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Offshore service vessel contribution to the air pollution in a port city

Estimation of aggregate emissions

for the Port of Bergen

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Abstract

The main subject of this thesis are emissions released by an offshore fleet visiting the Port of Bergen. In its first part, a problem of shipping-related pollution is introduced. It includes a description of main emission types as well as factors influencing the amount of pollution released by ships, like for example a type of fuel used by engines on board. Then, there is discussed an impact the air quality deterioration has on the environment and human health. Finally, some existing abatement solutions for vessels as well as ports' best practices are presented.

The result of the aggregation of SO_x, NO_x, NMVOC, CO, PM_{10} and $PM_{2.5}$ emissions released by the fleet arriving at the port during the years 2005-2015, including 4,887 port calls, shows that for each type of emissions, the emission inventories either went up or stayed stable at fairly high levels in the last couple of years (with the exception of SO_x, which since January 2015 has been strongly influenced by the new regulation on sulfur content present in marine fuel and therefore has experienced significant decrease in values). Taking into account sustained negative sentiments on the OSV market and a negative result of the comparison between the amounts of pollution ejected by offshore vessels and passenger cars travelling through the city center/port area, the findings of the study might urge the Port Authorities in Bergen to consider undertaking further actions directed towards curbing offshore vessel emissions in the near future.

Keywords: Shipping, Shipping pollution, Offshore vessels, Port cities, Air pollution.

Preface

This thesis has been written as a part of the program Master of Science in Economics and Business Administration at the Norwegian School of Economics.

The main reason behind the choice of the subject is related to a still existing gap in the port specific emission inventory studies, especially in port cities. Furthermore, there is still an increasing concern about the deteriorating air quality in the city of Bergen, which is known as one of the most popular destinations for tourists visiting Norway.

The process of conducting the study constituted a cognitive challenge that allowed to expand the understanding of the problem of shipping-related emissions as well as uncover possible solutions. Moreover, it allowed to gather useful experience and insights likely to be beneficial in the future career.

Special thanks go to the supervisor of the thesis, Roar Os Ådland, who was the source of constructive and insightful feedback as well as advice throughout the whole process of conducting the study. Moreover, there has to be recognized the contribution of Mr. Ove Daae Lampe from Christian Michelsen Research, who performed necessary preparation steps on the dataset used in the study as well as Mr. Ståle Eikeland, General Manager Maritime at Swire Seabed, who devoted his time for an in-depth interview and provided useful, experience-based information on offshore vessels operations and equipment.

Table of contents

List of Figures

List of Tables

1. Introduction

In the ongoing debate on the contamination of the atmosphere through air pollution shipping has earned renown of the least detrimental to the environment mode of transport. At the same time, shipping operations has been a source of various environmentally harmful outputs like bilge and ballast water, sludge, different types of garbage as well as volatile organic compounds (VOC) and chlorofluorocarbon (CFC) gases to name a few. Because of large efforts to reduce emissions attributed to other industries, a relative contribution of the emissions derived from vessel activities to the anthropogenic pollution has increased significantly. This in turn has drawn more attention to the impact these emissions have on the atmospheric composition and their influence on human health, especially in urban areas (Viana et al., 2014).

It has been estimated that 70% of the emissions related to vessel activities are ejected within 400 km from the coastline. This situation causes the deterioration of air due to the accumulation of sulfur (S), particulate matter (PM) as well as the formation of ozone in the lowest parts of the atmosphere (Endresen et al., 2009). What is more, it poses the greatest threat in harbor areas characterized by the high concentration of traffic. Exposed are also locations further inland and this because harmful particles can be transported by land-sea breeze winds even over a few hundreds kilometers from the place they were released (Eyring et al., 2010). Thereby, also the effect of land-based abatement measures is very often offset. According to the latest report on air pollution published by International Transport Forum in 2014, estimated emissions caused by shipping in port areas were substantial and equal to over 18 million tonnes of CO_2 and 0.4 million of NO_x, followed by 0.2 million tonnes of SO_x and 0.03 million tonnes of PM_{10} (Merk, 2014). This was the results of not only sailing and manoeuvring operations but also the practice of leaving the main engines switched on while berthing (De Meyer et al., 2008). Furthermore, according to the ITF estimates, the numbers mentioned above are going to quadruple through 2050 (Merk, 2014).

Taking into account the shares of calls in the worldwide shipping activity in 2011, European harbors were relatively clean with only 5% of SO_x and 7% of PM released in these port areas. At the same time, the distribution of harbors exposed the most to the harmful effects of gases was highly skewed, with top ten ports (including Singapore, Hong Kong and Rotterdam) contributing as much as 19% of CO_2 and 22% of SO_x port emissions respectively (Viana et al., 2014).

In Norway, shipping sector is responsible for around 9% of CO_2 released to the atmosphere each year; out of which 55% is caused by the inland sea traffic (including fjord areas). What is more, 7% of all emissions are released in ports (DNV GL, 2014, 2016). According to the bottom-up analysis conducted by SINTEF in 2007, supply vessels operating within Norwegian boundaries accounted for 12% of all emissions caused by shipping (Flugsrud et al., 2010). In the following years, this share only increased (DNV GL, 2015) and this due to a steep downward trend in oil prices, which made its strong mark on worth NOK 527,000 billion 2014 Norwegian offshore supply industry (“The service and supply industry”, 2016) resulting in lost contracts, scrapings and layups. The figure below gives an indication of how the offshore market situation in the region was developing between 2005 and 2015.

Figure 1. Development of the average spot day earnings for PSVs with 500-899 m^2 deck area; North Sea region. Based on World Offshore Register by Clarkson Research Services.

Fewer contracts for offshore vessels have directly translated to more ships waiting in major industry ports and longer hotelling (here, understood as the whole range of operations performed by a vessel when stationary at berth). This in turn, as this study will try to show, might be a cause of the higher concentration of air pollution, especially severe in city-ports like Bergen, where ships are berthed in close proximity to a city center and densely populated districts.

Even though there already exists a solid body of research estimating ship transport-related emissions, this research area is still relatively new and most of the so far conducted studies have taken either very holistic approach or concentrated only on a small number of vessels. This in turn has led to mixed results the researchers have arrived at. In the light of the above, more accurate and comprehensive research is necessary, particularly due to the fact that never before has the industry been in such a great need of restructuring and innovative solutions both in terms of increasing energy efficiency and decreasing the environmental footprint.

1.1 Study aim and relevance

The main aim of the study is to estimate aggregate emissions released by offshore vessels visiting the Port of Bergen in the period between 2005 and 2015. By doing this, we would like to address a gap in the analysis of the emission inventories in ports, which ships operating within the offshore industry contribute to. The findings from the conducted research will help regulatory bodies as well as the Port Authorities evaluate the necessity for further actions, derive future strategy and the direction of changes so important in view of more and more severe adverse effects of poor air quality and urban pollution on human health and the surrounding environment. The choice of the port is based on the traffic volumes, its importance for the Norwegian offshore industry as well as the size and the urban quality of the affected area.

The Port of Bergen, located in the center of the second-biggest city in Norway, is a crucial base for the dispatch of goods to and from the west coast of the country. Additionally, it is of a paramount importance for the management of supplies for the offshore installations located in the North Sea. A distinguishing factor in case of Bergen, having a strong impact also on this study, is the topography of the city, which is surrounded by mountains. This has its meteorological meaning as a direct cause of temperature inversion (an increase in temperature with height, especially in winter season) and resulting high precipitation levels.

The study is focusing on offshore supply vessels (OSV) arriving and berthing at the Bergen Port. These include PSVs (platform supply vessels), AHTSs (anchor handling tug supply vessels) and other service vessels engaged mainly in the transport of the equipment, materials and stores to offshore installations.

The assessment is made on the basis of an 11-year period, between years 2005 and 2015 and the research questions are as follows:

What are the aggregate levels of emissions offshore vessels visiting the Port of Bergen are responsible for ?

Is the contribution of the offshore fleet to the air quality deterioration large enough to make the Port Authorities undertake additional abatement measures? What could they be?

In order to find the right answers to the problems stated above, a set of data collected with the help of the Automatic Identification System (AIS) was analyzed. AIS is a system that allows to continuously track and broadcast comprehensive data on specific vessels and details related to their operations both at sea and within the port areas (Perez et al., 2009). By means of the following analysis, a bottom-up estimation of the amount of emissions ejected by incoming vessels during their port calls was made. The process was completed by an extensive literature review on the topic of abatement solutions for shipping-related emissions.

1.2 Outline

In the second chapter of this thesis, a general problem of air pollution in the shipping industry is presented. Then, the main types of emissions ejected by vessels are described, including their impact on the natural environment and human health. Finally, a certain range of abatement technologies and solutions, mostly related to vessel's equipment, is covered.

In the third chapter, an overview of the existing literature focusing on port emissions is presented. This part is also a reference point to the methodology section in the next chapter, which is based not only on case-specific assumptions but also builds on previous studies, especially conducted on the case of the Port of Bergen.

In chapter number four the main findings from the study are revealed. This includes the presentation of the port calls statistics, including their duration and trends. The development of the traffic intensity is then juxtaposed with the offshore vessels market situation prevailing in the last years. Finally, the aggregate results for each of the emission types covered by the study as well as the contribution of each mode of a vessel’s operation to the total emission levels are presented.

The sixth chapter is the discussion chapter, where the overall contribution of the offshore fleet to the pollution problem in the city area is assessed. This is done by comparing the emission levels the fleet is responsible for with the corresponding emissions released by passenger cars travelling through the city center/port area during the same time period. Finally, the existing measures for curbing pollutions from ships, also taken by other ports/port cities, are presented.

In chapter number seven, the limitations of this study are described. What is more, some suggestions for further research are made. Then, in chapter eight the main conclusions from the whole study are drawn. Finally, the thesis is completed by the section with bibliography including all the sources the presented work is based on.

2. Air pollution in shipping

2.1 Shipping emissions and environmental policy

Despite a large dominance of the road sector in emission volumes, there are shipping and aviation industries that have recently experienced the highest growth rates of CO_2 released globally (Directorate-General for Internal Policies, 2015). What is more, shipping is said to be responsible for around 20% of NO_x and 7 % of SO_2 emitted globally (Merk, 2014). While the international research on the impact of shipping industry on the level of air pollution is still an emerging area, the severity of the increasing problem and the urgent need for right policies and the implementation of mitigating measures has already been proved. According to the study co-authored by Schembari (2012), while in the year 2000 the emissions caused by vessels were at around 20-30% of the emissions released on the land area, the projections for the year 2020, which are also in line with the most recent trends, show that the emissions connected to shipping activities will be equal or even surpass the land-based ones. Yet other studies (Buhaug et al., 2009; Eyring et al., 2005) project that without stricter regulations and more control exercised over the amount of emitted particles, the emissions coming from vessel activities might increase by as much as 250% until 2050 (taking the year 2007 as a base year). Then, Buhaug et al. (2009) as well as Harrould-Kolieb and Savitz (2010) estimate that CO_2 inventory the maritime sector is responsible for has already risen above 1 billion tons. In order to put this into perspective, if the shipping sector were seen as a country, it would become the 6th largest emitter of air pollution worldwide. According to Jennifer Chu (2013) from the Massachusetts Institute of Technology (MIT), back in 2005, the emissions derived from shipping as well as particles and gases released while conducting activities within ports were a direct cause of 3,500 early deaths in Southern California. Even if over 10 years old, the results of this study are said to be highly relevant also in the current setting.

