing association, the fuel sales are allocated to the residential sector (Kittilsen et al., 2018; *Boliger og næringsbygg* in Figure 18). A significant part of the fuel is bought by distribution companies rather than by end users, and thereafter the fuel is further distributed to final users. In this case, the distribution per business sector is performed assuming that the direct fuel sales distribution is also representative for the business split fuels sold by distribution companies. This constitutes an important uncertainty, as this assumption may not be correct (Kittilsen et al., 2018).

The comparison between fuel consumption in EmSite and tax-free diesel sales shows a large difference for the business and construction sector (*Bygg og anlegg* in Figure 18), as much higher values are obtained by EmSite. As EmSite only represents a part of the construction activity than occurred in Norway, this difference may highlight the uncertainties behind the distribution of fuel sales in business sectors. This is in line with Kittilsen et al., 2018 and indicative of the uncertainties within the distribution of fuel sales. Within the petroleum sales statistics, the share of tax-free diesel sold to large distributors has been 40-60% of total sales between 2009 and 2019. This amount is distributed among the different business sectors using the same share as from the direct sales.

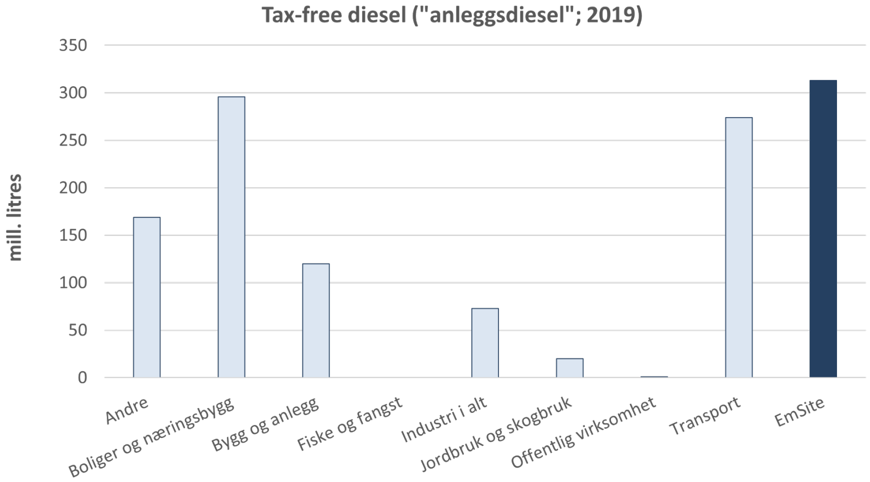

Figure 18: EmSite diesel consumption and tax-free diesel ("anleggsdiesel") sales (Data source: SSB-Table 11174, Statistics Norway). "Boliger og næringsbygg": residential and commercial/industrial building. "Bygg og anlegg": building and construction. "Fiske og fangst": fishing and hunting. "Industri i alt": overall industrial sector. "Jordbruk og skogbruk": agriculture and forestry. "offentlig virksomhet": public sector.

5.3. Closing remarks – EmSite assessment

Fuel consumption and emissions from NRMM in building and construction depends on a large number of variables such as engine power, equipment conditions, meteorological conditions, and equipment operator skills. In our study, engine power is considered in the three phases of the construction process. The operator conditions are indirectly accounted for when dealing with simple and difficult work conditions, however, the different energy demand seems to be smaller than reported in the literature (Caterpillar Performance Handbook, 2018).

The lack of information from road construction constitutes one of the largest challenges when evaluating the results from the EmSite model, as the magnitude of CO_2 emissions from road construction is unclear and varies across types of road projects. For instance, CO_2 emissions have been reported to vary between 159 t CO_2 km^{-1} and 7020 t CO_2 km^{-1} across different examples of road construction projects, and the differences depend on the type of project and the terrain (NTP, 2021). For one of the detailed projects in the aforementioned report, information on the split of emissions indicates that 60% of the CO_2 is emitted from the transport of material to and from the construction sites. EmSite only considers direct emissions from NRMM in the construction sites, and emissions from the transport of material or personnel from/to the construction site are considered as part of on-road transport.

6 Future needs

As it has been emphasised in this report, the availability of information regarding activity or factors that affect emissions is essential for the development of bottom-up emission inventories. Over time, new data sources are made available, and this will support the improvement of high-resolution emission models such as EmSite.

The **annual updates** of emissions from NRMM in building and construction requires establishing contact and collaboration with the Norwegian Mapping Authorities in order to get updated datasets of *matrikkelen*. This will also allow us to evaluate possible uncertainties for the year 2020, as the current dataset was delivered in November 2020, and it may miss a few construction projects.

The **construction of infrastructures other than buildings** constituted one of the biggest challenges during this project due to the lack of data with sufficient coverage, along with information that can support accurate estimates of the energy demand. The data sources investigated during the project, and potential data holders, did not provide the needed information. For the future, we see the need to investigate alternative data sources that can provide the missing information concerning historical location and duration of construction projects other than building, along with the energy demand associated with. For instance, we foresee the need of a tighter collaboration with the Norwegian Public Road Administration (SVV).

One of the aspects that needs to be considered in the near future is the use of **biofuels** such as biodiesel and bioethanol, which is highly relevant for the GHGs emission estimates. Some municipalities in Norway such as Oslo have strong incentives to reduce emissions from the building and construction sector. In this case, a procurement strategy is in place that requires that construction machinery used in municipal construction projects have zero-emission technology, and when the technology is not available, biofuels should be used. At national level, the use of biofuels may become more relevant in the coming years, as by 2021 there is no requirement on fuel supplier to ensure that an amount of tax-free auto-diesel is biodiesel (omsetningskrav), but this requirement is suggested from July 1st 2022[10]. The use of **electric machinery** has moreover increased in the last few years, as more electric NRMM are available in the market. However, no information was found about the activity associated with these machines, nor the location where electric machinery has been used, especially in the most recent years.

