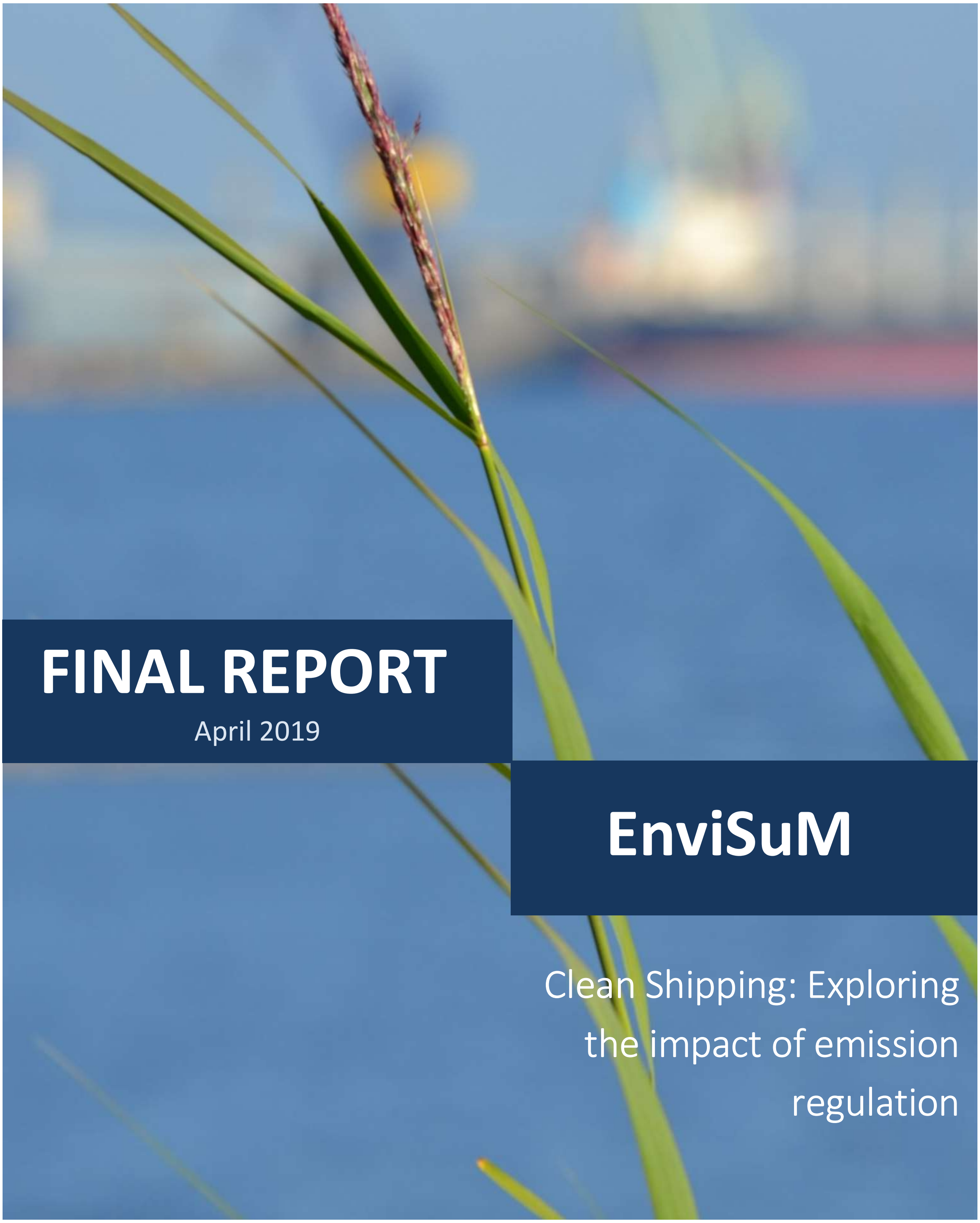

FINAL REPORT

April 2019

EnviSuM

Clean Shipping: Exploring the impact of emission regulation

Interreg Baltic Sea Region

EnviSuM

EUROPEAN UNION

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INTRODUCTION

Informing the debate

The environmental impact of the maritime industry has been under much public discussion, culminating in 2015 when regulations limiting sulphur content from shipping vessels came into effect in the Baltic Sea.

Since then, the maximum sulphur content of fuel used by all ships navigating the Sulphur Emission Control Area (SECA) must be no more than 0.1 per cent. Up-to-date information on the technical efficiency and socio-economic impacts of different clean shipping solutions and their capacity to comply with the regulations, however, is currently very limited.