The studies mentioned above are a clear signal that the industry calls for regulatory measures, which, according to many and including the European Commission, are not yet in place (“Reducing emissions from the shipping sector”, 2016). Before introducing current and prospective regulatory framework related to the air pollution caused by marine traffic, it is worth to elaborate more on the relevant types of emissions as well as the technical side of their sources, namely types of engines and fuel used by offshore vessels.

2.2 Main types of emissions

There are three major sources of emissions ejected by vessels, namely main and auxiliary engines as well as boilers. From a general perspective, every single vessel activity is to some extent contributing to air pollution. While the largest aggregate volumes are released when sailing, not to underestimate are the harmful particles emitted by vessels whose engines combust fossil fuels for operations of moving in and out of a port area as well as in time of loading and unloading (Trozzi, 2003). The main type of engines installed on offshore vessels is a diesel engine and this due to its energy efficiency, lower costs of operations, high durability as well as reliability. At the same time, diesel engines are also responsible for a great amount of emissions ejected to the atmosphere. In the theory of thermodynamic equilibrium, the conversion from the chemical energy to the mechanical force which drives a diesel engine should generate only CO_2 and H_2O (Prasad and Bella, 2010). Despite this fact and due to numerous reasons like turbulences in chambers, non-optimal concentration of fuel and air as well as different ignition timings, there is also a range of other, harmful gases and particles released during a combustion process.

When analyzing marine transport-related emissions, it is first worth to divide them into two groups: greenhouse gases (GHG) and non-GHG. According to the Greenhouse Gas (GHG) Protocol established by the World Resources Institute (WRI) and the World Business Council on Sustainable Development (WBCSD), within the GHG category, six main chemical compounds can be distinguished:

- carbon dioxide (CO_2)
- methane (CH_4)
- nitrous oxide (N_2O)
- hydrofluorocarbons (HFCs)
- perfluorooctane sulfonate (PFCs)
- sulfur hexafluoride (SF_6)

The most studied and the most relevant to the maritime sector is carbon dioxide (CO_2), which is also known to be the main reason for the existence and the development of global warming phenomenon. According to the estimates from the year 2012, shipping-related CO_2 constitutes 2.7% of total CO_2 emissions (Merk, 2014). While the increase of CO_2 emissions released by platform supply vessels as well as anchor handlers has been brought to a halt, further reductions are difficult to achieve, especially now, in the face of a reduced inflow of capital and frequent terminations of planned investment projects.

Moving on to the non-GHG emissions (or so called “indirect GHG”) produced by the shipping industry, it is worth to concentrate on five of them, especially since these are also the types of emissions this study is focused on:

- carbon monoxide (CO)
- sulfur oxides (SO_x)
- nitrogen oxides (NO_x)
- particulate matter (PM) (including black carbon)
- non-methane volatile organic compounds (NMVOC)

To start with, carbon monoxide (CO) is an odorless and colorless gas generated during the incomplete combustion, at the time when the oxidation process is not properly completed. Sulfur oxide (SO_x), on the other hand, is a by-product created during the process of combustion of sulfur-containing hydrocarbons such as oil, gasoline and coal. In line with the results of the study conducted by the European Policy Center, maritime sector has a place among the top emitters of this gas and this due to the cheap heavy fuel oil (residual fuels) characterized by very high sulfur content that is frequently used in international shipping (Miola, 2010). As estimated for the year 2011, marine fuel was on average 2,700 times dirtier than the fuel used in strictly regulated road transport sector (Adilakshmi et al., 2013). Nonetheless, the amount of SO_x emitted by offshore vessels is very limited, mostly due to the widespread use of marine distillate fuel containing less than 0.5% of SO_x.

The third group of pollutants consists of nitrogen oxides (NO_x). Contrary to the fuel-dependent CO_2 and SO_2 emissions, the amount of NO_x released is directly related to the combustion process, the type of engine installed and its rate speed in particular.

The next one, particulate matter (PM) is a mixture consisting of several hundred gas and particle compounds that most often emerge due to the partial combustion of hydrocarbons in lube and fuel oil and so in the form of so called "black carbon". How much PM is generated depends on the expansion and the combustion process as well as the temperature and the quality of the fuel (mainly sulfur and ash content) and the lubrication oil (Burtscher, 2005). Worth noting is also a positive correlation between PM and SO_x emissions: the lower the amount of SO_x produced, the lower the level of PM (Helfre and Boot, 2013).

Last but not least, there are non-methane volatile organic compounds (NMVOC), which, taken together, make a combination of organic compounds different in their chemical structure yet with a similar influence and a behavior in the atmosphere. They contribute, among others, to the increase in the tropospheric ozone concentration and, by that, to the radiative forcing (National Atmospheric Emission Inventory, 2016).

2.3 Types of fuel used in the offshore sector

For now, no replacement of diesel power systems is to be expected, and this due to the lack of sound alternatives that would match the power density of the diesel. Hence, when developing measures for preventing air pollution from ships, the main focus has to be put on technologies curbing diesel engines emissions, the problem which is directly related to the quality of the fuel used to power them.

The properties of diesel fuel are very often intercorrelated. Fuel density and viscosity, aromatics content and cetane number, which is an indicator of the combustion speed of the fuel, are a good example of this. There is also sulfur content itself, a crucial factor for determining and controlling the amount of SO_2 and PM_{10} emissions. In the past, the main type of fuel used for marine engines was Heavy Fuel Oil (HFO) - pure or almost pure residual oil, often containing some waste products like used motor oil. Later on, a cleaner versions of Intermediate Fuel Oil (IFO) was popularized, with IFO 380 and IFO 180 including up to 12% of distillate oil content. Still, especially in case of IFO 380, its high viscosity often leads to the improper atomization and thus to incomplete combustion of fuel, which directly influences the amount of harmful particles and gases released to the air during the whole process. Currently, with an increasing worldwide pressure for regulations banning the usage of HFO as well as low oil prices, shipping industry turned to higher quality, more expensive marine distillates - a blend of heavy oil and gasoil called Marine Diesel Oil (MDO) and distillate only Marine Gas Oil (MGO).

While 2-stroke low-speed engines are more popular with vessels in general and this due to their estimated lowest specific fuel oil consumption (SFOC), higher power-to-weight ratio as well as lower demands when it comes to the fuel grade (according to the statistics, up to 95% of 2-stroke marine engines are fueled by HFO), there are 4-stroke high-speed engines burning mostly MDO and MGO that are dominating the offshore vessel sector. This is also confirmed by the analyzed dataset, according to which 98% of vessels were equipped with 4-stroke high-speed engines. The same applies to auxiliary engines, which are mostly used to keep running generators for electrical power onboard (supplying electricity, hot water and heat). Also, the impact of auxiliary engines operations has recently been studied in more and more details when estimating the emissions at berth (Reşitoğlu et al., 2015).

2.4 Impact of the emissions derived from shipping

Shipping emissions not only influence the levels of gaseous and particulate pollutants, but also have a great impact on the formation of new particles in the densely populated areas thus transforming the composition of the atmosphere (among others ozone, sulfite and nitrate levels) and cloud microphysics (causing e.g. “ship tracks” phenomenon), which in turn causes climate changes (Davis et al., 2001; Endresen et al., 2003). Still, there exists a lot of uncertainty about the actual size of the impact produced and this due to many indirect effects as well as various components of vessel-induced emissions, which act differently on temporal and spatial scales. Nevertheless, there is no doubt that highly concentrated gaseous releases in port areas have a large influence on the population settled nearby. In the top 10 ports approximately 40 million people might have experienced direct results of both dry depositions and rainouts that occur due to the process of harmful particles mixing with the ambient air. Moreover, the external costs of NO_x, SO_x and PM emitted by ships are estimated to amount up to 12 billion per year in case of the 50 largest ports in the OECD

(Merk, 2014). Finally, contrary to the impact of other modes of transport, the combination of CO_x, NO_x and soot (black carbon) with sulfate and organic aerosols released by ships is, assuming the integrated effect and disregarding specific time of the release, claimed to contribute to a net global cooling (Fuglestvedt et al., 2008), whose abrupt waves might have a severe, negative impact on agriculture, especially in the least developed regions (Engvild, 2003).

Looking at the problem in more detail, there has so far been detected a correlation between NO_2 and CO emissions present in harbor areas and an increased occurrence of such diseases as asthma, emphysema and chronic bronchitis ("Public Health and Environmental Benefits of EPA's Proposed Program for Low-Emission Nonroad Diesel Engines and Fuel.", 2003). What is more, by raising ozone presence in the atmosphere NO_x emissions indirectly contribute to an increased human susceptibility to various infections and allergens, more frequent inflammations, chest pains as well as chronic cough. Long-term high exposure to these particles might even result in a premature lung aging, lung cancer and an incremental destruction of cardiovascular system, which eventually leads to the increased mortality (Corbett et al., 2007). Also SO_2 emissions have been linked with an aggravation of respiratory problems (especially asthma and emphysema) as well as premature births. Then, there is PM known to be a great contributor to severe cardiopulmonary diseases (Bailey and Solomon, 2004) with its tiniest elements constituting the greatest health hazard (Bagley, 1996). In fact, PM was classified by the World Health Organization (WHO) as "definitely carcinogenic to human beings" and is now treated on the same level of harmfulness as e.g. asbestos. What is more, research has confirmed that daily increases in PM concentration can be associated with the surge in the number of deaths in the following days (Lippmann et al., 2000; Moolgavkar, 2000c).

2.5 Overview of the solutions for compliance

Although, there have been conducted manifold studies on various ways to reduce vessel-induced pollution, a constant progress is required, with continuous updates on both costs and performance of existing solutions as well as new alternatives. Implementation of both technological solutions and a usage of alternative fuels that are to combat traditional air pollutants like NO_x, SO_x and PM are followed by systematic increase in energy consumption (e.g. during the refining phase of the fuel cycle). This in turn results in a proportional surge in CO_2 emissions and increased soot known in the industry as ‘‘diesel-dilemma’’. Decision on the most effective and efficient countermeasures vary according to different factors like for instance an age of a vessel (newbuild or older), its size, technical equipment on board or a current focus on emissions to abate. As a matter of example, according to the estimates of the International Maritime Organization (IMO), in case of new vessels current technology based on hull and propeller modification, accompanied by an implementation of some engine optimization techniques, enables to achieve up to 20% reduction in CO_2, while the potential of retrofit solutions for vessels already in operation is estimated to be around 10% (Third IMO GHG Study 2014, 2015).