Within current practices, the **heating** within the construction work is provided by the use of LPG heaters, diesel generators or fossil fuels (*mineralolje*) generators. The latter one is not included in EmSite due to lacking detailed data. This fossil fuel (*mineralolje*) will be forbidden in Norway for its use in heating construction sites from 2022 (NEA, 2021). Alternative energy sources for the heating phase are district heating, electricity, pellets and biodiesel (DNV, 2017). EmSite provides emissions from the heating in construction sites based on the use of LPG and diesel. Therefore, it is important to consider alternative energy sources, such as district heating and electricity, in future updates. In addition, a more detailed assessment on the use of electricity in building and construction needs to be carried out to evaluate EmSite results. Diesel and electricity are the most used energy sources in building and construction, reaching values up to 55 and 25%, respectively, followed by petrol, LPG and other fuels (20%; Bøeng et al., 2011). A better understanding on the use of electricity in building and construction is needed, specifically in relation to the building construction phases that results in emissions.

Building and construction activity may represent an important source of **non-exhaust PM** that can contribute to pollution levels during dry periods. The modelling of non-exhaust PM emissions presents

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[10] https://www.miljodirektoratet.no/hoeringer/2022/januar-2022/forslag-til-omsetningskrav-for-avansert-biodrivstoff-til-ikke-veigaende-maskiner-og-okt-omsetningskrav-til-veitrafikk/

important challenges as different processes influence emissions (Wind, Mechanical upheaval, Traffic and Tyre, Freight). A detailed case-study based assessment, at for instance a specific location, by means of observation data (PM monitoring, meteorology) in combination with inverse modelling and site-specific activity data, will provide additional insights on the processes behind non-exhaust emissions, in addition to validation of exhaust EmSite emissions.

7 Concluding Remarks

Building and construction activities largely vary in space and time and cover a wide range of project types. To our knowledge, no method exists to estimate and spatially distribute emissions based on the exact location on where the construction activity takes place or the characteristics of the construction project. The bottom-up EmSite model is, therefore, “one of its kind” to calculate emission from NRMM in building and construction at national scale.

The EmSite model calculates emissions of air pollutants and GHGs emissions, including PM non-exhaust emissions, at high spatio-temporal resolution. EmSite is based on a complete national database that defines the exact location of building and construction activity from 2010 to 2020. Moreover, it takes into account variables that influence emissions, such as ground conditions to define the energy demand for large NRMM, and meteorology to constrain the heating phase of unfinished buildings. These factors are also used as key parameters to determine the non-exhaust emissions.

The EmSite model is based on the combination of different datasets that allows to determine:

I. the location, area and duration of construction projects at point resolution with an additional radius of influence based on the dimension of the construction site;
II. energy demand for NRMM at different phases of the construction project; ground work, heating and building/finalisation, where the activity is mainly associated with large NRMM, heaters/generators and small NRMM, respectively;
III. dynamic emission factors for large NRMM, small NRMM and heaters/generators running on diesel, and to a lesser extent on gasoline and LPG, estimated based on machine park and the introduction of new technologies over time.

The final outcome from the EmSite model is gridded emissions of air pollutants and GHGs at 250 metre resolution, that by aggregating at different administrative divisions levels are also available at municipality, county and national level.

Emissions from NRMM in building and construction decline overtime in the case of air pollutants driven by the introduction of new technologies and European emissions standards for engines used in NRMM. CO_2 emissions, however, seem to show a less remarkable decline.

Emissions in EmSite have been compared with official emissions submitted to the CLRTAP and UNFCCC in the case of air pollutants and GHGs emissions, respectively. The activity behind EmSite emissions represents lower levels than construction occurs in Norway as activities other than building construction are lacking. Based on the comparison with official reported figures, air pollutant emissions in EmSite are higher than officially reported due to higher emission factors in EmSite than those used in official reporting. CO_2 emissions in EmSite are, however, lower than official figures and consistent with the lower activity levels in EmSite. EmSite CO_2 emissions at municipality level seems to capture high level of construction activity in Norwegian municipalities (e.g., Lørenskog), which is not captured in the available GHG accounting at municipality level. This opens important questions, such as the current over-allocation and under-allocation of emissions in the GHG accounting at municipality.

A preliminary key finding of the study is that the heating phase is the most energy intensive activity within building and construction, representing up to 66% of the total energy demand, which stands for 77% and 67% of total NO_x and CO_2 emissions from NRMM in building and construction activity. However, this needs to be further evaluated as electricity constitutes an important energy source in building and construction activity, and additional information is needed on the use of electricity in the different phases of the construction process.

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Appendix A

EmSite Emission Factors for NRMM

Table A 1: EmSite emission factors ($g \cdot kWh^{-1}$) for large diesel NRMM since 2005 to 2020. FC: fuel consumption.

	NOx	VOC	CH_4	CO	N_2O	PM	PM_{10}	$PM_{2.5}$	BC	FC
2005	10.00	0.63	0.02	2.29	0.04	0.30	0.30	0.30	0.18	252.95
2006	8.91	0.53	0.01	2.01	0.04	0.26	0.26	0.26	0.17	252.95
2007	7.87	0.43	0.01	1.76	0.04	0.22	0.22	0.22	0.15	252.92
2008	7.64	0.42	0.01	1.74	0.04	0.22	0.22	0.22	0.15	252.92
2009	6.95	0.39	0.01	1.68	0.04	0.20	0.20	0.20	0.14	252.92
2010	6.04	0.35	0.01	1.60	0.04	0.18	0.18	0.18	0.14	252.92
2011	5.12	0.31	0.01	1.51	0.04	0.17	0.17	0.17	0.13	252.92
2012	4.97	0.31	0.01	1.51	0.04	0.17	0.17	0.17	0.13	252.92
2013	4.53	0.31	0.01	1.50	0.04	0.16	0.16	0.16	0.13	252.92
2014	4.02	0.30	0.01	1.50	0.04	0.15	0.15	0.15	0.12	252.92
2015	3.46	0.27	0.01	1.50	0.04	0.14	0.14	0.14	0.11	252.92
2016	3.24	0.25	0.01	1.50	0.04	0.12	0.12	0.12	0.09	252.92
2017	2.88	0.24	0.01	1.50	0.04	0.11	0.11	0.11	0.09	252.92
2018	2.41	0.21	0.00	1.50	0.04	0.09	0.09	0.09	0.07	252.92
2019	2.02	0.18	0.00	1.50	0.04	0.07	0.07	0.07	0.05	252.92
2020	1.57	0.16	0.00	1.50	0.04	0.05	0.05	0.05	0.04	252.92

