Shipping emissions in a Nordic port: assessment of mitigation strategies

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Abstract

We use a bottom-up approach to develop a comprehensive emissions inventory for the Port of Oslo for current and future scenarios, including compliance with environmental legislation. We estimate the emission of air pollutants (NO_x, PM_{10}, SO_2) and greenhouse gases (GHGs; CO_2, CH_4, N_2O) from shipping and land activities in the port. The inventory shows that oceangoing vessels are the main contributor, providing 63-78% of the total NO_x, PM_{10}, SO_2 and CO_{2e} emissions. The main contributors among oceangoing vessels are international ferries, cruises and container vessels, and the main contributors to emissions among harbour vessels are domestic ferries. We estimate the emissions from oceangoing vessels for different operational modes, obtaining the highest values at berth followed by emissions during vessel manoeuvres. We evaluate a 2020 scenario that takes account of (i) the expected increase in maritime traffic; (ii) compliance with a new regulation regarding sulphur content in ship fuel (<0.1%); and (iii) implementation of various mitigation measures. These measures include implementation of onshore power, and its combination with a speed reduction zone in the port, and the increase use of liquid natural gas (LNG). The results show that compliance with regulation provides a reduction of 90% and 10% in SO_2 and PM_{10} emissions, respectively. Onshore power in combination with a speed reduction zone provides reductions of up to 15% in NO_x and CO_2 emissions by 2020 compared with 2013, and further reductions of up to 23% (NO_x) and 17% (CO_{2e}) if we extend the use of LNG among domestic ferries.

Keywords: shipping emissions; oceangoing vessels; onshore power; mitigation

1. Introduction

Throughout the European Economic Area, monitoring of air pollution is a key societal concern owing to persistent exceedance of pollution levels established by European Commission air quality directives. The main sources of air pollution in the urban environment are industry, agriculture, on-road traffic and heating. On-road traffic is one of the main contributors to urban air pollution, emitting compounds (e.g. NOx, particulate matter, Volatile Organic Compounds) that have negative effects on human health, causing incidences of cancer and respiratory ailments (Raaschou et al., 2010). Over the last few decades, policy makers have made large efforts to reduce emissions from industrial sources; nowadays, these efforts concern reduction of emissions from on-road traffic. These emission reductions may involve an increase in the relative contribution of other pollution sources such as shipping, exacerbated by the expected increase in maritime traffic (e.g, Dalsøren et al., 2010). Dybedal et al. (2015) established that the number of cruise visitors to Norway has increased from about 200 000 to almost 700 000 over the last 15 years, and further increases are expected. Consequently, there is a need for the design of feasible mitigation measures to reduce emissions from the shipping sector. Such a reduction of emissions will help protect the quality of the urban environment, as well as help mitigate climate change.

Owing to the geographical and meteorological characteristics of Norway, its population, including urban areas, mainly resides along the coast. This geographical distribution, together with a long maritime tradition, makes harbour activities significant areas of economic growth in Norway, as well as sources of development and innovation in urban areas. However, emissions from shipping and its associated activities, contribute to air pollution and climate change. We understand relatively well the global contribution to emissions from shipping, as several studies address their emissions and potential impact at global and regional scales (De Meyer, et al., 2008; Volker et al., 2010; Corbett et al., 2010). However, the impact of shipping emissions in the urban environment has received less attention, even though 70% of shipping emissions occur within 400 km of land and, especially, at berth. Viana et al., (2014) reviewed the impact of shipping emissions on urban air quality in coastal areas in Europe, and concluded that the largest impact came from shipping in the Mediterranean basin and the North Sea.

Currently there are strict regulations on sulphur and nitrogen dioxide emissions by the maritime sector (IMO 2013) and, in particular, in the emission control areas (ECA). Annex VI "Regulations for the prevention of Air Pollution from ships" of the International Maritime Organization (IMO, 2013) came into force in May 2005. This limits the sulphur content of marine fuels on a global basis to i) 4.5% m/m prior to 1st January 2012; ii) 3.5% m/m on and after 1st January 2012; and iii) 0.50% m/m on and after 1st January 2020. The Annex VI imposes stricter regulations in the ECA, where the sulphur content of maritime fuel oil is not to exceed: i) 1.5% m/m prior to 1st July 2010; ii) 1.0% m/m on and after 1st July 2010; and iii) 0.1% m/m on and after 1st January 2015. Regarding NOx emissions, Annex VI contains a 3-tier approach that identifies the allowable emissions of total NOx depending on the engine speed. These regulations are a significant step forward; however, there remains a need for further measures targeting specific subsectors (e.g., type of vessels), climate change drivers (e.g., CO_2, black carbon) and the impact from harbour activities near urban centres (Viana et al., 2014).

Development of detailed emission inventories is essential for the design of effective measures to reduce emissions, and for providing boundary conditions for air dispersion models. Several methods exist for developing shipping emission inventories, e.g., methods based on reported fuel consumption, fuel sales, flag of the vessels, automatic identification system (AIS), and ship call activity data, which is based on the registration of vessels when they visit ports. In this study, we use ship call activity data to develop a comprehensive emission inventory that aims to identify the main contributing subsectors from harbour activities. These activities include shipping at different operational modes, land traffic and cargo handling equipment (CHE). One of the novelties of our study is that it takes into account emissions from harbour vessels (e.g., domestic ferries, tugboats); hitherto, most studies only consider emissions from oceangoing vessels (OGV). Our study evaluates the implementation of onshore power, its combination with speed reduction zone (SRZ) and the increased use of liquefied natural gas (LNG) as measures to reduce emissions. To our knowledge, this study is one of the few that considers emissions of air pollutant and greenhouse gases (GHGs) at the scale of the harbour area, includes harbour activities and accounts for different mitigation measures. Our study is complemented with the analysis of SO_2 measurement data from Oslo city in combination with meteorological conditions to assess the current potential impact of shipping emissions on urban air quality.

2. Methodology

In this section, we will describe the area of interest, methods to estimate emissions, the collection of input data and the selection of scenarios.

2.1. The Port of Oslo

The Port of Oslo is the biggest and busiest in Norway. It is located in the North Sea, at the north end of Oslo Fjord, at about 96 km from the Gulf of Skagerrak and 270 km north-northwest of the coast of Denmark. The shipping activities are mainly associated with the transport of goods, bulk cargo (e.g., chemicals, oil, salt, cement), and the transport of passengers (e.g., international and domestic ferries, cruise vessels). We estimate emissions following a bottom-up approach for the domain showed in Fig. 1, which corresponds to the area inside the calling identification line, which is the reference line from where vessels report arrival to the port.