With the main attention placed on the type of emissions ejected by vessels, there are to be distinguished mainly SO_x, PM and NO_x abatement measures. For the first two, one option is a reduction of sulfur content in marine fuel. As mentioned before, due to the oil price downturn as well as more and more stringent regulations in force, the marine sector has been changing fuel blend used in vessels to cleaner, more eco-friendly MDO and MGO. This trend is also reflected in the dataset from the Port of Bergen. Here, in the time period 2005-2015, mere 5% of the whole incoming fleet used high sulfur HFO (15 out of 292 vessels for which fuel data were available).

Another conventional measure working towards the reduction of SO_x from exhaust gas is based on either wet or dry scrubbing. At the moment, scrubbers are one of the main solutions used in order to control gaseous emissions. More widespread wet scrubbers focus on removing the polluting matters with the help of the scrubbing liquid, which is either spread over the polluted gas stream or forced through it. There has also been employed systems that dispose of the liquid solution by substituting it with a dry reagent or slurry (e.g. of limestone) which, when injected into a polluted exhaust stream, eliminate unwanted gasses and particles. However, the downside of this method is the formation of large volumes of precipitates as a by-product of the process of sulfur oxides reaction with a sorbent. A far simpler method, though still with limited application, is based on using seawater for wet scrubbing, with the natural alkalinity of seawater used as a sorbent. Important here is the fact that it is not only almost completely free of by-products (with the exception of a small increase in the concentration of sulfate in seawater) and highly effective (from 65 up to

94%), but it also displays economic advantages when it comes to capital and operational costs involved (Kjølholt et al, 2012; Erying, 2009). When it comes to PM, one of the solutions worth mentioning is post-combustion oxidation with the help of diesel oxidation catalyst, which converts particulate matter into harmless products. Still, this solutions is estimated to contribute to only 10-30% reduction of PM in marine applications ("Emissions from ships operating in the Greater Metropolitan Area", 2015).

Last but not least, there are measures combating NO_x emissions, which can be divided into three groups. First group includes strategies requiring modifications in engine controls like aftercooler upgrades and engine derating, which, by retrofitting, closes the gap between the optimized and the operational speed. Possible here are also: an introduction of injection timing delays (which works based on the correlation: the later the injection, the higher the soot and the lower the NO_x emissions), fuel system modifications decreasing back-pressure[1] as well as an implementation of marine diesel-electric propulsion (which assures lower fuel consumption and lower emission levels due to the optimization of diesel loading). To the second group belong pre-engine technologies to be implemented in air or fuel system: fuel water emulsification (FWE) (currently, the most efficient, consumption-neutral technology lowering both soot and NO_x), humid air motors (HAM) (which decrease the temperature during the combustion process) and combustion air saturation systems (CASS) (with droplets of water humidifying the air before it enters the engine cylinder). In the last category, post-engine technologies, focus is placed on modifications in exhaust systems. Here, a key technology to meet the latest requirements is selective catalytic reduction (SCR). SCR works by injecting a liquid-reductant (Diesel Exhaust Fluid (DEF) as well as a reaction catalyst, which, combined with ammonia or urea, convert nitrogen oxides into nitrogen, water as well as negligible amounts of carbon dioxide.

The aim of combating harmful emissions can also be achieved by investing in alternative fuels like hydrogen diesel, biodiesel (the main advantage of which is that its various types can be replaced or blended with petroleum with little or no engine modification needed) as well as LNG (which has already been proved to be a commercially available solution, with

[1] Back pressure - a pressure of an exhaust gas produced by an engine aimed at overcoming the hydraulic resistance of an exhaust system and discharging the gases into the atmosphere.

the option of fuel cells producing electric power while using hydrogen from LNG) (de Wilde, 2006). In general, LNG is considered to be a cheaper alternative to distillates and heavy fuel oil and several ports such as Bremen, Rotterdam and Gothenburg have already started to promote using LNG by the implementation of various incentive schemes that grant subsidies to vessels operating on LNG fuel. Nevertheless, LNG is, at least for the time being, advised to be implemented only as a part of a dual-fuel solution, not yet as a stand-alone fuel option. Furthermore, yet still under laboratory research, there are also new hybrid propulsion systems equipped with battery serving as an energy storage. Here also, the main target is the offshore service vessels sector. Last but not least, as a response to the increasing pressure placed on port authorities to devise and implement sustainable port strategies, there is a cold ironing solution, which provides vessels mooring at berth and using their auxiliary engines with sustainably generated shore power. This topic, however, will be described in more details later on.

3. Literature review

In the literature, there exist two main methodologies for estimating emissions derived from shipping: fuel consumption-based method (a so called top-down approach) and fleet activity-based method (a bottom-up approach). They differ mostly due to the level of precision. According to the first one, emission inventory is calculated with the use of fuel sales statistics combined with the corresponding emission factors for a given type of fuel. The latter focuses on detailed information on operations of a defined vessel group or class on a given route and aggregates emissions resulting from different types of vessels' activities in order to arrive at the total amount of pollution released by the fleet. While the top-down approach is more often used for general, large-scale (mostly international) estimations and bears a higher level of uncertainty, for more local studies focused on spatial context a bottom-up approach is suggested (IMO GHG Study 2014, 2015; ICF Consulting 2005; Winther, 2008). In fact, Chang, Song and Roh (2013) applied and compared both approaches in their study on the emission inventory in the Port of Incheon, Korea finding large inconsistencies between the results of the two.

At the same time, there exist certain challenges related to the bottom-up methodology and this mostly due to the use of average input parameters for fuel consumption and engine load levels, which tend to vary with the size of an engine, its age, fuel type applied as well as a general market situation (Eyring et al., 2009). Taking a step further, also an inherent complexity of links between factors influencing air quality assessment like emission dispersion levels, meteorological conditions prevailing at a given location and the pace of chemical reactions occurring as a consequence of emission elements mixing together leads very often to under-or overestimations of the impacts (Holmes and Morawska, 2006). There have been studies for that matter pointing out the need for a more thorough analysis of ship plume chemistry, a conclusion based on discovered overestimations in modelling its impact on NO_x levels (Song et al., 2003; von Glasow et al., 2003).

Moving on to port specific studies, Dalsøren et al. (2009) found out that emissions released by vessels during their activities in a port area account for 5% of the total emissions coming from navigation activities. Furthermore, Winnes et al., (2015) distinguished five different operating modes of ships within a port area: in fairway channel, at anchor, in port basin, at berth and under manoeuvring, with the division of contributions to overall CO_2 emission levels displayed in the figure below.

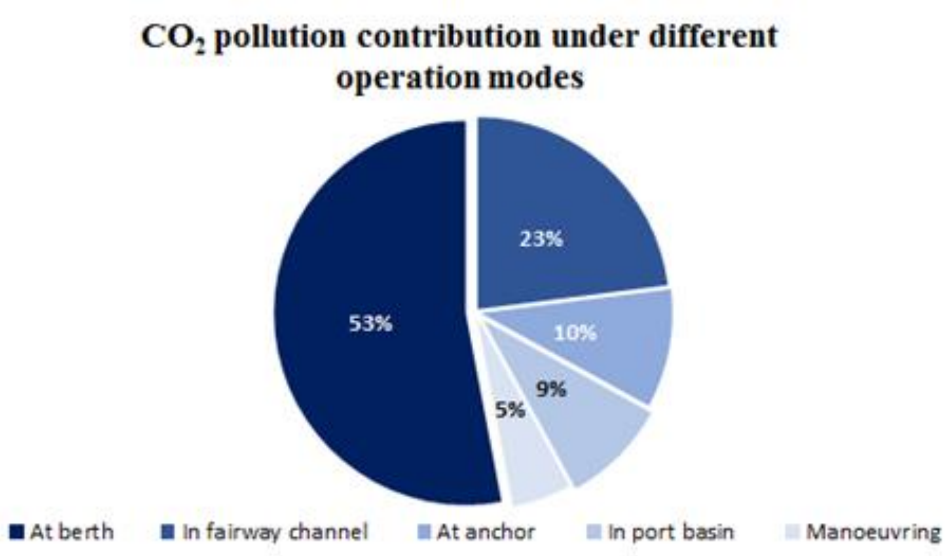

Figure 2. Contribution to the total CO_2 emissions based on operational mode. Reprinted from *Reducing GHG emissions from ships in port areas*, by Winnes, H., Styhre, L., Fridell, E., 2015, Research in Transportation Business and Management, 17, 6.

A general summary of the most relevant and recent studies on port emissions can be found in the table below:

Author	Geographical area of the study	Object of the study
Han et al. (2011)	Port of Incheon, Korea; 2007	Entire fleet, equipment, port trucks and trains
Villalba and Gemechu (2011)	Port of Barcelona, Spain; 2008	Comparison of sea-based emissions (entire fleet at berth) with land-based emissions (from port's own activities)
Saraçoglu et al. (2013)	Port of Izmir, Turkey; 2007	Entire fleet in the port area

Song and Shon (2014)	Port of Busan, Korea; 2006, 2008, 2009	Entire fleet in the port area
Castells Sanabra et al. (2014)	13 main Spanish ports; n.d.	Ro-Ro, container and passenger ships under manoeuvring and hotelling
McArthur and Osland (2013)	Port of Bergen, Norway; 2010	Entire fleet at berth
Goldsworthy and Goldsworthy (2015)	34 Australian ports; 2010/2011	Entire feel under all operational modes within the legal boundaries of ports (transit, loading, manoeuvring, anchoring, berthing)
Tichavska and Tovar (2015)	Port of Las Palmas, Spain; 2011	Entire fleet, 50,000 vessel particulars
Wolf et al. (2016)	Port of Bergen, Norway; 2015/2016	Supply and cruise ships, road traffic in the port area

Table 1. Summary of previous studies estimating port emissions. Adapted from *Environmental cost and eco-efficiency regarding vessel emissions in Las Palmas Port,* by Tichavska, M., Tovar, B., 2015.

In general, the results of the studies on pollution and its impacts are very specific to the studied area and thus hard to generalize. While Habibi and Rehmatulla (2009) estimated British emissions at berth to have been close to ten times greater than those coming from port's own activities, Villalba and Gemechu (2011) who focused on emissions released in the Port of Barcelona achieved the same level of GHG emissions for both ship operations at berth and land-based sources in the port.