Table A 2: EmSite emission factors ($g \cdot kWh^{-1}$) for small NRMM since 2005 to 2020. FC: fuel consumption

	NO_x	VOC	CH_4	CO	N_2O	PM	PM_{10}	$PM_{2.5}$	BC	FC
2005	8.61	1.09	0.03	3.16	0.04	0.68	0.68	0.68	0.43	261.81
2006	7.76	0.79	0.02	2.63	0.04	0.50	0.50	0.50	0.35	260.90
2007	7.40	0.65	0.02	2.37	0.04	0.41	0.41	0.41	0.31	260.43
2008	7.12	0.61	0.01	2.33	0.04	0.39	0.39	0.39	0.29	260.43
2009	6.69	0.57	0.01	2.27	0.04	0.36	0.36	0.36	0.28	260.33
2010	6.21	0.54	0.01	2.27	0.04	0.33	0.33	0.33	0.26	260.43
2011	5.78	0.50	0.01	2.25	0.04	0.29	0.29	0.29	0.23	260.50
2012	5.41	0.49	0.01	2.25	0.04	0.28	0.28	0.28	0.21	260.56
2013	5.04	0.42	0.01	2.20	0.04	0.21	0.21	0.21	0.17	260.37

2014	4.64	0.41	0.01	2.20	0.04	0.19	0.19	0.19	0.15	260.35
2015	3.78	0.41	0.01	2.20	0.04	0.19	0.19	0.19	0.15	260.35
2016	3.30	0.39	0.01	2.20	0.04	0.17	0.17	0.17	0.13	260.30
2017	3.24	0.38	0.01	2.20	0.04	0.16	0.16	0.16	0.13	260.28
2018	2.60	0.34	0.01	2.20	0.04	0.11	0.11	0.11	0.09	260.19
2019	2.26	0.31	0.01	2.20	0.04	0.06	0.06	0.06	0.05	260.09
2020	2.25	0.32	0.01	2.39	0.04	0.07	0.07	0.07	0.06	260.95

Table A 3: EmSite emission factors (g·kWh^{-1}) for heaters/generators (2005 to 2020). FC: fuel consumption.

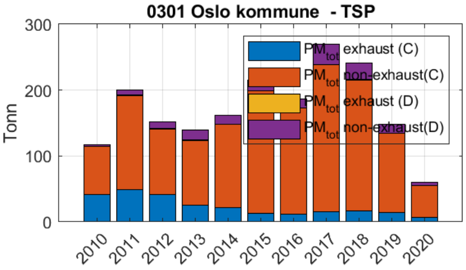
	NO_x	VOC	CH_4	CO	N_2O	PM	PM_{10}	$PM_{2.5}$	BC	FC
2005	9.88	1.49	0.04	3.83	0.04	0.91	0.91	0.91	0.52	262.97
2006	9.88	1.49	0.04	3.83	0.04	0.91	0.91	0.91	0.52	262.97
2007	9.19	1.23	0.03	3.39	0.04	0.75	0.75	0.75	0.45	261.41
2008	8.94	1.15	0.03	3.27	0.04	0.71	0.71	0.71	0.43	261.04
2009	8.60	1.08	0.03	3.14	0.04	0.67	0.67	0.67	0.41	260.81
2010	8.08	0.91	0.02	2.81	0.04	0.56	0.56	0.56	0.36	260.18
2011	7.70	0.85	0.02	2.71	0.04	0.52	0.52	0.52	0.34	260.04
2012	7.17	0.77	0.02	2.61	0.04	0.47	0.47	0.47	0.31	259.94
2013	6.62	0.63	0.02	2.37	0.04	0.37	0.37	0.37	0.26	259.46
2014	6.24	0.54	0.01	2.23	0.03	0.31	0.31	0.31	0.23	258.27
2015	5.36	0.44	0.01	2.05	0.03	0.24	0.24	0.24	0.19	253.13
2016	4.89	0.41	0.01	2.01	0.03	0.22	0.22	0.22	0.17	251.03
2017	4.52	0.40	0.01	1.97	0.03	0.21	0.21	0.21	0.17	246.77
2018	4.16	0.38	0.01	1.96	0.03	0.20	0.20	0.20	0.16	245.10
2019	3.79	0.37	0.01	1.97	0.03	0.18	0.18	0.18	0.14	245.16
2020	3.68	0.35	0.01	2.08	0.03	0.15	0.15	0.15	0.12	250.22

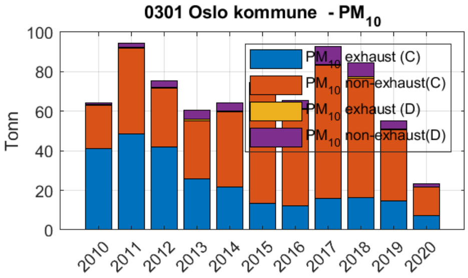
Table A 4: EmSite emission factors (g·kWh^{-1}) for gasoline NRMM (2005 to 2020). FC: fuel consumption.