We divide the vessels into two groups, oceangoing vessels (OGV) and harbour vessels (HV). The OGV consist of bulk carriers, ro-ro vessels (including car carriers), container vessels, cruises, international ferries, general cargo and oil/chemical tankers (Table 1). Among the oceangoing passenger vessels, the international ferries operate the whole year around whereas the cruise vessels mainly operate in the spring and summer seasons. In 2013, the Port of Oslo had around 3000 calls or registers of arrivals (Table 1), with the international ferries (34.25%) the most frequent, followed by general cargo (22.20%) and container vessels (14.95%). We split emissions from OGV in the operational mode as emissions during cruising, emissions during manoeuvring, and emissions at berth. The emissions considered in this paper occur over the geographical domains shown in Fig. 1.

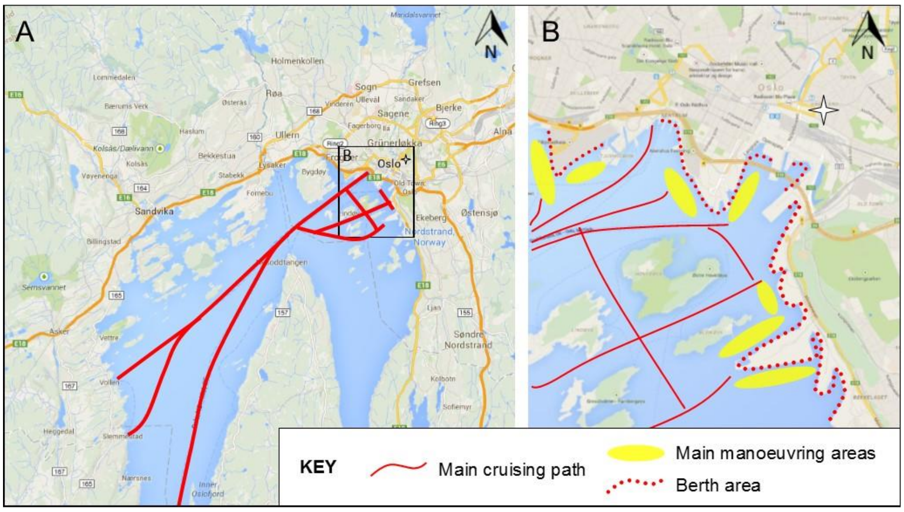

Fig. 1: Emission model domain (A) and detailed close-up (B) indicating the main cruising paths (solid red lines), the main manoeuvring areas (yellow colours), and the berth areas belonging to the Port of Oslo (dotted red lines). The star on panel B represents the position of the SO_2 monitoring station.

Table 1: Number of calls of oceangoing vessels registered in the Port of Oslo and average annual operating time (AAOT), in hours (h), of the harbour vessels for 2013.

Vessels	
Oceangoing vessels	**Calls**
Bulk Carrier	251
RO-RO	153
Container	449
Cruise	158
International Ferry	1029
General Cargo	667
Oil / Chemical Tankers	297
TOTAL	3004
Harbour vessels	***AAOT (h)***
Commercial Fishing	7
Domestic Ferry	545
Recreational	140
Supply Vessels	60
Tug - Push boat	120
Work boats	30
Other vessels	140

The HVs mainly operate within the port area and consist of commercial fishing boats, domestic ferries, supply vessels, tugboats, and workboats, among others (Table 1). The domestic ferries operate the whole year around, with higher activity in spring and summer, while other HVs mainly operate in summer. The HVs that mostly operate in the Port of Oslo are the domestic ferries with an annual average operating time of about 545 hours (Table 1). The land activities considered in our study are vehicle traffic, including the contribution from light, medium and heavy-duty vehicles, and the cargo handling equipment (CHE), which consists of forklifts, cranes, reach stackers, and terminal tractors.

2.2. Emission estimates

We estimate emissions based on the methodology published by US EPA (2009) and on the activity log of the Port of Oslo for 2013, which provides detailed information on arrivals, departures and operating time for individual vessels. Emissions from OGV are additionally evaluated according to the operational mode when cruising (“at sea”; Equation 1), when manoeuvring (Equation 2) and at berth (Equation 3). Emissions factors for each pollutant (*i;* g/kWh), type of vessels (*j*) and under different operational mode (Equation 1 to 3) are taken from the European Commission and ENTEC UK Limited (2005), Cooper and Gustafsson (2004) and the US EPA (2009). For the 2020 scenario, we modify the emission factors for SO_2 and PM_{10} according to the sulphur content below 0.1% in the marine fuel and assuming that vessels comply with new regulation imposed by the Annex VI (IMO, 2013) for the ECA.

We carry out estimates as a function of vessel engine (kW) and load factor (LF; dimensionless) under the different operational modes. We estimate the LFs for OGV during cruising as a function of the speed reported by the Port of Oslo, whereas at manoeuvring and at berth, the LFs suggested by US EPA (2009) are used (Table 2). The total horsepower (*HP;* kW) of the main engine (ME) and auxiliary engines (AEs) is retrieved from the world shipping register (World Shipping Register, 2014) based on the International Maritime Organization (IMO) figures, as a unique reference for each vessel. 30% and 98% of the horsepower values of individual vessels is retrieved for HV and OGV, respectively. We use the average horsepower provided by US EPA (2009) to complete the missing information about vessels and the CHE (Equation 5).

$$E_{i,OGV\text{"at sea"}} = \sum EF_{i,j,OGV\text{"at sea"}} * LF_{j,OGV,\text{"at sea"}} * 2 * t_{j,OGV,\text{"at sea"}} * HP_{j,OGV,ME} \qquad 1$$

$$E_{i,OGV\text{"man."}} = \sum EF_{i,j,OGV\text{"man."}} * LF_{j,OGV,\text{"man."}} * (t_{j,OGV,\text{"man.IN"}} + t_{j,OGV,\text{"man.OUT"}}) * HP_{OGV,ME} \qquad 2$$

$$E_{i,OGV\text{"at berth"}} = \sum EF_{i,j,OGV\text{"at berth"}} * LF_{j,OGV,\text{"at berth"}} * t_{j,OGV,\text{"at berth"}} * HP_{OGV,AE} \qquad 3$$