Two studies presented above refer directly to the research area of this work, namely the Port of Bergen. The first one, authored by McArthur and Osland is a comprehensive analysis of emissions generated by the whole incoming fleet in the year 2010, including 19,912 port calls with 308,438 hours spent at berth. The authors not only aggregate corresponding inventories for each type of emissions analyzed, but also estimate the economic impact of generated pollution, with the main focus placed on cruise ships. In their estimations, McArthur and Osland follow the methodology presented earlier by Tzannatos (2010) and Trozzi (2010) and based on the following equation:

$$E_{ijk} = T_{ij}(AE_i x\ LF_i x\ EF_k)$$

where E_{ijk} is a given type *k* of emission released by a ship *i* during a port call *j*, *T* is the time spent at berth by a ship during one port call, AE_i is an auxiliary engine power of a ship and LF_i is the corresponding loading factor provided in this case by Dalsøren et al. (2009) for each ship type and contingent on the averages for the world fleet based on earlier studies of Cooper (2003), Whall et al. (2002) and Flodström (1997). Lastly, there are specific emission factors EF_k given by the Statistics Norway, National Emissions Inventory (Sandmo, 2010).

A summary of the results McArthur and Osland arrived at is presented in the table below and will be later on compared against the numbers coming from the own analysis. Importantly, since modelling the auxiliary engine power in this particular study was based on a sample including vessels equipped with only main diesel electric engines, overestimations of auxiliary engines' fuel consumption are likely. Also, the emissions for each emission type are expressed in tonnes.

Vessel type	NO_x	SO_2	PM_{10}	$PM_{2.5}$	CO_2
Offshore	77.22	2.26	1.01	0.96	4583.88
Tug/salvage	3.82	0.11	0.05	0.05	226.63

Table 2. OSV emission inventories in the Port of Bergen in 2010. Adapted from *Ships in a city harbor: An economic valuation of atmospheric emissions* by McArthur, D.B., Osland, L., 2013, Transportation Research Part D Transport and Environment, 21, 50.

The second study, published by The Nansen Environmental and Remote Sensing Center has more climate than monetary focus. Wolf et al. concentrated their research on analyzing the impact both ship as well as road traffic have on the concentration, circulation and spread of air pollution in the port and nearby area. In their models, the authors accounted for specific atmospheric conditions existing in Bergen like the direction of the wind as well as the inversion of the temperatures occurring in winter time (Husby, 2014). They found that, especially under inversion situations, the direction of the wind in the area has a positive impact on the air quality, with a high probability of pollution being transported over the fjord and “clearing” the air in the city center and the port area.

4. Methodology

When estimating the emission inventories in the Port of Bergen, each and every incoming vessel was approached separately. The formula by Tzannatos and Trozzi presented before was applied but also extended by differentiating between three main operation modes vessels visiting the port operate in: approaching (sailing), manoeuvring (slow movement of a ship between a port entry and a berthing area) and hotelling. This resulted in the formulation of the following equation:

$$EI_k = \sum E_{i,j,k,approach} + E_{i,j,k,manoeuvring} + E_{i,j,k,hotelling}$$

where EI_k is the emission inventory for an emission type *k*, while $E_{i,j,k}$ represents the aggregate value for an emission type *k* released by a vessel *i* during its call *j*. For each of these three modes, the impact of both main and auxiliary engines is taken into consideration. Despite the fact that main engines are major pollution emitters, especially in studies focusing on emissions released by vessels at berth what cannot be neglected is the operational impact of auxiliary engines, when main engines are switched off and the shore-side electricity is not used.

Aggregating emissions in each of the three modes required making certain assumptions related to the distances. Our assumptions are as follows:

Sailing

1. The entry points at which the AIS data were collected are:

   ✓ Askøybrua, west of the harbor (to 60° 23′ 43.6″ N, 5° 12′ 56″ E)

   ✓ Eidsvåg, north of the harbor (60° 26′ 48.3″ N, 5° 16′ 43.3″ E)

2. The „in-port” area is marked by a green buoy located next to Nordnes (60° 24′ 2.6″ N, 5° 18′ 25.4″ E)

3. The berth is located at the Skolten terminal (60° 24′ 3.4″ N, 5° 18′ 46.6″ E)

4. The respective distances are:

   - ✓ Askøybrua - Green buoy: 5.058 km
   - ✓ Eidsvåg - Green buoy: 5.328 km

All vessels are assumed to cover the distance between Askøybrua/Eidsvåg and the green buoy with the speed of 9 knots in the average time of 20 minutes. These numbers reflect the information collected from an expert, a representative of Swire Seabed company.

Manoeuvring

The manoeuvring mode is assumed to take 1 hour one way, including covering the distance of 0.210 km between the green buoy and the berth. This assumption is also based on the information provided by the expert from Swire Seabed.

Taking a step further and decomposing the $E_{i,j}$ factor, the formula applied in the study is:

$$E_j = \sum_m T_m \; x \; EF_{k,t,f}\left(FC_{m,main} + FC_{m,aux}\right)$$

where T_m is the time a given vessel spends in an operation mode *m* (approach, manoeuvring, hotelling) during each call, expressed in days, $EF_{k,t,f}$ is the emission factor for a pollutant *k* in kg/tonne of fuel, under the relevant Tier *t* regulation (Tier I or Tier II), for a fuel type *f* and $FC_{m,main}$, $FC_{m,aux}$ are respective fuel consumptions for each engine type in a given operation mode.

What is more, in the approach phase T_m equals:

$$2\ x\ T_{approach} = 2\ x\ \frac{Average\ distance\ sailed\ (km)}{Average\ approach\ speed\ (\frac{km}{h})} / 24$$

while under manoeuvring:

$$2\ x\ T_{\mathrm{manoeuvring}} = 2\ x\ 1\mathrm{h}$$

Also, in each case, multiplying the time spent for manoeuvring by a factor of two assures that operations during both arrival and departure for a given port call are accounted for.

Next, one of the main challenges when estimating the amount of the emissions released by vessels is being tackled. It is related to average engine loads and resulting fuel consumption levels for engines at each phase of a vessel's operation. Here, especially in case of auxliary engines, the data is not well documented. Hence, rough estimates had to be applied.

In the study, daily fuel consumption (*FC*) in the operation mode *m* for an engine type *e* (main or auxiliary) was estimated based on the number of active engines engaged in the normal propulsion, fraction of power necessary to achieve an average speed under a given operation mode *m* (*xMCR*), engine power expressed in megawatts (MW) as well as *SFOC*. The estimation method was adapted from the report "Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data" (EPA, 2000) and employed the following formula:

$$FC_{m,e} = No.of\ active\ engines_e * xMCR_{m,e} * Engine\ power * SFOC * 24/1000$$

where *SFOC* equals 0.200 kg/kWh for engines with the total power below or equal to 3 MW and 0.175 kg/kWh for engines with the total power of over 3 MW (Marin, 2016). Also, the last multiplication factor above (24/1000) allows to arrive at *FC* values expressed in tonnes per day.

When it comes to *xMCR*, the values applied in the formula follow the assumptions made in the previous work of Dalsøren et al. (2009) as well as included in the report published by Entec UK Limited in 2002:

xMCR when sailing		xMCR when in the port area			
		Manoeuvring and hotelling shorter than 1 h		Hotelling over 1 h	
Main engines	Auxiliary engines	Main engines	Auxiliary engines	Main engines	Auxiliary engines
50%	10%	20%	20%	0%	20%

Table 3. Main and auxiliary engine power usage in each operation mode. Adapted from *Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports*, by Dalsøren et al. (2009) and *Quantification of emissions from ships associated with ship movements between ports in the European Community*, by Whall et al., 2002.

Usually, in case of port stops longer than 1h, most of diesel main engines are shut down completely, while auxiliary engines serve as the only source of power, which in this study is the case for around 10% of port calls (EMEP, 2001). Important to point out for these 10% cases is that if a restart for a departure occurred with cold engines, it resulted in 1) an initial increase in CO during a start-up phase and 2) a general, slight increase in both HC and PM emissions (ENTEC, 2002). In fact, according to Miola and Ciuffo (2010), emissions ejected in harbor areas are mostly caused by engine acceleration and deceleration during starting and braking since, at that time, bow and stern thrusters are in full operation, which in turn translates into short term maximum auxiliary engine emissions (Cooper, 2003). Still, due to the lack of necessary data, these changes in emission values were modelled in the study.

Last but not least, there are different emission factors EF assumed for different engine types based on the year of production) as well as fuel used. Following the regulations included in the MARPOL Annex VI from October 2008, two categories for emissions factors were distinguished:

- Tier I – for diesel engines over 130 kW installed on vessels built before 1 January 2011

- Tier II - for diesel engines over 130 kW installed on vessels built between 1 January 2011 and 1 January 2016

In cases when a conversion year for a vessel was reported by Clarkson, a major conversion was assumed. Therefore, the renovation date became the referring point for the decision on the appropriate Tier.

Furthermore, since the Port of Bergen is located within the Emission Control Area for Sulfur Oxides and Particulate Matter (SECA) (MARPOL Annex VI, regulation 14.3.1), the following assumptions on sulfur content (S%) was made:

For vessels arriving before 1 January 2010	For vessels arriving between 1 January 2010 and 1 January 2015	For vessels arriving after 1 January 2015
1.5%	1%	0.1%

Table 4. Sulfur content in marine fuel used by vessels sailing within SECA. Adapted from *Sulfur Content in Marine Fuels Briefing Report,* by The Association of European Vehicle Logistics (ECG), 2013.

Additionally, in case of differences in values, the distinction between Heavy Fuel Oil and Marine Diesel/Gas Oil or Intermediate Fuel Oil has been made. Still, out of 399 vessels included, for 274 Marine Diesel/Gas Oil were reported as fuel types used. Hence, in cases when the data on fuel type were missing in the Clarksons World Fleet Register, these two fuel types were assumed by default.

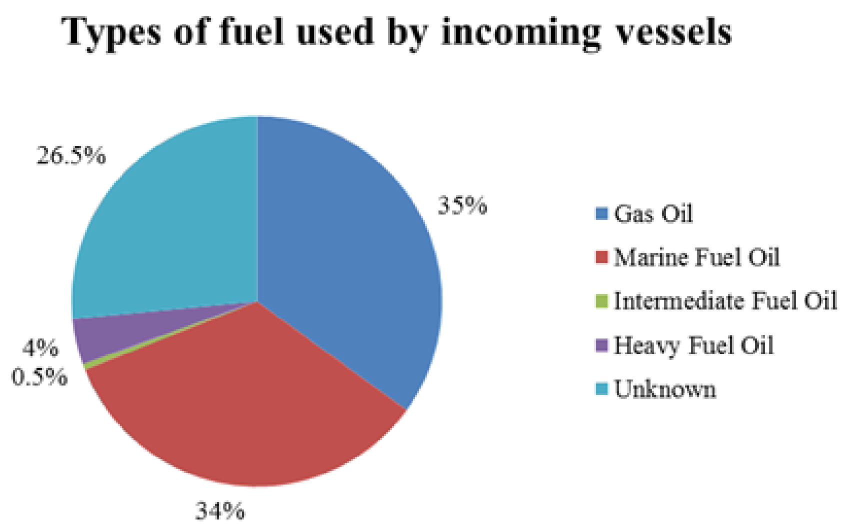

Figure 3. Fuel types used by vessels visiting the Port of Bergen.