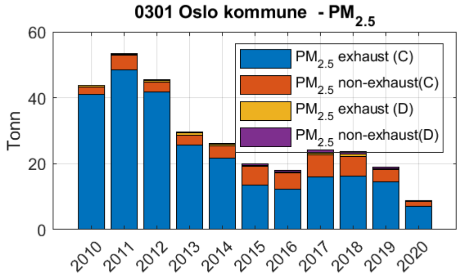
	NOx	VOC	CH4	CO	N2O	PM10	PM2.5	BC	FC
2005	3.99	10.70	0.36	437.30	0.03	0.08	0.08	0.004	513.91
2006	4.09	10.50	0.36	425.82	0.03	0.08	0.08	0.004	500.86
2007	4.14	10.43	0.35	420.09	0.03	0.08	0.08	0.004	494.33
2008	4.15	10.35	0.35	419.37	0.03	0.08	0.08	0.004	493.51
2009	4.16	10.31	0.35	417.93	0.03	0.08	0.08	0.004	491.88
2010	4.16	10.20	0.35	417.93	0.03	0.08	0.08	0.004	491.88
2011	4.17	10.08	0.34	417.58	0.03	0.08	0.08	0.004	491.47
2012	4.17	10.03	0.34	417.58	0.03	0.08	0.08	0.004	491.47
2013	4.18	10.00	0.34	416.50	0.03	0.08	0.08	0.004	490.25
2014	4.18	9.99	0.34	416.50	0.03	0.08	0.08	0.004	490.25
2015	4.18	9.99	0.34	416.50	0.03	0.08	0.08	0.004	490.25
2016	4.18	9.99	0.34	416.50	0.03	0.08	0.08	0.004	490.25
2017	4.18	9.99	0.34	416.50	0.03	0.08	0.08	0.004	490.25
2018	4.18	9.98	0.34	416.50	0.03	0.08	0.08	0.004	490.25
2019	4.18	9.98	0.34	416.50	0.03	0.08	0.08	0.004	490.25
2020	4.03	9.70	0.33	416.50	0.03	0.08	0.08	0.004	490.25

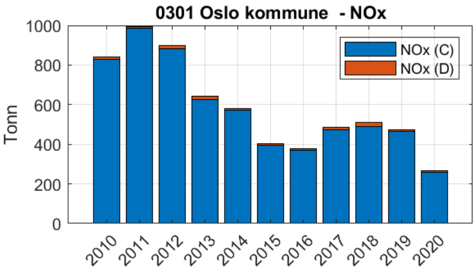
Appendix B

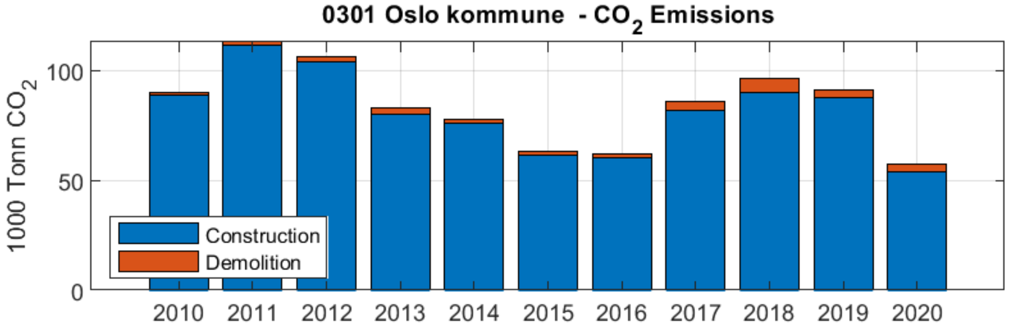
EmSite Emissions for Norwegian Municipalities (selection)

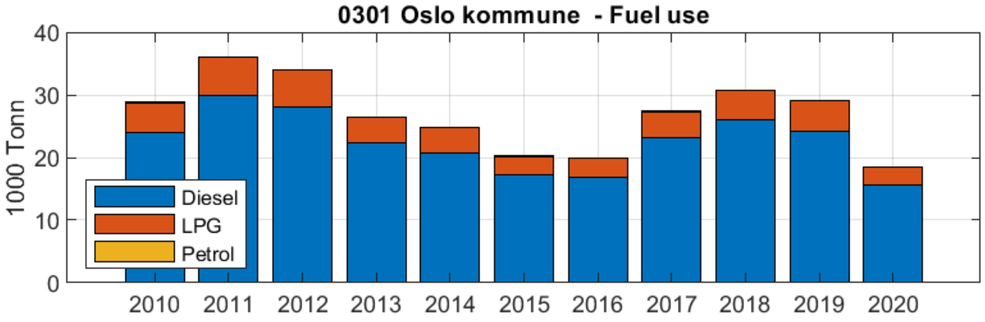

0301 Oslo kommune - TSP
Tonn
0
100
200
300
PM_{tot} exhaust (C)
PM_{tot} non-exhaust(C)
PM_{tot} exhaust (D)
PM_{tot} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

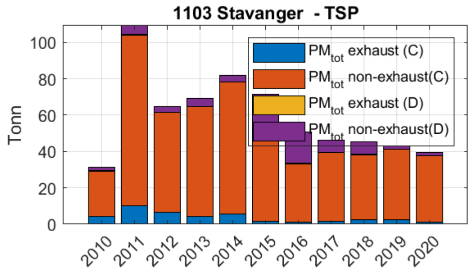

0301 Oslo kommune - PM_{10}
Tonn
0
20
40
60
80
100
PM_{10} exhaust (C)
PM_{10} non-exhaust(C)
PM_{10} exhaust (D)
PM_{10} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