For HVs, the Port of Oslo provides the annual operating time (AOT; Equation 4) of each harbour vessel (*j*). We also update the operating time of domestic ferries with data provided by the public transport authority for Oslo (Ruter AS), responsible for the domestic ferries. For the remaining vessels (i.e., fishing, recreational, supply and workboats), the AOT was estimated from the US EPA (2009) and values were scaled to the seasonal time activity of the Port of Oslo. For the different types of CHE (*j*, Equation 5) and vehicles operating within the port area (*j*, Equation 6), AOT and the annual operating distance (AOD), respectively, were provided by the Port of Oslo and the operators.

$$E_{i,HV} = \sum EF_{i,j} * LF_j * AOT_j * HP_j \tag{4}$$

$$E_{i,CHE} = \sum EF_{i,j} * LF_j * AOT_j * HP_j \tag{5}$$

$$E_{i,VEH} = \sum EF_{i,j} * AOD_j \tag{6}$$

Table 2: Load factors (LT) for ocean going vessels at cruising mode ("at sea"), manoeuvring ("man") and at berth, and for harbour vessels.

Vessels	LF "at sea"	LF "man"	LF "at berth"
Ocean Going Vessels			
Bulk Carrier	0.36	0.45	0.10
RO-RO	0.59	0.45	0.26
Container	0.28	0.48	0.19
Cruise	0.22	0.80	0.64
International Ferry	0.22	0.80	0.64
General Cargo	0.80	0.45	0.22
Oil / Chemical Tankers	0.44	0.33	0.26
Harbour Vessels			
Commercial Fishing		0.79	
Domestic Ferry		0.42	
Recreational		0.21	
Supply Vessels		0.43	
Tug - Push boat		0.31	
Work boats		0.51	
Other vessels		0.79	

Some of the domestic ferries from the public transport company partially use LNG as fuel (i.e., Kongen, Dronningen and Prinsen), and we have evaluated the result of extending the use of LNG to all domestic ferries by 2020. The NO_x and CO_2 emission factors for LNG domestic ferries are considered to be 0.54 and 608.7 g/kWh (ICF Jones and Stokes, 2009), respectively. We assume NO_x emission factors to be 92% lower than the NO_x emission factor for diesel fuelled vessel. The NO_x emission factor is below emission factors reported in the literature for passenger vessels (i.e., 1.1 g/kWh; Nielsen and Stenersen 2010), therefore our evaluation should be considered a best case scenario.

One of the objectives of our study is to evaluate the development of detailed emission inventories as essential methods for the design of effective measures to reduce emissions. Therefore, we compare the results obtained by the bottom-up approach with results obtained through a top-down approach based on marine fuel sales. We obtain information regarding marine fuel sales (split into maritime gas oil and heavy oil) for domestic and international shipping from Statistic Norway (SSB, 2014). We estimate emissions from Equation 7, based on the amount of fuel sales and a generic emission factor specific for the pollutant *i* and the type of fuel *f* (Cooper and Gustafson, 2004). In our study, we compare and discuss the results from the bottom-up and the top-down approaches.

$$E_i = \sum FS \; x \; EF_{i,f} \qquad (7)$$

2.3. Emission Scenarios

We study a current scenario for 2013, and a future scenario for 2020 (Table 3) with i) the implementation of onshore power for some OGV at berth; ii) the combination of onshore power with a speed reduction zone for OGV; and iii) the combination with an additional increase use of LNG by domestic ferries. Some of the measures are implemented over specific shipping companies and to preserve their identity we use fictitious names. These shipping companies are two international ferry companies that berth daily at the Port of Oslo (Color and Sea; fictitious names) and one cruise line company that visits Oslo in the summer (AIR; fictitious name). It is noteworthy to highlight that the current scenario for 2013 is characterized by the use of onshore power since 2011 by the international ferries that belong to the Color Company, and we assume that vessels use marine fuel with sulphur content below 1%. The current scenario (2013) also accounts for the use of LNG by some of the domestic ferries. The scenario for 2020 takes into account the predicted increase in maritime traffic by each type of vessel reported by the Port of Oslo, compliance with a new regulation regarding sulphur content in marine fuel below 0.1% and the implementation of the different mitigation measures (Table 3). Table 4 shows the predicted increase in maritime traffic reported by the Port of Oslo.

Table 3: Description of the 2020 scenarios considered in our study related to onshore power and the implementation of SRZ combined with onshore power. SRZ: Speed Reduction Zone. w/SP: with onshore power.

Scenarios	Description
SCENARIOS RELATED TO ONSHORE POWER	
BAU	Business as usual 2020; Color uses onshore power
Color + Sea w/SP	Color and Sea use onshore power in 2020
Color + Sea + AIR w/SP	Color, Sea and AIR use onshore power in 2020
SCENARIOS RELATED TO SRZ AND ITS COMBINATION WITH ONSHORE POWER	
SRZ12	Implementation of SRZ at 12 knots (Color uses onshore power)
SRZ12 + Sea w/SP	Implementation of SRZ at 12 knots (Color uses onshore power) + Sea uses onshore power
SRZ12 + Sea + AIR w/SP	Implementation of SRZ at 12 knots (Color uses onshore power), Sea + AIR use onshore power

To assess the implementation of a speed reduction zone with a limit at 12 knots affecting OGV (Table 3), we estimate emissions by modifying the LFs of the main engine of each vessel during cruising. We estimate the LFs for each type of vessel assuming that propulsion power varies by the cube of the speed and is, furthermore, a function of the maximum speed of the vessel. The results are shown in Fig. 2. We calculate the time during cruising ($t_{OGV,\text{"at sea"}}$ in Equation 1) for a speed of 12 knots. We do not modify the time spent cruising and the LFs for bulk carriers and oil/chemical tankers as their speed is already reported to be below or at 12 knots. An important aspect to take into account is that emissions of some pollutants are directly related to fuel consumption and, therefore, to the speed.