Tier I emission factors

Emission type	Fuel type	Value	Unit
NO_x	HFO	79.3	kg/tonne fuel
	MDO, MGO, IFO	78.5	kg/tonne fuel
CO		7.4	kg/tonne fuel
NMVOC	HFO	2.7	kg/tonne fuel
	MDO, MGO, IFO	2.8	kg/tonne fuel
SO_x		20*S%	kg/tonne fuel
PM_{10}	HFO	6.2	kg/tonne fuel
	MDO, MGO,IFO	1.5	kg/tonne fuel

$PM_{2.5}$	HFO	5.6	kg/tonne fuel
	MDO, MGO,IFO	1.4	kg/tonne fuel

Table 5. Emission factors applied in aggregate emission calculations, Tier I. Based on *International maritime navigation, international inland navigation, national navigation (shipping), national fishing, military (shipping), and recreational boats,* by Trozzi and De Lauretis , 2016.

In case of Tier II emission category, the values for NO_x, PM_{10} and $PM_{2.5}$ are directly related to the type of engine installed. Hence, for the main engines the average revolutions per minute (RPM) value was calculated, which then indicated the assumption of high-speed diesel engine to be applied to all vessels. Also, the same assumption for all auxiliary engines was made by default.

Slow-speed diesel	Medium-speed diesel	High-speed diesel	Average calculated (based on 385 engines)
up to 300 RPM	300-900 RPM	over 900 RPM	1036 RPM

Table 6. Engine types based on revolutions per minute (RPM). Adapted from *Eco-Efficient Transport Interim report: Overview of potentials for an increased eco-efficiency in maritime shipping,* by Schippl and Edelman, 2013.

Tier II emission factors

Emission type	Fuel type	Value	Unit
NO_x	HFO	55.6	kg/tonne fuel
	MDO, MGO,IFO	55.1	kg/tonne fuel

CO		7.4	kg/tonne fuel
NMVOC	HFO	2.7	kg/tonne fuel
	MDO, MGO,IFO	2.8	kg/tonne fuel
SO_x		20*S%	kg/tonne fuel
PM_{10}	HFO	3.8	kg/tonne fuel
	MDO, MGO,IFO	1.5	kg/tonne fuel
$PM_{2.5}$	HFO	3.4	kg/tonne fuel
	MDO, MGO,IFO	1.3	kg/tonne fuel

Table 7. Emission factors applied in aggregate emission calculations, Tier II. Based on *International maritime navigation, international inland navigation, national navigation (shipping), national fishing, military (shipping), and recreational boats,* by Trozzi and De Lauretis , 2016.

For the rest of the emission types: SO_x under SECA regulations, NMVOC and CO, Tier II emission factors are the same as for Tier I for each fuel type.

Worth pointing out is the fact that emission factors applied in the study apply only to marine internal combustion engines operating on diesel fuel. What is more, no distinction was made between emission factors for main propulsion and auxiliary engines as such and this because, from a technical perspective, there are not expected to exist any significant differences between marine engines emission profiles for regular propulsion versus auxiliary engines (EPA, 2000; Marin, 2012).

Summing up, in order to aggregate emissions from all vessels visiting the Port of Bergen between January 2005 and July 2015, the following methodology was applied:

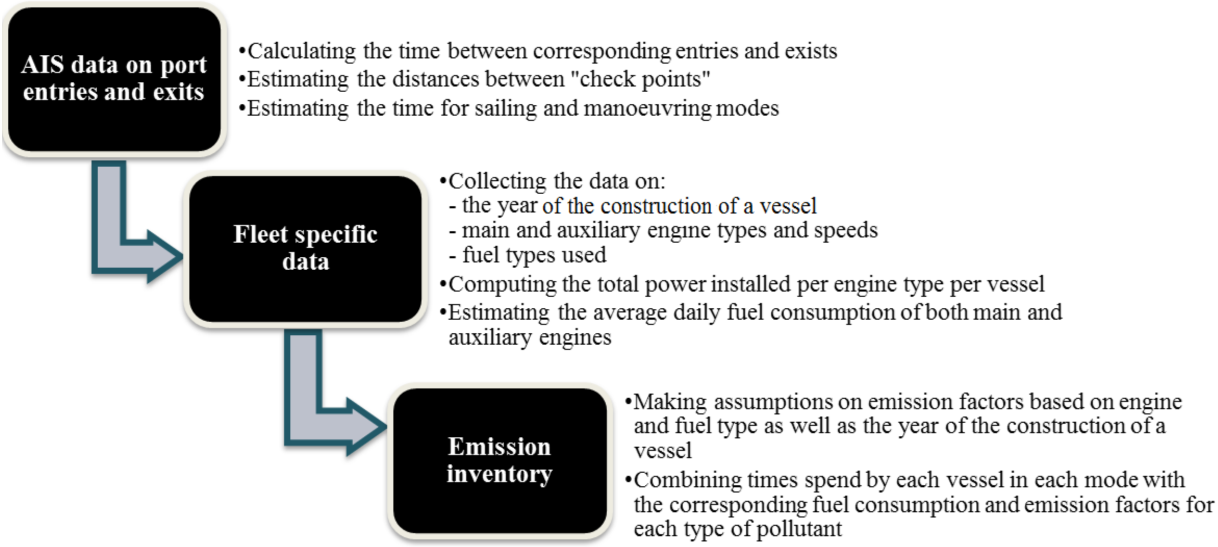

Figure 4. Description of the procedure for study conduct.

5. Empirical findings

In line with the terrestrial AIS data received from the Norwegian Coastal Authority (Kystverket), 400 different vessels visited the Port of Bergen from February 2005 until July 2015. Yet, due to the lack of available ship specific data in the Clarksons World Fleet Register, 389 vessels were taken into account and analyzed in this study. These 389 vessels combined visited the port 4,887 times throughout the whole period, with the total number of hours spent within the port area (here, understood as an area within which AIS data collection occurred) equal to 441,343. This in turn translated to an average length of a visit of about 3.76 days. Finally, all entry records indicating ships passing by the port were excluded from the analysis.

In the figure presented below, it can be observed that the year 2013 was characterized by the highest number of port calls (666), with the years 2012 (602) and 2009 (591) following suit. Worth to mention here is that in 2009, the North Sea PSV market experienced the second lowest daily spot rates of 6,095 GBP (with the lowest rates of 4,160 GPB in 2015). What can also be taken from the figure is the percentage change in the number of port visits. There can be noticed a peak between year 2007 and 2008, which coincided with the biggest drop in the PSV daily spot rates. It is then followed by a drop up until 2010 and more stable values from 2011 on. Important to note is that for this study, for the years 2014 and 2015 the data available were limited to June and July respectively. Therefore, there is a limited extent to which these two years were covered in the analysis. Also, in order to present the trend in the number of port calls per year, the total values for these two years were computed based on the previous years by applying Compound Average Growth Rate formula, which for the year 2014 as an example can be written as follows:

$$CAGR_{2014} = \left(\frac{Total\ number\ of\ port\ calls\ for\ 2013}{Total\ number\ of\ port\ calls\ for\ 2005}\right)^{\frac{1}{9}} - 1$$

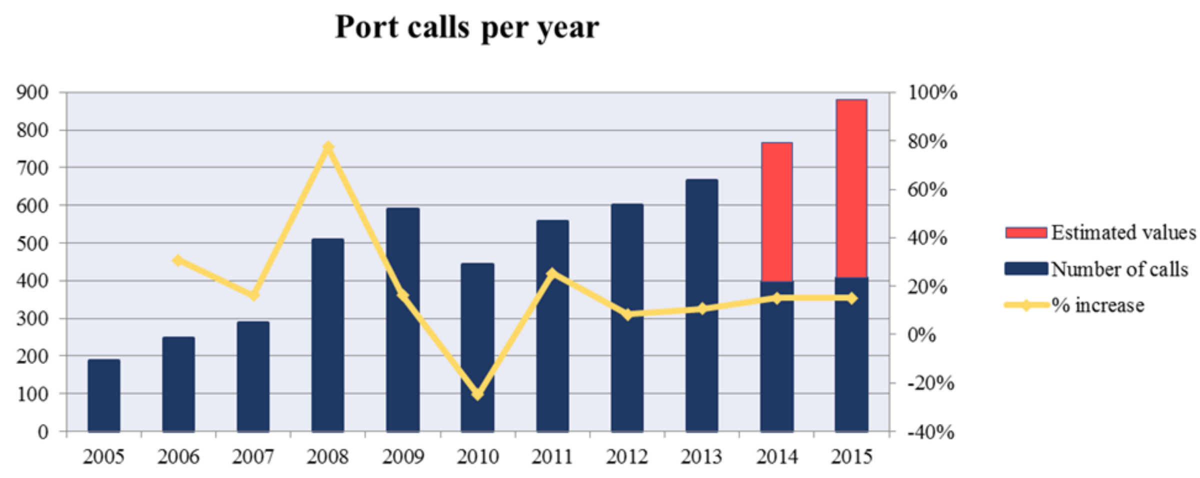

Figure 5. Number of port calls per year.

More detailed, monthly analysis of port calls revealed that by far the highest number of calls (100) took place in January 2014. Due to the missing data for January 2005, the average number of port calls for this month for all other years was taken, excluding the outlier of 100 for the year 2014. Based on this assumption, during the period of 11 years, January takes the second place based on the average number of port calls, with December having the most numerous visits. This would, to some extent, correspond with the seasonal trend in the daily PSV spot rates, which, in case of each analyzed year, tend to exhibit the lowest values around the beginning of the year. Still, when looking at the separate values for port visits, July and August are months which most often had the highest number of calls.

As the next step in the analysis of the findings from this study, an overall examination of seasonality for the period 2005-2013 was performed. For this purpose, two time series were studied: a monthly number of port calls as well as a monthly average duration of a port call. The statistical analysis of both autocorrelation function (ACF) and partial autocorrelation function (PACF) was conducted in order to discover the degree of similarity of both time series with their lagged versions over the following time intervals. As presented in the figures below, neither for the number of port calls nor for the average time spent in port any statistically significant seasonality was discovered. This is evidenced by the lack of regular peaks in the intervals corresponding to the same months as well as the fact that in each case the calculated values of autocorrelation as well as partial autocorrelation stay within the area of low correlation (marked in each figure in grey).