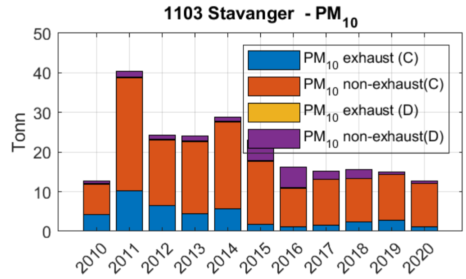

0301 Oslo kommune - $PM_{2.5}$
Tonn
0
20
40
60
$PM_{2.5}$ exhaust (C)
$PM_{2.5}$ non-exhaust(C)
$PM_{2.5}$ exhaust (D)
$PM_{2.5}$ non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

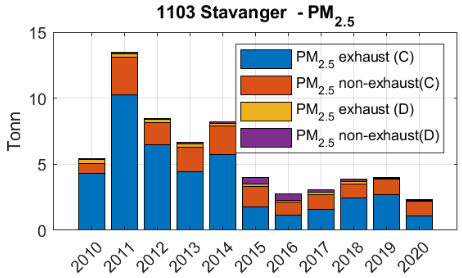

0301 Oslo kommune - NOx
Tonn
0
200
400
600
800
1000
NOx (C)
NOx (D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

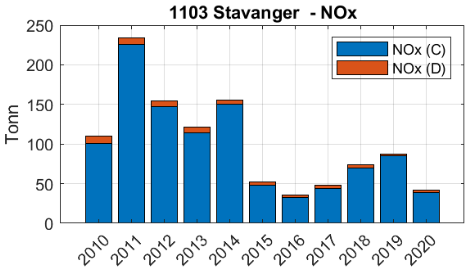

0301 Oslo kommune - CO_2 Emissions
1000 Tonn CO_2
0
50
100
Construction
Demolition
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

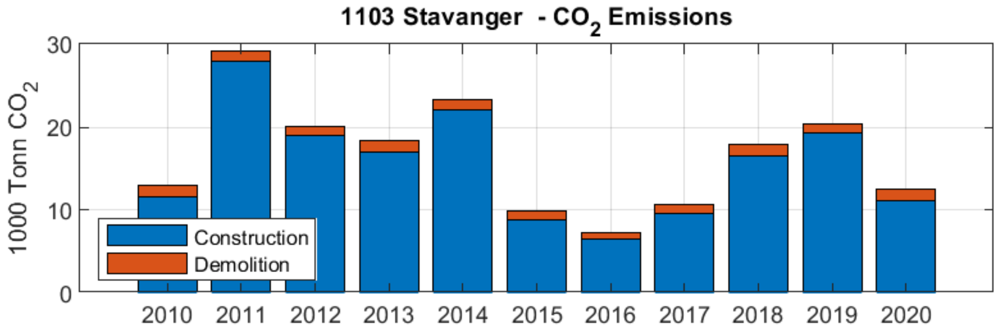

0301 Oslo kommune - Fuel use
1000 Tonn
0
10
20
30
40
Diesel
LPG
Petrol
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

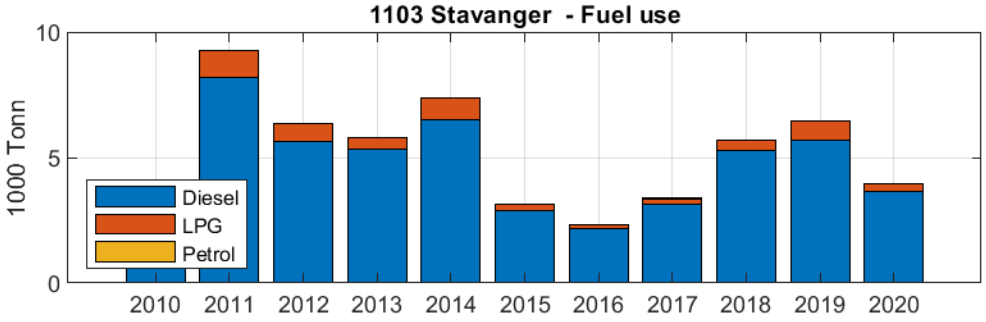

1103 Stavanger - TSP
Tonn
0
20
40
60
80
100
PM_{tot} exhaust (C)
PM_{tot} non-exhaust(C)
PM_{tot} exhaust (D)
PM_{tot} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

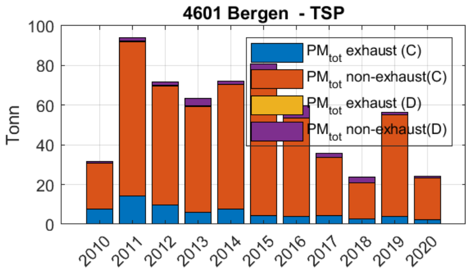

1103 Stavanger - PM_{10}
Tonn
0
10
20
30
40
50
PM_{10} exhaust (C)
PM_{10} non-exhaust(C)
PM_{10} exhaust (D)
PM_{10} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

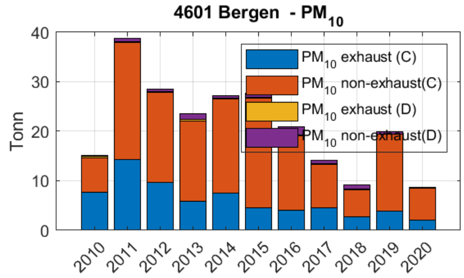

1103 Stavanger - $PM_{2.5}$
Tonn
0
5
10
15
$PM_{2.5}$ exhaust (C)
$PM_{2.5}$ non-exhaust(C)
$PM_{2.5}$ exhaust (D)
$PM_{2.5}$ non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