However, reducing speed may lead to suboptimal combustion, which may increase emissions of compounds such as NO_x. Although several studies address the relationship between NO_x emissions and the LFs, there is no agreement about the LF that guarantee the lowest NO_x emission rates. A study carried out based on more than 200 data points establishes that emission factors become relatively constant above a 40% load factor, with small differences between emission factors found at the 20% load factor (US EPA, 2000). Agrawal et al. (2008) establish a relationship between NO_x emission rates and the LF. Comparing the emission factors reported by Agrawal et al., (2008) with those used in our study for NO_x during cruising (European Commission and Entec, 2005), ours are higher. Consequently, in our study the emission factors are independent of the engine load factor.

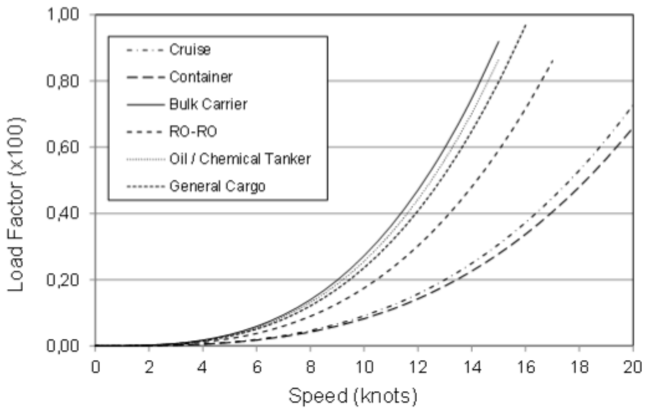

Fig. 2: Plot showing the load factor (dimensionless, x100) to speed (knots) relationship for our case study at the Port of Oslo.

Table 4: Predictive increase in maritime traffic in 2020 regarding 2013.

Vessels	Increase by 2020 (%)
Ocean Going Vessels	
Bulk Carrier	10.33
RO-RO	32.30
Container	19.71
Cruise	16.16
International Ferry	13.20
General Cargo	24.69
Oil / Chemical Tankers	8.80
Harbour Vessels	
Commercial Fishing	0.00
Domestic Ferry	13.20
Recreational	13.20
Supply Vessels	12.44
Tug - Push boat	16.16
Work boats	12.44
Other vessels	13.20

3. Results and Discussion

3.1. Current Emission Scenario (2013)

Table 5 and Fig. 3 show emissions estimated for 2013 and distributed per sectors (i.e. shipping, land activities). Total emissions are comparable with those reported for other ports, such as Bergen

(Norway) where NOx emissions are reported to be of about 663 tonnes in 2010 (McArthur and Osland, 2013). Other studies report slightly lower values, considering that they are bigger ports. For instance, estimates of NO_x and SO_2 emissions from the Port of Copenhagen are, respectively, around 555 and 130 tonnes.year^{-1} (Saxe et al., 2004). The number of calls from cruises in Oslo are around 158 whereas in Copenhagen, cruises reached a value of around 345 calls in 2013. Emissions reported by Saxe et al. (2004), based on modelling results, use 2001 as a reference year and only take into account emissions from OGV.

Table 5: Emissions (ton) obtained per vessel type and sector (traffic and CHE) for the Port of Oslo in 2013.

Vessels / Sector	NO_x	PM_{10}	SO_2	CO_2	CH_4	N_2O	CO_2-eq
Bulk Carrier	10.10	0.15	2.71	461.58	0.00	0.02	468.14
RO-RO	19.93	0.31	5.43	946.83	0.01	0.04	960.43
Container	59.13	0.99	16.17	2806.72	0.02	0.13	2846.12
Cruise	164.41	3.49	58.69	10741.32	0.06	0.45	10881.70
International Ferry	264.89	6.36	91.19	17223.79	0.09	0.72	17449.67
General Cargo	28.60	0.43	7.90	1371.41	0.01	0.06	1390.70
Oil / Chemical Tankers	42.27	0.65	12.35	2115.54	0.01	0.09	2144.95
Commercial Fishing	0.30	0.01	0.20	30.42	0.00	0.00	30.77
Domestic Ferry	79.41	3.41	48.86	10241.14	1.38	0.31	10364.97
Recreational	4.55	0.20	2.84	461.25	0.06	0.01	466.66
Supply Vessels	1.82	0.08	1.07	184.40	0.02	0.01	186.56
Tug - Push boat	6.38	0.28	3.75	646.89	0.08	0.02	654.47
Work boats	5.74	0.25	3.38	582.26	0.08	0.02	589.09
Other vessels	8.80	0.39	5.50	893.29	0.12	0.03	903.77
Trafikk	22.15	0.58	0.01	2043.99	0.04	0.03	2054.73
Cargo Handling Equipment	40.89	0.45	0.00	5538.06	0.05	0.10	5571.33
TOTAL	759.37	18.03	260.04	56288.88	2.03	2.04	56964.05

In our study, shipping is the main source of emissions from the port, as land activities only contribute, respectively, with about 8%, 5% and 14% of total NO_x, PM_{10} and CO_{2e} emissions, and the contribution of land activity to SO_2 total emissions is below 0.1% (Fig. 3c). Among shipping, OGV are the main contributors to emissions with values above 60% contributions to total NO_x, PM_{10}, SO_2 and CO_{2e} (Fig. 3).