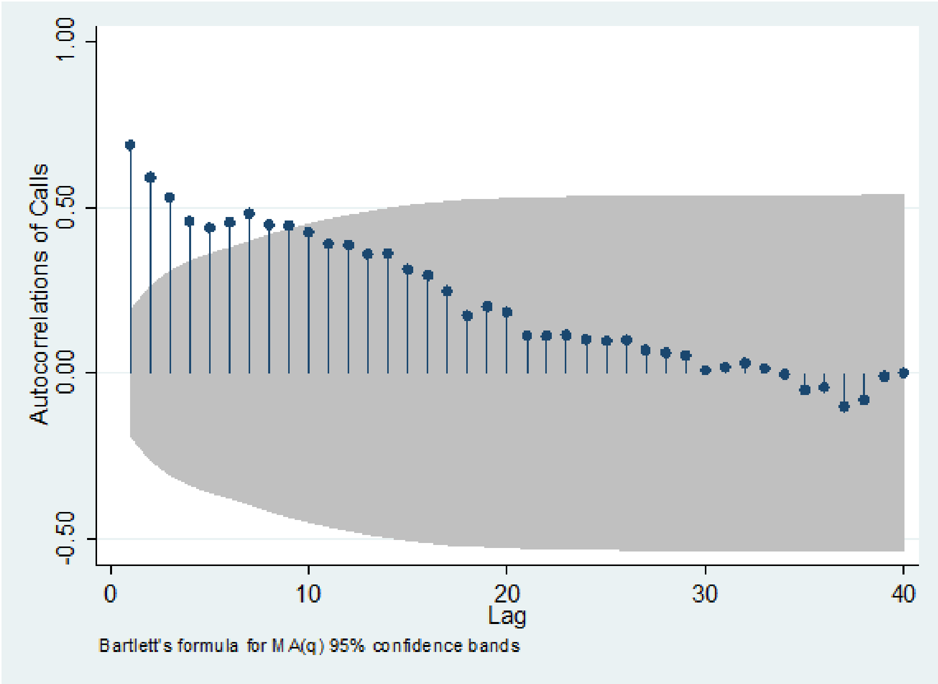

Figure 6. Autocorrelation function (ACF) for the monthly number of port calls.

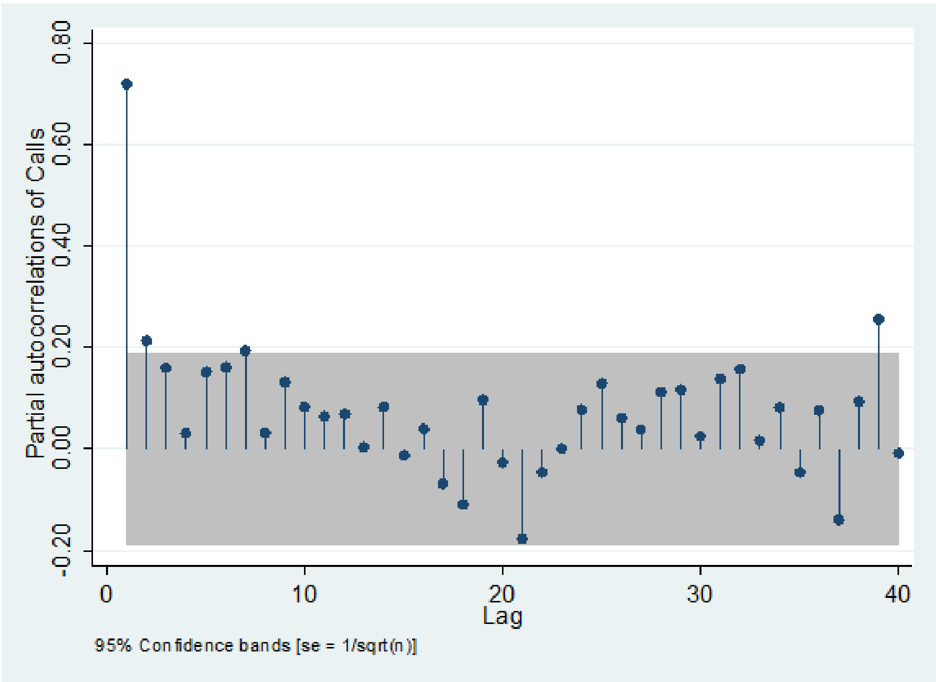

Figure 7. Partial autocorrelation function (PACF) for the monthly number of port calls.

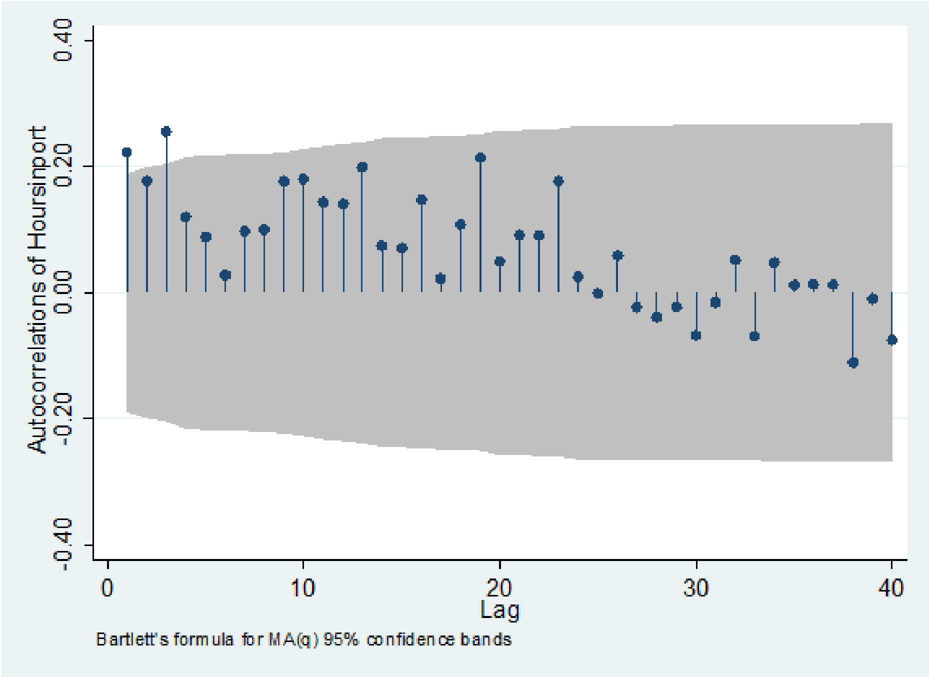

Figure 8. Autocorrelation function (ACF) for the average number of hours in port per port call.

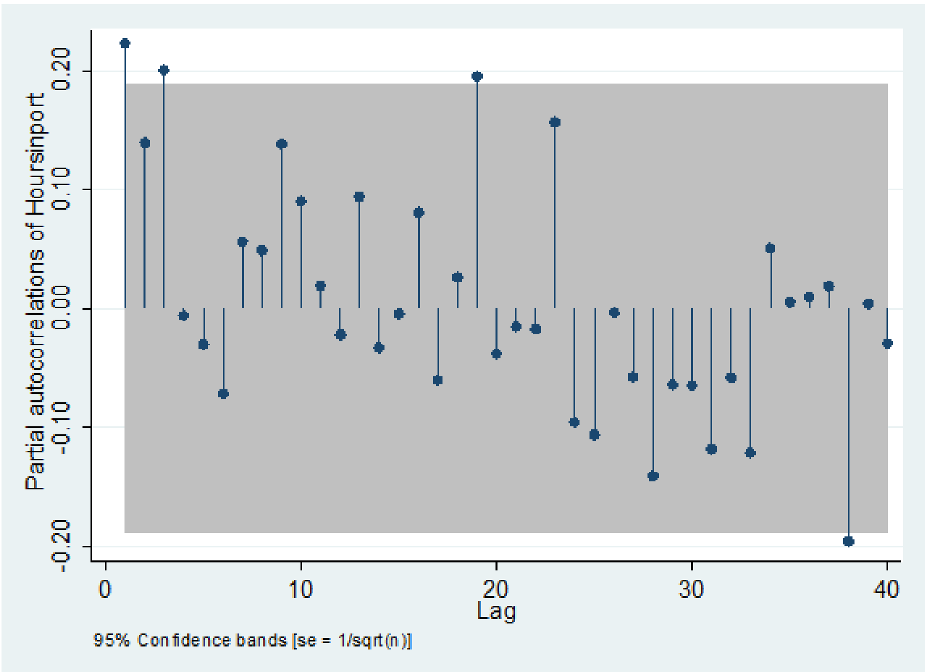

Figure 9. Partial autocorrelation function (PACF) for the average number of hours in port per port call.

When it comes to more detailed analysis of stays' duration, the values follow a different trend than the port calls statistics exhibits. While the highest growth in the number of vessels visiting the port took place between 2007 and 2008 (28%), the average duration of a stay actually decreased slightly. Again, while the years 2009 and 2013 dominated in the number of visits, the average stay was fairly short, between 3.2 and 3.9 days. Finally, when looking for similar patterns for both statistics, one can see that only 2010-2012 was a period when a similar increase in both port visits and their average duration was present.

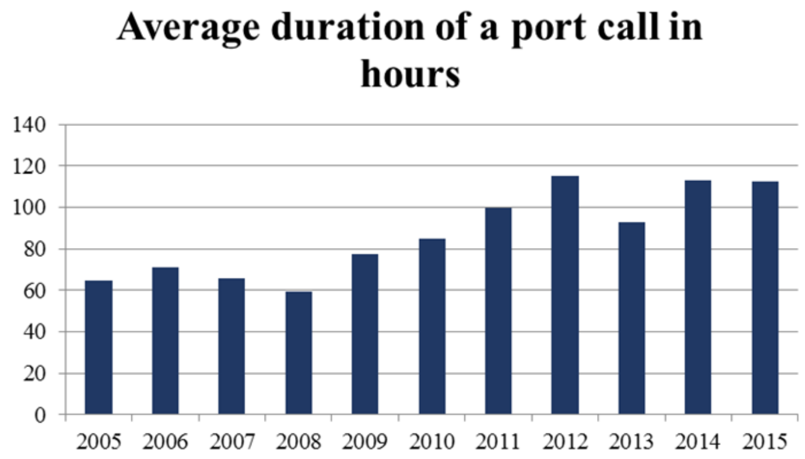

Figure 10. Average duration of a port call by year.

There could be put forward a hypothesis that, in general, the number of port calls and the duration of stays should be correlated with the situation prevailing on the offshore market in a given period. Comparing figures presented earlier in the chapter with the values for PSV daily earnings in the North Sea region, one can observe that indeed, when the rates began to fall with the beginning of the year 2010 and then again in 2013, there was also experienced an increase both in the number of port calls and the average stay duration.