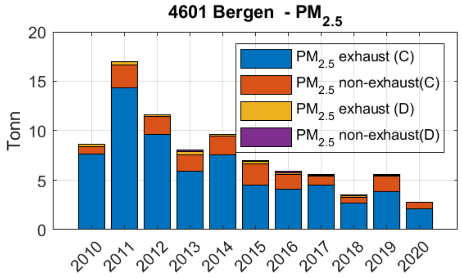

1103 Stavanger - NOx
Tonn
0
50
100
150
200
250
NOx (C)
NOx (D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

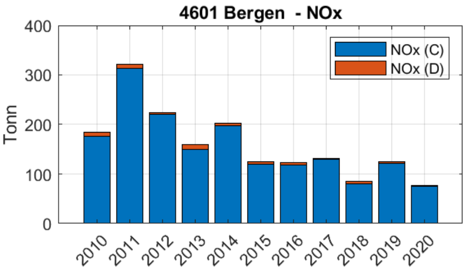

1103 Stavanger - CO_2 Emissions
1000 Tonn CO_2
0
10
20
30
Construction
Demolition
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

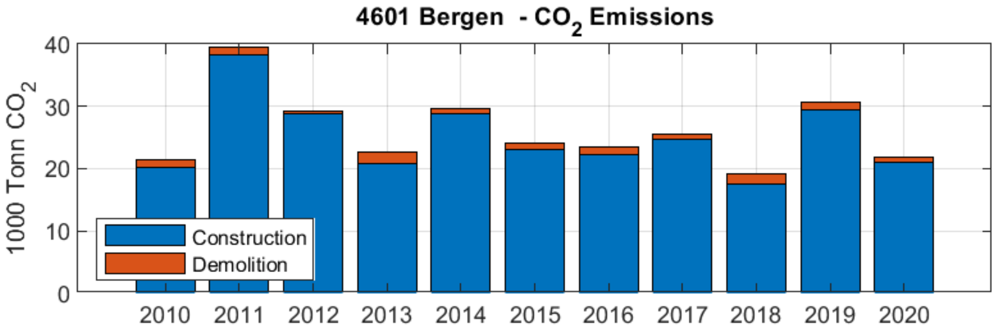

1103 Stavanger - Fuel use
1000 Tonn
0
5
10
Diesel
LPG
Petrol
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

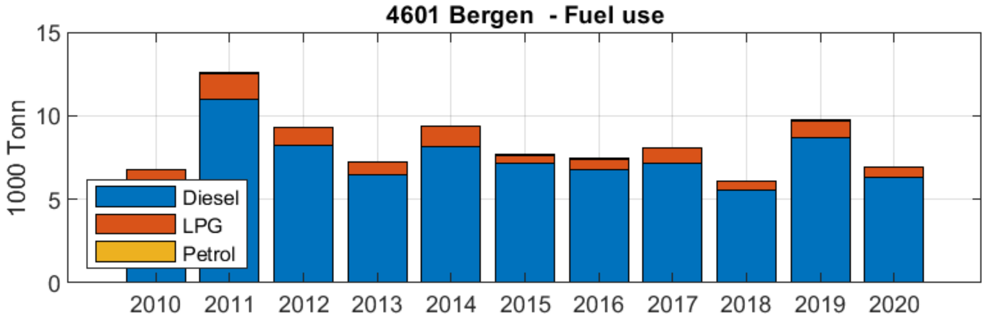

4601 Bergen - TSP
Tonn
0
20
40
60
80
100
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
PM_{tot} exhaust (C)
PM_{tot} non-exhaust(C)
PM_{tot} exhaust (D)
PM_{tot} non-exhaust(D)

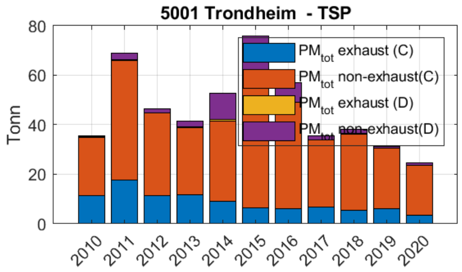

4601 Bergen - PM_{10}
Tonn
0
10
20
30
40
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
PM_{10} exhaust (C)
PM_{10} non-exhaust(C)
PM_{10} exhaust (D)
PM_{10} non-exhaust(D)

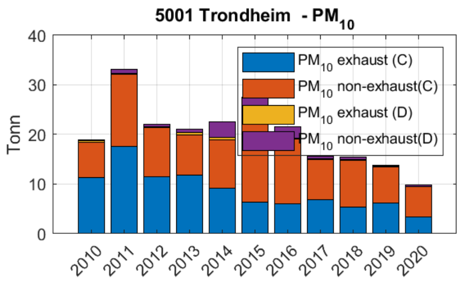

4601 Bergen - $PM_{2.5}$
Tonn
0
5
10
15
20
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
$PM_{2.5}$ exhaust (C)
$PM_{2.5}$ non-exhaust(C)
$PM_{2.5}$ exhaust (D)
$PM_{2.5}$ non-exhaust(D)

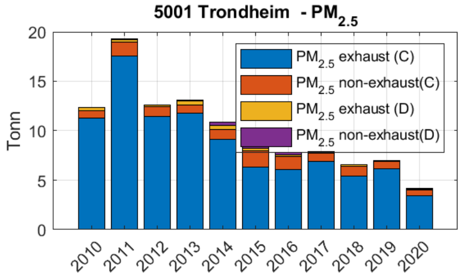

4601 Bergen - NOx
Tonn
0
100
200
300
400
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
NOx (C)
NOx (D)

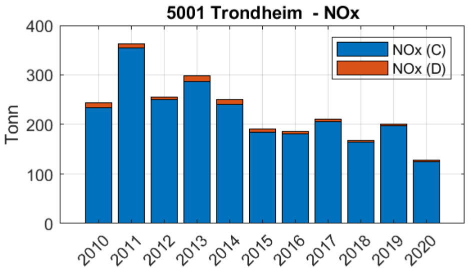

4601 Bergen - CO_2 Emissions
1000 Tonn CO_2
0
10
20
30
40
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Construction
Demolition