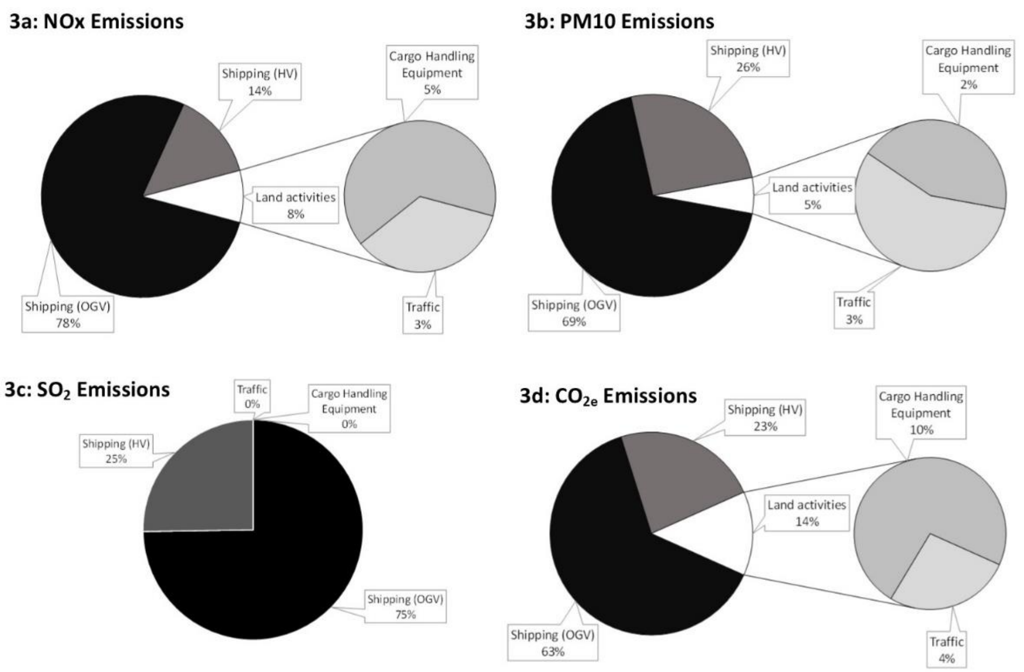

Fig. 3: Emission contribution per sectors operating in the Port of Oslo (2013). HV: Harbour vessels; OGV: oceangoing vessels.

We distribute the emissions from OGV by operational mode as cruising, manoeuvring and at berth, obtaining that the highest emission values occur when OGVs are at berth followed by manoeuvring (Fig. 4). Around 55% of NO_x emissions from OGV occur at berth, contributing to 47% of total shipping emissions. This indicates that measures targeting vessels operating at berth may be the most effective for reducing total shipping emissions in port areas. The contribution of different operational modes has been addressed in other studies, where manoeuvring was estimated to contribute, respectively, around 6% and 10% to total NO_x and SO_2 shipping emissions (Corbett and Fischbeck, 1997). Our study shows higher contributions, as we estimate NO_x and SO_2 emissions during manoeuvring to be, respectively, around 20 and 18% of total shipping emissions. The differences between studies can be due to the size of the domain area considered, which determines the cruising time and, therefore, the relative contribution of cruising to total shipping emissions. Similarly, we can define the time spent manoeuvring by the geography of the area and/or topography of the sea bottom. These factors determine operational time and, thus, emissions. This shows the importance of detailed and comprehensive studies in port areas before implementing measures to reduce emissions and mitigate their impact on urban air quality and climate change.

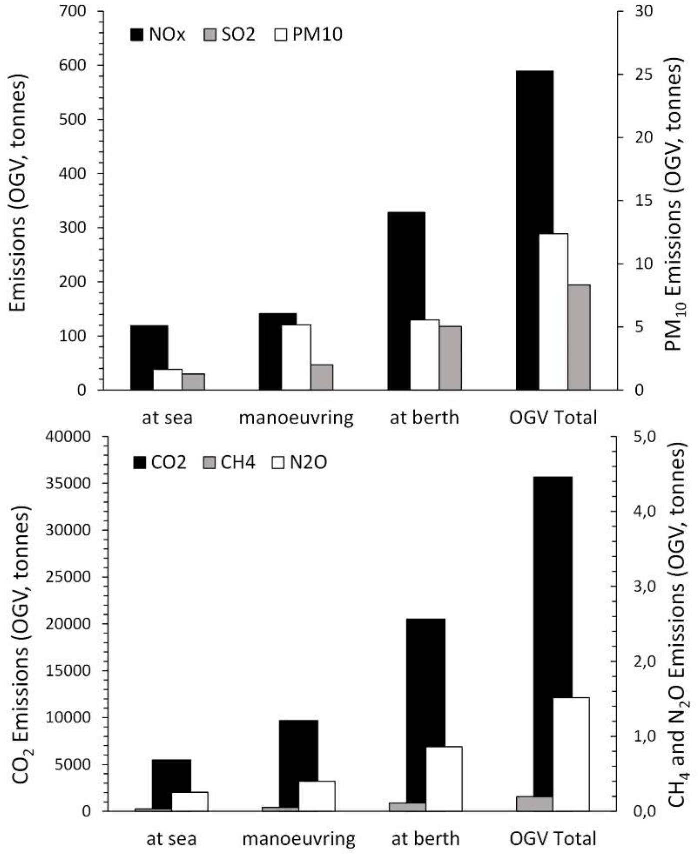

Fig. 4: Emissions of air pollutant and GHGs from oceangoing vessels (OGV Total), distributed by operational mode at sea, manoeuvring and at berth.

Fig. 5 shows contributions of the different types of oceangoing and harbour vessels, and the sectors operating on land (i.e., CHE and traffic) for CO_{2e} and NO_x (SO_2 and PM_{10} show similar contributions). International ferries and cruises are the main contributors to total emissions, and among the HVs, domestic ferries are the biggest, with, respectively, 10% and 18% contribution to total NO_x and CO_{2e} emissions (Fig. 5). It is noteworthy to mention that emissions from cruises mainly occur during one season. Cruises operate during the summer, with their high contribution to emissions associated with their large engine power. The average total power of cruises visiting the Port of Oslo in 2013 is about 45 000 kWh, whereas the average total power of container vessels is about 8 300 kWh.

The contribution of each sector to total emissions varies between harbours. A study carried out in a container port in the United States shows that heavy trucks are the biggest contributors (40%) to NO_x emissions, followed by OGV (32%), CHE (23%), trains (4%) and vehicles operating in the port domain (1%; Bailey et al., 2004). These figures differs from those obtained in our study, as for instance traffic is one of the smallest contributions with about 3% and 4% contribution to NO_x and CO_{2e}, respectively (Fig. 5). The length and distribution of the road network for heavy-duty vehicles within the port domain may explain these differences, as it will define the annual operating distance for vehicles, and hence the annual emissions. The type of port may also be a reason. Approximately

30% of the calls in ports of the US are from container vessels, double the percentage of calls by container vessels in the port of Oslo (15% in 2013). Additionally container vessels can differ in size and engine power. The total average engine power for container vessels in our study is about 8 300 kWh, and the average value recommended by US EPA (2009) for developing emission inventories is about 37 000 kWh. This indicates that container vessels visiting Oslo are smaller than those visiting US harbours.