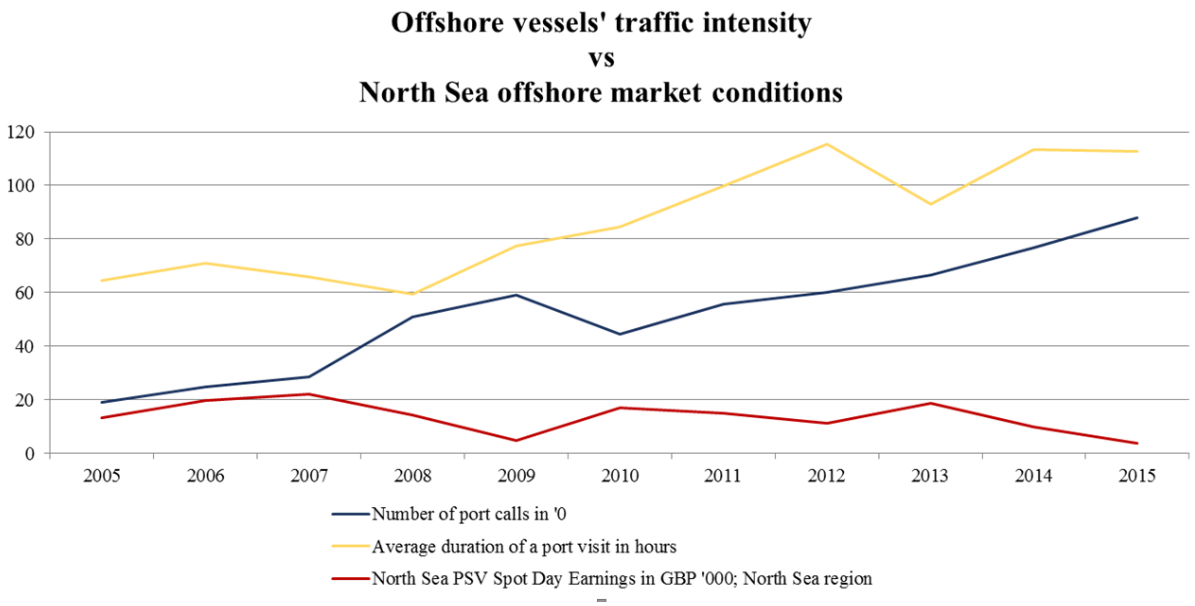

Figure 11. Comparison between the level of the traffic in the Port of Bergen and the offshore market situation in the North Sea region. Based on World Offshore Register by Clarkson Research Services.

Moving on to the analysis of the emission inventories, six different types of emissions released by vessels visiting the Port of Bergen, namely SO_x, NO_x, NMVOC, CO, PM_{10}, $PM_{2.5}$ were studied and their values aggregated.

The summary of the total values for each emission type, expressed in tonnes, is presented in the table below. Again, the values for the years 2014 and 2015 include only the period from January until June and July, respectively.

Emission type	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
SO_x	0.37	0.45	0.45	1.07	1.55	0.61	0.87	0.84	0.82	0.37	0.09
NO_x	98	131	141	304	454	259	351	331	335	165	238
NMVOC	3.4	4.5	5.0	10.6	15.9	9.0	12.6	12.1	12.5	6.5	9.0
CO	9.2	12.4	13.3	28.6	42.8	24.4	33.9	32.9	33.5	18.2	24.7

PM_{10}	2.5	4.0	4.1	7.5	10.7	6.7	7.9	7.2	7.4	4.1	5.6
$PM_{2.5}$	2.3	3.7	3.8	6.9	9.9	6.2	7.3	6.6	6.8	3.7	5.2

Table 8. Summary of emission inventories by the emission type.

What can be observed here is a considerable decrease in the amount of SO_x emissions in the year 2015 (even if only half of the year is considered), which was a direct result of the stricter policy regarding the allowed amount of sulfur included in the marine fuel. Furthermore, since the year 2012 there was a constant increase in the amounts of the rest of the emission types, with the values for 2015 forecasted to be higher than in the year 2009, which during the period of the nine full years studied dominates as the year with the greatest amounts of pollution released.

Comparing the values for the year 2010 with the corresponding results of the study by McArthur and Osland, we can see some significant differences, with the values for NO_x, PM_{10}, $PM_{2.5}$ over three times higher than the ones the authors arrived at in 2013. This mismatch in findings can be ascribed mainly to the different emission factors applied in the calculations, which in case of McArthur and Osland were equal to 53.4 for NO_x, 2.4 for NMVOC, 1.562 for SO_x, as well as 0.7 and 0.665 kilograms per tonne for PM_{10}, $PM_{2.5}$ respectively. Also, the size of the fleet and the number of calls under analysis could have been different, since in the journal paper from the study, there is only mentioned the total number of analyzed calls and this including all types of vessels visiting the port in 2010.

Finally, it is worth to have a closer look at the values of the emissions released at each mode of operations. As we can see in the table below, on average, hotelling was responsible for over 50% of all pollution emitted in the analyzed area. This result is in line with the findings of the study conducted earlier by Maragkogianni and Papaefthimiou (2015), in whose case, with only two modes of operation included, hotelling accounted for 88.5% of all emissions, while manoeuvring for 11.5%. Then, in our study, also the shares in total emissions for each of the three modes were very similar for each emission type.

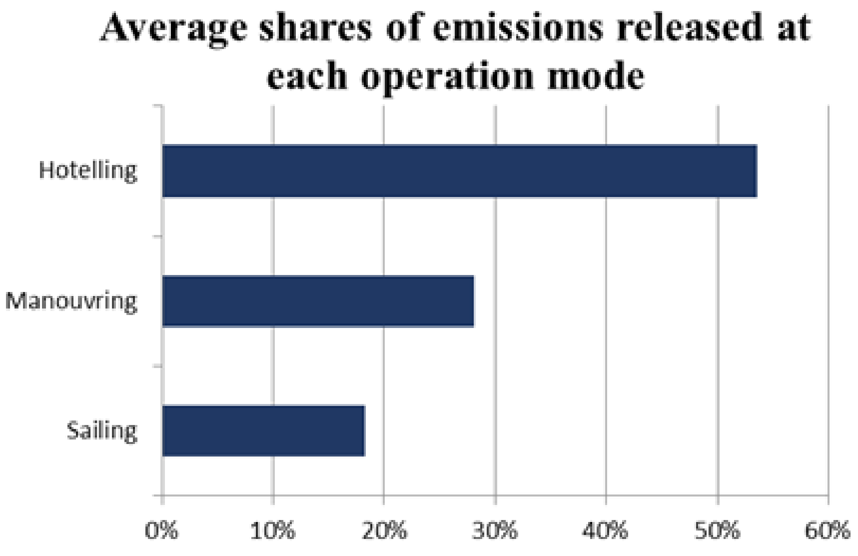

Figure 12. Average contribution of each mode of operation to the total emissions released by vessels in the studied period.

6. Discussion

6.1 Offshore vessel versus passenger car emissions

As it was presented in the previous chapter, the values for almost all emission types except So_x were either increasing or stable around their high levels in the last couple of analyzed years. This could be ascribed to low oil prices translating into decreasing returns and fewer contracts in the offshore market. The market ended up being oversupplied with vessels and the daily spot contract rates for the OSVs reached the bottoms, the situation which has been lasting now for the time longer than anyone could have expected. This all combined became a reason for more and more vessels visiting the Port of Bergen more frequently and for a longer period of time causing the emission levels pertaining to ship operations go up. Still, in order to assess whether there exists an urgent need for measures aimed at curbing the impact of the offshore fleet to be taken by the Port Authorities, it is worth to add to the values of emission inventories presented earlier an additional perspective.

In the past, there were made some comparisons between the levels of emissions released by offshore vessels and passenger cars, which stated that, on average, a PSV emits as much pollution per day as 4,800 cars do (Haga, 2014). Yet, according to the main findings derived from the meteorological simulations and the corresponding scenario analysis prepared by Wolf at al. (2016), NO_2 and $PM_{2.5}$ released by road traffic present in the city center of Bergen have much bigger influence on the pace of air quality deterioration than the equivalent emissions ejected by four cruise ships and twenty five supply vessels at berth.

In order to be able to better assess these two findings, together with the aggregation of the emissions from vessels, a brief comparison study was conducted, in which also the pollution caused by cars travelling to and from the city center area (bounded in this case by Sandviken toll ring station from the north and Damsgårdsveien toll ring station from the south) was estimated. The assumptions on the number and the type of cars in the area were based on the information collected from the Statistics Norway (SSB) database as well as the Transportation Department of Hordaland Municipality. Finally, the emission factors in grams per mile were obtained from the report “Updated Emission Factors of Air Pollutants from Vehicle Operations in GREETTM Using MOVES" released by the Argonne National Laboratory.

The aggregate yearly car emissions of NO_x, CO, PM_{10} and $PM_{2.5}$ in the period 2005-2013, compared with the values pertaining to the offshore fleet in the same period yielded the following, average results:

NO_x	The total emissions released by the offshore fleet were **3838** times higher than the emissions caused by passenger cars travelling to and from the city center area
CO	The total emissions released by the offshore fleet were **36** times higher than the emissions caused by passenger cars travelling to and from the city center area
PM_{10}	The total emissions released by the offshore fleet were **3140** times higher than the emissions caused by passenger cars travelling to and from the city center area
	The total emissions released by the offshore fleet were **3133** times higher than the emissions caused by passenger cars travelling to and from the city center area

Table 9. Summary of the comparison between the average aggregate emissions released by offshore vessels and passenger cars in the period 2005-2013.

When looking at the values in the table above, it can be easily observed that except for CO emissions, the pollution levels the vessels are responsible for are way higher in comparison to passenger cars, especially when taking into account the fact that the number of cars registered by the two toll ring stations was during each analyzed year over 120 times higher than the number of port calls. What is more, if we bring into the picture policy measures like increasing the number of toll rings and fees for travelling within them as well as raising taxes for cars emitting the highest levels of NO_x and CO_2 the national government and the local authorities have recently been focusing on, taking further steps in order to curb emissions released in the port area seems to be a reasonable and, especially looking at the problem from the long-term perspective, a necessary strategy. Existing regulatory policy on shipping pollution as well as different kinds of emission abatement solutions that have also proved successful in case of other harbors and that the Port as well as the local authorities in Bergen might want to examine in more detail are presented in the next section.

6.2 Shipping pollution regulations in brief. Alternative, port-based solutions for abating emissions at berth.

In the face of a trade-off between technology-based and performance-based solutions, shipping industry has gradually been implementing regulatory measures with the aim of limiting the environmental footprint and the impact maritime transport has on the air quality. When it comes to Norway, the country follows closely both international regulatory regime as well as the requirements developed within the EU structures under the European Free Trade Association EEA Agreement. What is more, the current focus of the Norwegian Maritime Authority is placed on developing regulations on Exhaust Gas Cleaners (Scrubbers) as well as measures preventing a transfer of alien organisms via ballast water and sediment from ships (necessary actions to be taken as a result of the Ballast Water Convention entering into force in 2017). At the same time, in case of offshore vessels, a general interpretation of existing regulation might pose some difficulties, especially due to the problems with the distinction between passenger and cargo vessels, for which very often different rules apply. To exemplify this, one can recall SOLAS, which, while widely regarded as the most important international treaty on the safety of merchant ships, does not make any direct reference to OSVs.