In order to develop future environmental regulations, policy makers and authorities need more knowledge. The shipping industry also needs to make informed investment decisions. To allow for knowledge-based decision making, discussions are needed involving maritime authorities, policy makers, NGOs, and the private sector.

Our approach

We have answered questions on the shipping industry's compliance with environmental regulations, examining the technical efficiencies of different techniques for removing pollution from exhaust gases. We have also explored the cost-effectiveness of various compliance measures used across the industry.

Modelling methods have enabled us to assess current and future compliance costs as well as look at the effects on public health and the environment. We have taken a closer look at three cities in the region to spread best practice on air quality measurement and modelling at a local scale. We have provided analysis to make recommendations that will improve the welfare of the people of the Baltic Sea Region.

For environmental regulation to be effective, compliance needs to be monitored and non-compliance needs to be sanctioned. We have also presented findings on compliance levels and reflect on the attitudes of ship-owners responsible for meeting the regulations.

The project aims to support maritime businesses and economic growth. Clean shipping solutions provide the potential for businesses to innovate. The development of clean shipping technologies leads to spin-off enterprises and allows European industry actors to lead the way in global markets. The Baltic Sea Region is a forerunner in this respect, acting as a living laboratory for clean shipping.

The effectiveness of SECA was analysed by comparing the costs and benefits of the regulation according to a framework presented in Lähteenmäki-Uutela et al. (2018). As part of this work, we have developed a free web-based economic decision-making tool to help companies estimate investment costs and decide what investments to make to comply with SECA regulations.

In addition to promoting technological development and improving future regulation, we have been active in sharing the results with the wider community. Finding ways to meet the increasing demand for improved air quality will ultimately bring economic opportunities as well as wellbeing for the people of the region.

This report

First, in **Chapter 1**, we look at different emission abatement strategies including measurement results from different types of vessels. This section also presents results on the effects of switching fuels, the modelling used to measure ship emissions and compliance monitoring.

In **Chapter 2**, we explore air quality based on emission results. Local air quality was modelled for three urban areas - Gothenburg, Gdansk/Gdynia and St. Petersburg.

The effects of shipping emissions on public health and environment are assessed in **Chapter 3**.

In **Chapter 4** we discuss the economic consequences of SECA. This includes costs as well as positive effects of SECA, such as inducement to innovate and the enhanced reputation of the Baltic Sea Region.

We conclude in **Chapter 5** by looking to the future environmental shipping regulations.

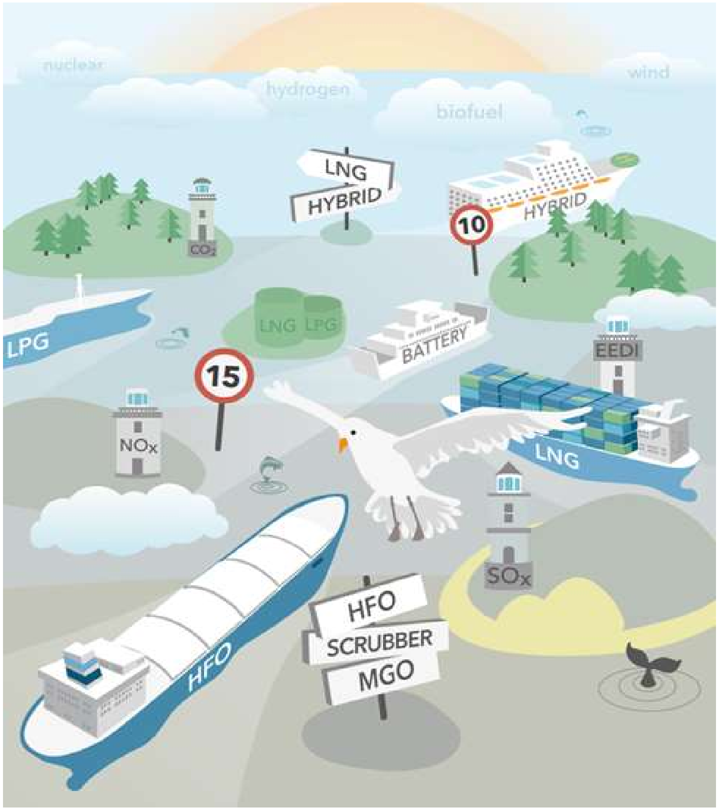


Image source: DNV-GL

Interreg Baltic Sea Region EnviSuM

CHAPTER 1

EMISSIONS AND ABATEMENT STRATEGIES

Stricter environmental regulations in 2015 demanded sulphur emissions from shipping were reduced to 0.1 per cent from 1 per cent. These limits are prompting rapid change within the global shipping industry and have increased interest in new fuels and energy efficiency measures.