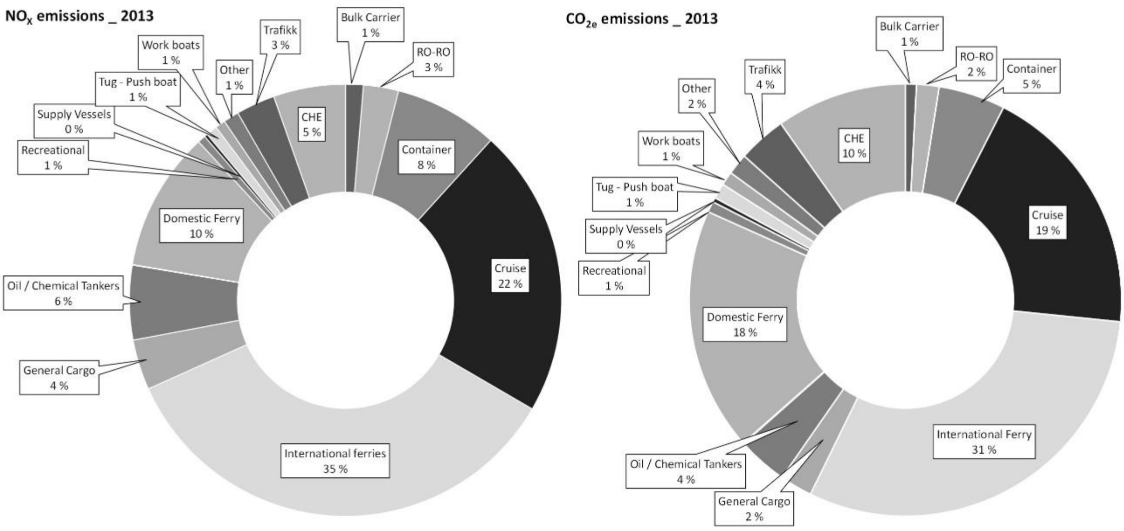

Fig. 5: Contribution to NO_x and CO_{2e} emissions (2013) from the type of vessels, traffic and CHE.

Development of comprehensive emission inventories is challenging. It requires methods suitable and feasible for every harbour area. The bottom-up method employed in our study is accurate and appropriate regarding the spatial location of the emissions. However, our approach is relatively expensive compared to the top-down approach, as it requires substantial amount of data and, therefore, resources to analyse these data. To evaluate more affordable approaches, we compare the results obtained through a top-down approach (i.e., marine fuel sales) with those from the bottom-up approach presented in this study. Based on the top-down approach, we estimate NO_x shipping emissions in Oslo region to be around 1 033 tonnes in 2013, compared with around 700 tonnes estimated through a bottom-up approach (Table 5). These methods differ in the geographical location of the emissions, as the fuel sale method assume that emissions occur where the fuel is sold. Thus, emissions estimated through the marine fuel sale approach correspond to the Oslo administrative region, whereas emissions estimated through the bottom-up approach correspond to the area from the ship calling line (Fig. 1), which includes Oslo region and part of the neighbouring administrative region (Akershus). Consequently, we are able to establish that emissions obtained from the top-down approach tend to be too high. The top-down approach has several disadvantages, such as 1) the lack of information regarding location of the emissions, 2) it is not able to account for emissions from harbour activities occurring on land (i.e., traffic and CHE), or 3) it is not able to distinguish emissions according to operational mode (i.e., cruising, manoeuvring or at berth). However, as previously reported (ENTEC, 2005), the fuel sale approach may be considered a screening method and worthy for further research. Additional research is needed to determine suitable methods for developing detailed emission inventories for harbouring areas, and which additionally provides estimates on a regular basis (e.g., yearly) and assessment of mitigation measures. Along these lines, a promising method to estimate emissions is one based on the automatic identification system (AIS) from both land and satellite (e.g., Winther et al., 2014).

3.2. Future Emission Scenarios (2020)

We show emissions for 2020 in Table 6. They take account of the expected increase in maritime traffic (Table 4) and compliance with a new IMO regulation regarding sulphur content in marine fuel (content has to be <0.1% from January 2015; IMO 2013). We consider this scenario to be business as usual (BAU; Table 7), as it does not consider significant changes, only the naturally expected (i.e. new regulation from 2015, maritime traffic increase). The evaluated 2020 scenarios are those after feasible implementation of onshore power for selected OGVs, the establishment of a speed reduction zone and the increased use of LNG by domestic ferries. To assess these scenarios, emissions are compared with the current scenario (2013; Table 5) established as a baseline as it is assumed to be less uncertain. We estimate emissions to increase by 8-15% for NO_2, CO_2, CH_4 and N_2O by 2020 with respect to the baseline (2013) under a BAU scenario (BAU in Table 7 and Fig. 6). This is consistent with the expected increase in maritime traffic. However, emissions of PM_{10} and SO_2 decrease (>90% for SO_2, 10% for PM_{10}) owing to the assumption that the vessels consume lower sulphur (<0.1%) marine fuel than in 2013 (<1%).

The regulation regarding low sulphur marine fuel has brought about a discussion on its implications for vessel owners, especially concerning the high cost the fuel and the use of scrubbers as an alternative. Scrubbers consist of a system that uses seawater and chemicals to remove sulphur from engine exhaust gas, with discharge to the sea of the resulting sulphates. The use of scrubbers may involve a reduction of, respectively, about 95% and 60-80% of SO_x and PM, based on information from scrubber manufactures (see review in Helfre and Couto Boot, 2013). Recent research addresses the cost of using scrubbers versus shifting to low sulphur marine fuel, concluding that the price of the marine fuel will mainly determine this choice, and that the lifespan of the vessels is determinant. Thus, retrofitting a vessel with relatively short lifespan would not be worthwhile (Jiang et al., 2014). Mitigation measures targeting operations at berth may be the most effective as emissions from vessels at berth are the most significant out of those considered in this study. Implementing onshore power for the international ferries from the Sea Company (Color + Sea w/SP, Table 7) entails that emissions of NO_x and N_2O in 2020 are kept at a similar level as in the baseline (2013), thus offsetting the increase in emissions due to higher maritime traffic. Emissions of CO_2 decrease by 5% with respect to the emissions in 2013 (Table 7). The implementation of onshore power for all feasible vessels gives about 5% reduction of NO_x and N_2O, around 10% reduction of CO_2, 25% reduction of PM_{10} and above 90% of SO_2, with respect to the emissions in 2013 (Color + Sea + AIR w/SP; Table 7).

Table 6: Emissions (ton) estimated for different types of vessels and sectors (traffic and CHE) operating in the Port of Oslo in 2020.