When focusing specifically on the recent policy measures aimed at curbing pollution, two examples, though still not fully applicable to offshore vessels (until 1 July 2019) can be recalled: The Energy Efficiency Design Index (EEDI) as well as the Ship Energy Efficiency Management Plan (SEEMP). The EEDI is a technical measure, which estimates vessel's energy efficiency on the basis of ship's emissions, capacity and speed and sets a specific threshold in grams of CO_2 per capacity mile (for instance tonne mile) according to a type and a size of a vessel. The lower the value of the EEDI, the more energy-efficient a ship is and the lower the harmful impact it has on the natural environment. Ship Energy Efficiency

Management Plan (SEEMP) on the other hand aims at achieving highest energy efficiency scores by providing entities managing vessels with certain approach schemes and best practices as well as monitoring measures. Both programs are estimated to reduce global shipping-induced emissions by the average 330 million tonnes each year by 2030, which will translate into savings of around USD 310 billion for the whole shipping industry (IMO, 2011). Moreover, as a consequence of all the above, estimated in 2011 relative ratio of the demand for heavy fuel oil to gas oil of 80/20 is until 2030 expected to reverse (Norwegian Shipowners' Association, 2014).

Among other, alternative solutions to the shipping pollution problem discussed and debated on both by the IMO and the European Commission are restrictions on vessel's speed when approaching the harbor as well as an international fund that would set up a structure and targets for an international shipping emission reduction plan. The idea of the fund is not new and follows a successful example of Norway, which, by signing the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone in year 1999, committed itself to make additional efforts to cut NO_x emissions. In order to achieve this, in 2008 15 business organizations representing the Norwegian shipping industry established the so called "NO_x Fund". The Fund operates on the non-profit basis and is financed by payments made by participating enterprises (11 NOK per kilo NO_x for the offshore industry, 4 NOK for other sectors like aviation, fishing, shipping, supply-vessels etc.) with the fees working as a replacement for NO_x taxes on the national level (Johnsen, 2013).

Additionally, there has also emerged a set of voluntary initiatives for curbing emissions related to shipping in the areas where the official regulations are not yet in place. For example, The Maritime Singapore Green Initiative (MSGI) established in 2011 is a voluntary program of the Maritime and Port Authority of Singapore (MPA) with a view to incentivizing the implementation of SO_x abatement technologies as well as driving a change towards a widespread implementation of liquefied natural gas (LNG) as an alternative source of maritime fuel. All vessels with the EEDI exceeding the requirements established by the IMO and equipped with the approved scrubber solutions get their Initial Registration Fee reduced by 75% and Annual Tonnage Tax cut by 50% ("MPA's Maritime Singapore Green Initiatives, RCN-MPA MOU Meeting", 2013).

Then, in case of the Port of Hong Kong and the Port of Shanghai, the regulation from April 2016 binds all the berthing vessels to use for all their engines and machinery on board fuel oil with sulfur content not exceeding 0.5% mm. Also European ports, including Oslo, Hamburg, Bremerhaven, Amsterdam and Rotterdam decided to offer port fees reductions based on the outstanding NO_x, SO_x and CO_2 emissions cuts. Here, especially active in terms of emission abatement projects are ports of Rotterdam and Amsterdam, both belonging to the World Port Climate Initiative, the union of fifty five world's key ports under the auspices of the International Association of Ports and Harbors, whose aim is to reduce the threat of the global climate change by means of joint measures. Only in 2015, the Port Authority of Rotterdam decided to grant the vessels scoring high on the WPCI's own Environmental Ship Index around EUR 2 million in bonuses. Here, worth to note is the fact that also The Port of Bergen introduced in 2016 a discount on port fees for ships achieving good scores based on the ESI. As of September 2016, 114 different ships arriving at Bergen Port were allowed to pay lower fees, with a half of them getting 20% reduction and another half 50% one.

In Norway, there is currently to be observed a national focus placed on shore power, especially due to the fact that since 2015 vessels arriving at the EU ports have been obliged to either use fuel with the maximum level of sulfur at 0.1% or connect to the grid onshore. This is a regulation Norway follows closely also internally. In the Port of Bergen such a land-based solution was introduced as the world's first installation of this kind compliant with international standards for the shore power. Its pilot phase was launched in January 2015, which coincided with an implementation of new, stricter rules related to the level of particulates PM_{10} and $PM_{2.5}$. In June 2015, a solution providing 60Hz, with option for both 440V and 690V, was provided at Skolten terminal and made available to supply ships mooring at Bergen docks (in the past, 35 shore power connections were provided to smaller vessels, including speedboats). As for the pricing strategy, the initial charge of NOK 1/kWh (excluding VAT) was introduced, coupled with preferential port fees for the lowest-emitting vessels (Port of Bergen (BOH), 2015).

For Bergen, providing shore power to hotelling vessels is a part of a bigger project aiming at a full electrification of the harbor. Only the installations available now cost as much as 7.5 mln NOK. At the same time, for existing vessels to adapt to the electrical shore side connection the investment of around NOK 500,000 is required (Stensvold, 2014; Andersen, 2015). So far, there has been three ships using the available facilities: Skandi Vega owned by DOF as well as two Solstad Offshore vessels: Normand Prosper and Normand Ranger. What is more, two additional ships for which Bergen is a frequent port of call are currently undergoing modification giving them the access to the shower power at berth. According to the information provided by the Port Authorities, as of September 2016 shore power solution was in use 101 out of 284 days. Furthermore, a new shore construction able to accommodate offshore vessels is currently being built in the Hurtigruten terminal (BOH, 2016).

Despite the unfavourable offshore market situation in the last couple of years as well as a rejected application for the 185 mln NOK financial support for the development of the shore power solution, which the port submitted to Enova[2] in February 2016, all mentioned above might imply the beginning of a positive trend both for the industry and the Port of Bergen. According to the estimates, the expansion of the land-based electricity connection will allow to reduce by up to 95% over 70% of all SO_x, NO_x and PM emissions generated in the port, which offshore vessels as well as cruise ships are together responsible for (Schneider Electric, 2016).

Concluding, while more and more attention has been placed on the emissions derived from ship transport by the regulatory agencies, there still exist areas, including offshore vessels sector, where measures are not yet properly defined or enforced. This leaves room for voluntary actions to be undertaken by ports, which should aim at preserving the air quality both in the harbor and the neighboring areas. Taking into account a strategic position of the Port of Bergen on the North Sea offshore market as well as its increasing traffic, the Port Authorities may be willing to introduce more stringent regulations or adopt any other, alternative, incentive-based measures presented above, which would in turn encourage ship owners and operators to consider more closely and keep in check the environmental footprint their vessels are responsible for.

[2] Enova is a public enterprise aiming at promoting efficient energy consumption and sustainable energy generation. It is owned by the Ministry of Petroleum and Energy and disposes of funds allocated to the Energy Fund (enova, n.d.).

7. Limitations

As every study, also this one is to certain extent burdened by limitations that a reader should be aware of. Firstly, one of the most often named limitations regarding AIS data-based studies is the reliability of the data itself. Also in case of this study, some of the entries had to be excluded due to the very high level of unreliability (multiple port entries in the very short period of time with no exit records etc.). Secondly, despite the availability of the detailed AIS data, there had to be taken certain data processing steps which allowed to fill in existing gaps and inconsistencies. These included among others missing data for the second half of both 2014 and 2015 as well as inconsistent port entry and exit times. What is more, since information on fuel type was missing for 108 vessels, the assumption on the fuel of higher quality has been made, which in turn might have led to an underestimation of sulfur emissions. Moreover, despite the fact that there exist some studies confirming that emission factors differ considerably under different operating modes (Winnes and Fridell, 2010; Fu et al., 2013) and different load conditions (Petzold et al., 2010), the factors applied in the study have the same values for each of the two components. This assumption was made due to the lack of specific data and while in case of large and regional scale studies it should not pose any significant accuracy problems, when used in aggregating air pollution in more local areas, as it is for the Port of Bergen, it tends to yield mixed results (Zhang et al., 2016). Furthermore, the values for emission factors are very much correlated with the existing, available technology and hence tend to vary from year to year (Huskotte and Denier van der Gon, 2010). Therefore applying the same emission factors for different years for all the emission types except SO_x might have negatively influenced the accuracy of the results.

Finally, in case of vessels staying at berth, boilers are responsible for a large portion of the overall fuel consumption. Still, they tend to have emission factors lower than main and auxiliary engines due to installed scrubbers (Hulskotte and Denier van der Gon, 2010). Therefore their impact was excluded from the study. Also, the performance of the visiting fleet under specific weather conditions and their influence on the emission inventories was not taken into consideration.

Then, in order to arrive at more accurate results, the real-life measurements of vessel speed, fuel consumption as well as engine loads should be included in the calculations, especially taking into account the fact that the estimations for engine loads vary considerably from study to study with some research using 20% loads under manoeuvring condition while others 1%. This usually leads to the results for aggregate emissions spanning across the large scale. Worth to point out here is also the fact that the uncertainty related to the load factors for main engines was reported by the IMO as one of the two most crucial parameters influencing the confidence level for the bottom-up emission estimations (IMO, 2014).

Concluding, it is important to remember that this study is based on a number of assumptions either own or based on the findings included in the earlier works on the subject. Hence, the results carry a certain level of uncertainty that should be taken into consideration.

8. Conclusions

The main focus of this thesis and the accompanying study was placed on finding the aggregate values for six type of emissions released by offshore vessels visiting the Port of Bergen. The approach outlined was based on the bottom-up, fleet activity-based analysis, where each port call was considered separately. The information on the characteristics of each individual vessel that visited the port within the analyzed period of eleven years was collected, including engine specific data as well as fuel type used (which, taken together, largely dictate ship's emission levels). This was later on matched with the specific entry/exit AIS data and combined with the distinction between three different modes of operation and the application of different emission factors for different regulatory policies. The procedure allowed to arrive at the detailed results, which were then aggregated in order to draw certain conclusions from monthly/yearly amounts of pollution emitted to the atmosphere by the offshore fleet. Finally, some of the necessary assumptions made throughout the process were backed by the information gathered during the in-depth interview with Mr. Ståle Eikeland, General Manager Maritime at Swire Seabed, a subsea company, which had its fleet visiting the port frequently during the years 2005-2015.

The final result of the emission assessment procedure shows that since the year 2010 the amounts of pollution released by the offshore fleet in the port area either increased or kept stable on relatively high levels. This situation is most probably related to fewer contracts for vessels due to the long-lasting, unfavorable situation present on the offshore market that might not reverse any time soon. The finding, combined with the increasing concern about the deteriorating air quality, especially in the port cities, seems to call for more action from the side of the Port Authorities, who might consider taking further steps going beyond the existing shore power project. These in turn would not only assure lowering the contribution of the Port to the air pollution present in the city center of Bergen but also positively impact the health of inhabitants of the areas nearby.

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