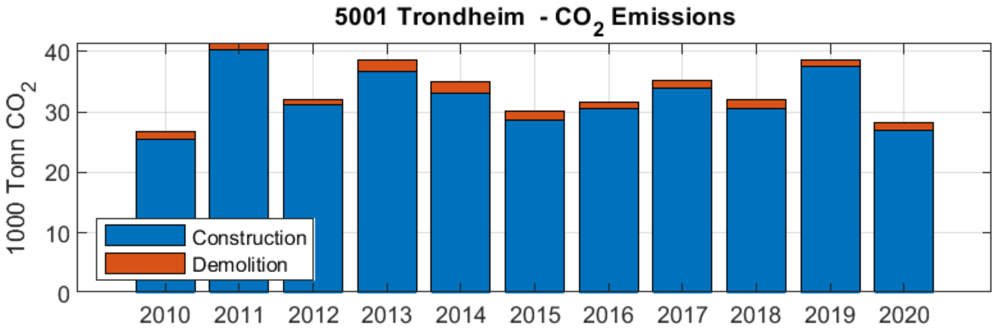

4601 Bergen - Fuel use
1000 Tonn
0
5
10
15
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Diesel
LPG
Petrol

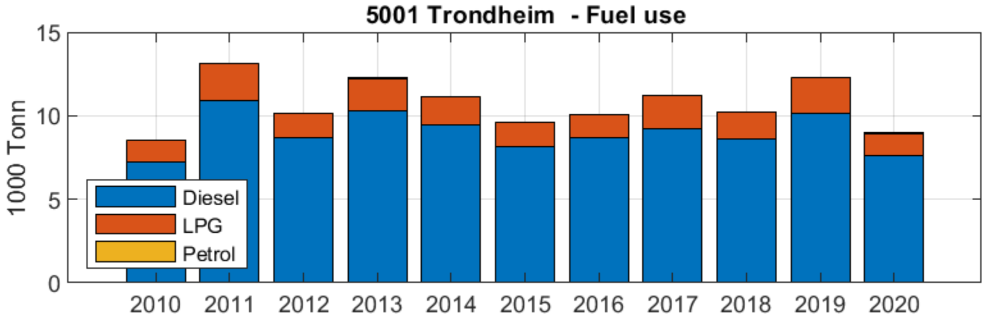

5001 Trondheim - TSP
Tonn
0
20
40
60
80
PM_{tot} exhaust (C)
PM_{tot} non-exhaust(C)
PM_{tot} exhaust (D)
PM_{tot} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

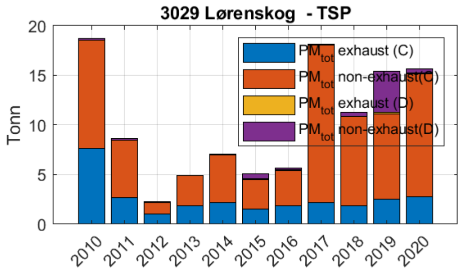

5001 Trondheim - PM_{10}
Tonn
0
10
20
30
40
PM_{10} exhaust (C)
PM_{10} non-exhaust(C)
PM_{10} exhaust (D)
PM_{10} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

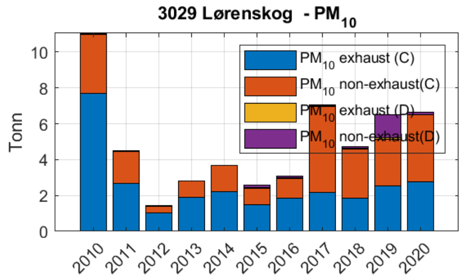

5001 Trondheim - $PM_{2.5}$
Tonn
0
5
10
15
20
$PM_{2.5}$ exhaust (C)
$PM_{2.5}$ non-exhaust(C)
$PM_{2.5}$ exhaust (D)
$PM_{2.5}$ non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

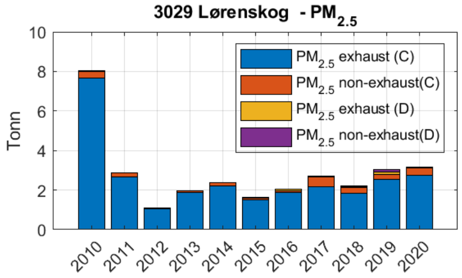

5001 Trondheim - NOx
Tonn
0
100
200
300
400
NOx (C)
NOx (D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

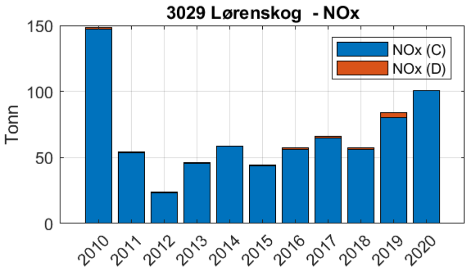

5001 Trondheim - CO_2 Emissions
1000 Tonn CO_2
0
10
20
30
40
Construction
Demolition
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