Vessels / Sector	NO_x	PM_{10}	SO_2	CO_2	CH_4	N_2O	CO_2-eq
Bulk Carrier	11.14	0.14	0.30	502.91	0.00	0.02	510.15
RO-RO	26.37	0.35	0.71	1232.15	0.01	0.06	1250.14
Container	70.78	0.92	1.92	3269.38	0.02	0.15	3316.55
Cruise	190.98	3.20	6.76	11391.90	0.07	0.52	11554.96
International Ferry	299.89	5.01	10.25	17600.03	0.11	0.82	17855.74
General Cargo	35.67	0.47	0.98	1665.59	0.01	0.08	1689.65
Oil / Chemical Tankers	45.99	0.63	1.33	2240.04	0.01	0.10	2272.05
Commercial Fishing	0.30	0.01	0.00	30.42	0.00	0.00	30.77
Domestic Ferry	89.89	3.32	1.03	11592.97	1.56	0.35	11733.15
Recreational	5.15	0.20	0.06	522.14	0.07	0.02	528.26
Supply Vessels	2.04	0.08	0.02	207.33	0.03	0.01	209.76
Tug - Push boat	7.41	0.28	0.09	751.42	0.10	0.02	760.23
Work boats	6.45	0.24	0.08	654.70	0.09	0.02	662.37
Other vessels	9.97	0.38	0.12	1011.21	0.13	0.03	1023.06
Traffic	17.74	0.61	0.02	2369.67	0.05	0.12	2408.04
Cargo Handling Equipment	8.30	0.52	0.00	6429.69	0.06	0.04	6442.39
TOTAL	828.07	16.36	23.66	61471.53	2.30	2.35	62247.27

Table 7: Percentage change in emissions for different 2020 scenarios with respect to 2013. w/SP: with onshore power. Color, Sea and AIR are fictitious names for the two international ferry companies that berth daily in the Port of Oslo and a cruise company that visit Oslo during the summer. SRZ12: speed reduction zone at 12 knots for OGV.

Scenario	NO_x	PM_{10}	SO_2	CO_2	CH_4	N_2O
BAU	15.18	-10.40	-90.91	8.14	13.48	14.91
Color + Sea w/SP	0.04	-20.85	-92.42	-5.08	11.53	-0.32
Color + Sea + AIR w/SP	-4.98	-24.32	-92.91	-9.48	11.12	-5.57
SRZ12	4.95	-15.87	-91.59	1.65	12.47	6.94
SRZ12 + Sea w/SP	-10.18	-26.32	-93.09	-11.57	10.55	-8.24
SRZ12 + Sea + AIR w/SP	-15.21	-29.76	-93.59	-15.97	9.91	-13.28

In Table 7 and Fig. 6 we show the results of implementing a speed reduction zone for OGV operating in the area, along with the results from the combination with onshore power. A speed reduction zone at 12 knots is typically chosen in existing speed reduction programmes, for instance at the Port of Long Beach and in San Diego. In a 2020 scenario without implementing mitigation measures (BAU in Table 7), emissions will be higher for all compounds except for PM_{10} and SO_2, which are strongly affected by the type of marine fuel used. Appling a speed limit programme at 12 knots (SRZ12), emissions will still increase with respect to 2013 between 1 and 7% for CO_2, N_2O and NO_x, and by 12% for CH_4. Emissions are lower than in BAU, thus implementing a SRZ offset the increase in maritime traffic. Combining speed reduction zone with onshore power results in emission values that are more promising as higher reductions are achieved. For NO_x, CO_2 and N_2O there is a reduction of emissions up to 15% (Table 7) with the implementation of onshore power for ferries from the Sea Company and the AIR cruises (NO_x emissions in Fig. 6; SRZ12 + Sea + AIR w/SP).

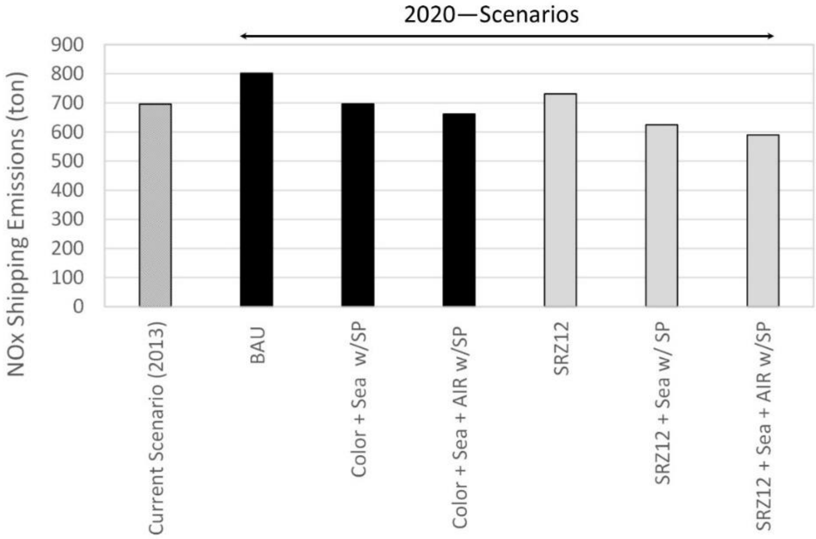

Fig. 6: NO_x shipping emission reductions under the different 2020 scenarios considered in our study (Table 2) compare to current scenario (2013).

Our detailed emission inventory showed that the partial contribution of HVs is between 14 and 26% of total NO_x, PM_{10}, SO_2 and CO_{2e} (2013; Fig. 3), and a similar partial contribution to total emissions occurs in 2020 (Table 6). Among HV, the domestic ferries were found to be the highest contributors to emissions (Domestic Ferry, Fig. 5), therefore, measures targeting this sector may have a relatively high impact on emission reductions. Some of the domestic ferries from the public transport company partially use LNG as fuel (i.e., Kongen, Dronningen and Prinsen), and we have evaluated the result of extending the use of LNG to all domestic ferries by 2020. We find a reduction of total PM_{10} shipping emissions of 24%, and increases in emissions of 7% for NO_x and CO_{2e} if no other measure is implemented (BAU - 2020). The reason of this increase is that implementing LNG to all domestic ferries does not offset the increase in shipping emissions due greater maritime traffic in 2020. However, if we combine the use of LNG by domestic ferries, onshore power for feasible OGVs and a speed reduction zone at 12 knots, then we see a significant reduction of NO_x, PM_{10} and CO_{2e} emissions by, respectively, 23, 43 and 17%.