Limits set within Emission Control Areas (ECAs) can be met either using additional machinery on board, such as scrubbers or catalysts, or by employing a different fuel to power engines. This could be marine diesel oil (MDO) to meet SO_X emission limitations, or liquefied natural gas (LNG), which complies with both SO_X and NO_X emission limitations.

Under existing exhaust regulations, ship-owners are required to choose their own method of being compliant. Gas-fuelled engines are expected to become an important substitute for diesel engines and the utilisation of dual-fuel engines as a solution for lowering emissions appears particularly promising.

The measurements resulting from this work formed the starting point of the project and the findings were used as the basis for further analysis of economic and environmental effects of emission regulations.

Liquid Natural Gas

The increased availability of lower priced and environmentally-friendly LNG makes it attractive to ship operators seeking to reduce operating costs.

International policies and regulations, as listed below, have a key role in the development of LNG use in the maritime industry

1. IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).
2. IMO Interim Guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships MSC 285(86) (IGF Interim Guidelines)
3. International Association of Classification Societies Unified Requirement M59: Control and Safety Systems for Dual Fuel Diesel Engines.
4. IMO International Code of Safety for Ships using Gases or other Low-flashpoint Fuels – IGF Code.
5. Classification Societies Rules for Gas Fuelled Ships.
6. ISO Guidelines for systems and installations for supply of LNG as fuel to ships.
7. ISO Standard Installation and Equipment for Liquefied Natural Gas – Ship to shore interface and Port.

Ship management using LNG

LNG technology requires substantial changes in ship management and onboard practices. These need to be implemented strategically, to address issues as diverse as environmental compliance, class compliance, safety, reliability, operating efficiency, maintenance planning (control and cost), resource allocation and spare parts management.

Engine room management addresses following key issues

- objectives and safety analysis
- arrangement of hazardous areas and spaces
- gas-fuelled engines and systems
- gas storage and bunkering arrangements
- gas piping systems
- access, airlock and pressurization
- ventilation systems
- control systems
- electrical equipment
- gas detection systems
- testing and trials

LNG performance

The environmental performance of LNG as a marine fuel was analysed using a lifecycle approach known as “well-to-wake” (WtW) (Figure 1.1). This allows the main greenhouse gases associated with LNG, namely CO_2 and CH_4, to be evaluated.

A range of parameters was used to describe the entire lifecycle of a particular fuel type and is usually expressed as CO_2 equivalent emission, per unit of supplied energy (CO_{2eq}/MJ). Ship operators and engine makers frequently refer to the Tank-to-Wake (TtW) emissions that occur during fuel combustion and this includes the aspect of engine efficiency.

LNG-fuelled engines are currently available for a range of propulsion, power and speed demands such as four-stroke medium speed engines, as well as two-stroke, slow speed and large bore options.

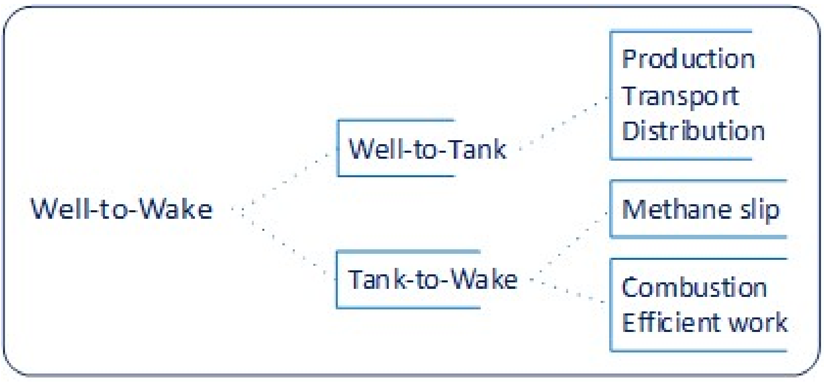


Fig. 1.1 Marine engine LNG life-cycle analysis structure.

The exhaust emission of a diesel engine is affected mainly by design and operational adjustment of fuel injection assembly and compression ratio. Another factor is scavenge uniformity - the way in which remnants of gas remain in parts of the engine cylinder after it is flushed (scavenged) post-combustion. The combustion process is specifically identified by quantitative values, such as indicated mean effective pressure, maximum pressure.