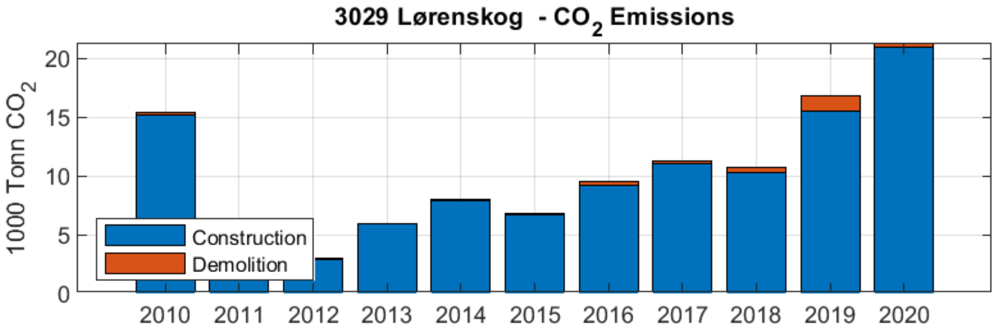

5001 Trondheim - Fuel use
1000 Tonn
0
5
10
15
Diesel
LPG
Petrol
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

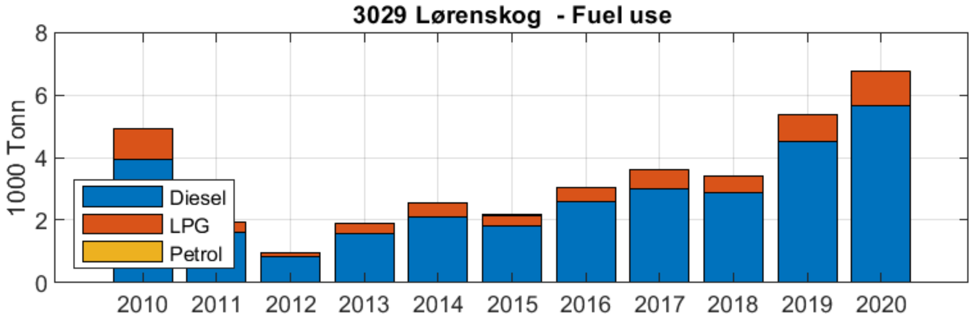

3029 Lørenskog - TSP
Tonn
0
5
10
15
20
PM_{tot} exhaust (C)
PM_{tot} non-exhaust(C)
PM_{tot} exhaust (D)
PM_{tot} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020


3029 Lørenskog - PM_{10}
Tonn
0
2
4
6
8
10
PM_{10} exhaust (C)
PM_{10} non-exhaust(C)
PM_{10} exhaust (D)
PM_{10} non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020


3029 Lørenskog - $PM_{2.5}$
Tonn
0
2
4
6
8
10
$PM_{2.5}$ exhaust (C)
$PM_{2.5}$ non-exhaust(C)
$PM_{2.5}$ exhaust (D)
$PM_{2.5}$ non-exhaust(D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020


3029 Lørenskog - NOx
Tonn
0
50
100
150
NOx (C)
NOx (D)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020


3029 Lørenskog - CO_2 Emissions
1000 Tonn CO_2
0
5
10
15
20
Construction
Demolition
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020


3029 Lørenskog - Fuel use
1000 Tonn
0
2
4
6
8
Diesel
LPG
Petrol
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

Appendix C

EmSite National Emissions

Table A 5: EmSite air pollutant emissions at national level. CONST: construction. DEMO: demolition. ne: non-exhaust emissions. Units: ton

Type	Y	PM25ne	PM10ne	TSPne	NOx	VOC	CO	NH3	PM	PM10	PM25	BC
CONST	2010	24	240	793	7259	838	2116	2	348	348	348	227
CONST	2011	49	492	1627	9893	1198	2985	3	481	481	481	317
CONST	2012	40	401	1327	7820	929	2415	2	360	360	360	241
CONST	2013	47	467	1543	6845	773	2125	2	278	278	278	195
CONST	2014	47	470	1556	7231	830	2280	3	275	275	275	198
CONST	2015	45	450	1488	4751	539	1635	2	164	164	164	123
CONST	2016	42	420	1390	4712	550	1704	2	158	158	158	119
CONST	2017	41	409	1354	5453	678	2049	2	184	184	184	139
CONST	2018	35	345	1143	4890	639	1985	2	163	163	163	122
CONST	2019	26	256	846	4842	666	2098	2	152	152	152	113
CONST	2020	20	204	674	3134	435	1532	2	86	86	86	63
DEMO	2010	1	5	17	160	9	42	0	5	5	5	4
DEMO	2011	1	14	46	137	8	40	0	4	4	4	3
DEMO	2012	2	19	64	132	8	40	0	4	4	4	3
DEMO	2013	2	23	76	136	9	45	0	5	5	5	4
DEMO	2014	3	26	85	110	8	41	0	4	4	4	3
DEMO	2015	3	35	114	104	8	45	0	4	4	4	3
DEMO	2016	3	29	96	105	8	49	0	4	4	4	3
DEMO	2017	3	26	85	98	8	51	0	4	4	4	3
DEMO	2018	2	21	70	102	9	64	0	4	4	4	3
DEMO	2019	2	17	55	78	7	58	0	3	3	3	2
DEMO	2020	1	7	22	49	5	47	0	1	1	1	1

Table A 6: EmSite GHGs emissions at national level. CONST: construction. DEMO: demolition. Units: ton

Type	Year	CO2	CH4	N2O
CONST	2010	794785.46	27.06	35.33
CONST	2011	1138221.77	39.54	50.70
CONST	2012	956099.39	30.96	42.55
CONST	2013	904150.49	26.39	40.24
CONST	2014	989929.81	29.23	44.16
CONST	2015	754506.70	19.22	33.59
CONST	2016	791835.84	19.90	35.27
CONST	2017	944853.97	25.01	42.17
CONST	2018	915690.03	23.80	40.87
CONST	2019	957883.66	25.33	42.79
CONST	2020	691070.31	16.57	30.78
DEMO	2010	21187.16	0.22	0.92
DEMO	2011	21430.18	0.20	0.94
DEMO	2012	21258.84	0.20	0.93
DEMO	2013	24132.10	0.22	1.05
DEMO	2014	21897.03	0.19	0.96
DEMO	2015	24180.60	0.19	1.06
DEMO	2016	26046.31	0.19	1.14
DEMO	2017	27185.51	0.19	1.19
DEMO	2018	34015.44	0.21	1.48
DEMO	2019	31085.98	0.17	1.36
DEMO	2020	25017.60	0.11	1.09

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