3.3. Influence of shipping emissions at urban locations

Based on available information concerning total emissions in 2013 in the model domain we are able to establish that the Port of Oslo contributes, respectively, around 12% and 2% to total emissions of NO_x and PM_{10} (Høiskar et al., 2014). Regarding CO_2, a previous study established emissions in 2012 due to wood burning and traffic are of about 750 000 $ton.yr^{-1}$ (Sundseth et al., 2015), indicating that CO_2

emissions from the port would account for about 7.5% of the total emissions. Regarding SO_2, it is still being monitored as part of the national monitoring network program. Therefore, measurement data have been evaluated to establish potential impact of shipping in SO_2 urban concentration levels.

We have evaluated SO_2 hourly concentration levels (2013) in combination with wind speed and direction to establish the potential influence of shipping at urban locations. Measurements of SO_2 are available from a monitoring station close to the coast (Grønland; Fig. 1). The meteorological data is from a station (Valle Hovin), considered as representative of the meteorology of the area. Hourly values of SO_2 measured in Oslo are relatively low, with annual mean concentrations of 3 μgm^{-3} and maximum values of 49.3 μgm^{-3} in 2013. However, peaks above 20 μgm^{-3} are observed at regular intervals and especially during summer, when values above 30-40 μgm^{-3} (July 2013) are registered. Comparing the occurrence of SO_2 peaks and the activity data from the Port of Oslo allows us to determine a relationship between high concentration levels and the presence of international ferries and cruises at berth. Fig. 7 shows the bivariate polar plot of SO_2 concentration and its variation as a function of wind speed and wind direction, suggesting potential candidates for the SO_2 sources. Bivariate polar plot are used as diagnostic tools to identify possible pollution sources based on variables such as concentration levels, wind speed and wind direction (e.g. Carslaw et al., 2006; Carslaw, 2014). In our study, we have limited this plot to those predictions from more than two available measurements, thereby reducing the uncertainty in the calculation. By applying this condition, we remove most of the predictions at high speed. The SO_2 concentration has its highest values for a regime of southwest winds, agreeing with the orientation of the Port of Oslo. The southwest direction shows the highest probability of SO_2 concentration levels higher than the 90th percentile (4.5 μgm^{-3}; Fig. 7). The evaluation of measurements data shows that the port may contribute to concentration levels in the urban environment (e.g., SO_2).

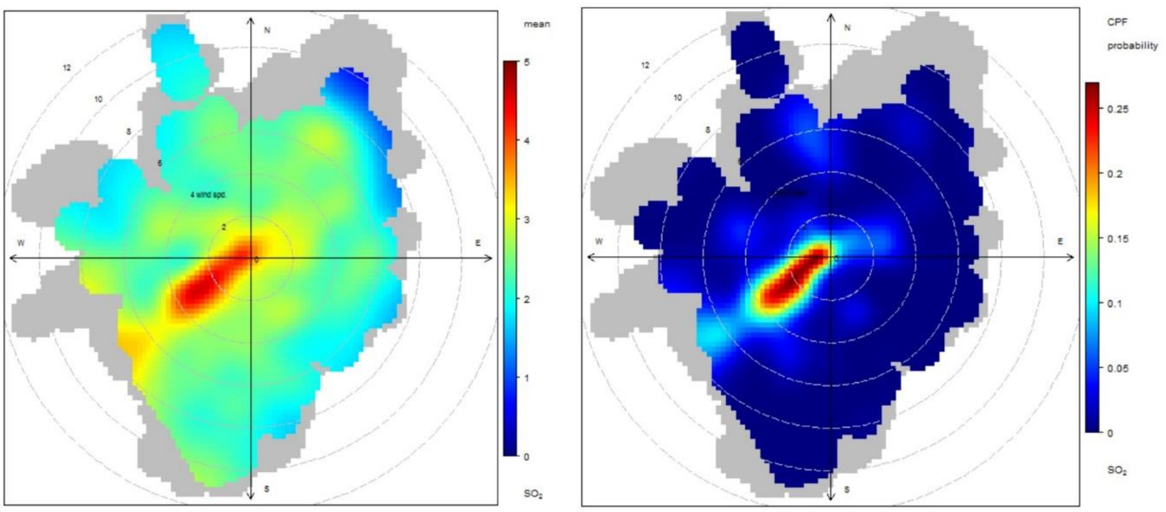

Fig. 7: Bivariate polar plot of SO_2 concentrations as a function of wind speed and direction (left) and the cumulative probability distribution function at the 90th percentile (4.5 μgm^{-3}; right).

4. Conclusions

Our study shows the importance of a detailed emission inventory as a basis for designing effective measures to reduce emissions from shipping in harbour areas. Differences in emissions and in the contribution from different sectors exist between ports, which can be explained by differences in the type of operation both at sea (OGV and HV) and on land (Traffic and CHE). We therefore need comprehensive knowledge of emissions from ports, as they contribute and influence the air quality of the urban environments where they are located. Based on our study, we expect air pollutants such as NO_x, NO_2, PM and CO_2 to be of concern in the near future. The recently implemented new IMO regulation targeting the sulphur content (<0.1%) in marine fuel will have a positive effect on SO_2 emissions. Our study shows that compliance with the regulation involves a reduction of, respectively, about 90% and 10% in SO_2 and PM_{10} emissions. One aspect that has not been discussed in our study is the consequences of reducing shipping emissions for the formation of secondary both organic and inorganic aerosols, so the foreseen reduction in precursor components (NO_x, SO_2, volatile organic compounds - VOCs) will also involve a reduction in particle formation.

In the Port of Oslo, we have identified OGV as the main contributor to emissions, especially when OGV are at berth. Therefore, onshore power can provide an effective measure to reduce emissions. We obtain significant reductions in emissions from the combination of different mitigation measures (e.g. onshore power with speed reduction zone). The implementation of a speed reduction zone, which is policy related, will reduce emissions, especially in combination with other measures. Onshore power in combination with speed reduction zone involves reductions in emissions of up to 15% for NO_x and CO_{2e} with respect to the current situation (2013). Further reductions in emissions of up to 23% (NO_x) and 17% (CO_{2e}) will occur if the use of LNG by domestic ferries is increased.

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