LNG engines can either be gas-fuelled engines powered exclusively by LNG or dual-fuel that switch between MDO or HFO and LNG. Dual-fuel operation can be maintained with low and high-pressure gas admission systems (Figure 1.2). Combined high-pressure gas injection and diesel pilot flame, dual-fuel engines represent a particularly efficient utilisation of LNG.

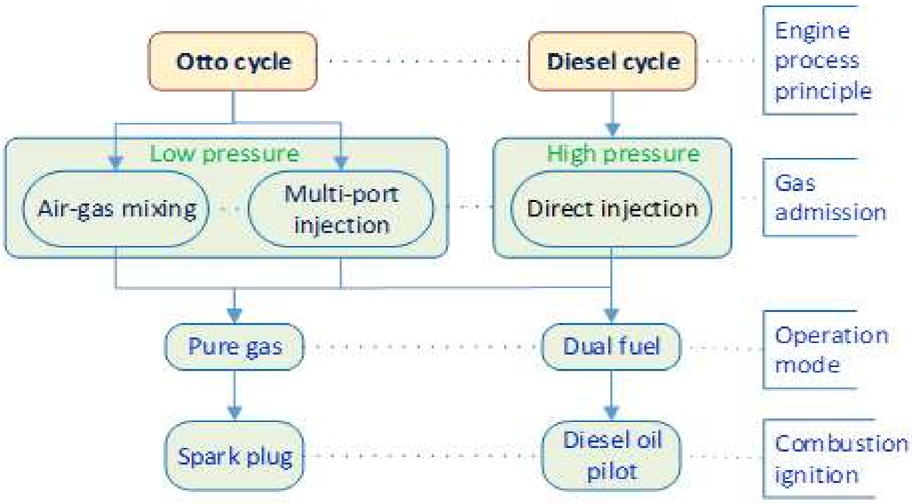


Figure 1.2 Engine concepts for LNG fuelled ships.

Due to the different combustion characteristics of natural gas compared to MDO fuel, a dual-fuel engine cannot safely achieve the replacement rates of diesel fuel at low or high rated loads and still achieve satisfactory performance at the same time. By optimising engine combustion and gas admission, however, these extremes can be fine-tuned to achieve the better performance.

Dual-fuel and gas engines can comply with the MARPOL Tier III limit if the lean-burn operation is achieved, which will reduce significantly NO_X emissions. Further details on MARPOL limits can be found in the Notes section at the end of this report.

Gas energy combustion efficiency is similar to a diesel engine, but due to the lower ratio of carbon per energy content, LNG combustion is associated with lower CO_2 emissions. LNG use is also fundamentally cleaner with respect to emissions of particulate matter.

Downsides of LNG

Most popular contemporary LNG engines with premixed lean-burn combustion processes have two major flaws- methane slip and abnormal combustion, called knocking.

Methane slip is the emission of unburnt gas and can be divided into two categories

- operational emissions
- engine emissions.

Operational emissions occur under certain operating conditions when methane may vent into the atmosphere. Emissions occur throughout the supply chain from the shipping terminal all the way to combustion in the engine, for example through leaks in pipe connections, couplings and so on. There may also be minor methane releases during refuelling operations, as well as during storage on land and ship.

One of the main sources of engine methane slip is thought to be flame quenching inside dead volumes, around a combustion chamber or inside a boundary layer near a cylinder wall. In addition, crevices in the engine combustion chamber, cold cylinder liner walls and the scavenging process also have a big impact on methane slip.

In high-pressure dual-fuel engines methane slip may be considered negligible. In low pressure dual-fuel engines, however, methane slip is a major challenge. Given the impact of methane on global warming is much higher than that of CO_2, the existence of methane slip in LNG engines may reduce their ability to meet greenhouse gas targets.

The second major flaw in LNG engines is abnormal combustion, called knocking, where combustion runs in an uncontrolled manner and causes pressure to increase rapidly in the combustion chamber. It results in a shock wave, which leads to vibrations in the engine body.

Several design and operational factors can cause knocking but a crucial influence is the air-fuel (gas) ratio that has be controlled within a narrow range. Engine knocking is a destructive phenomenon, which creates both mechanical and thermal load to main components of the engine. Direct effects of prolonged knocking on the engine can cause serious damage.

Engine types currently in service

One of the objectives of the EnviSuM project was to assess the energy and environmental performance of LNG-powered vessels. An analysis was carried out to identify the number of vessels and the type of engines currently in service that are fuelled by LNG.

There are 410 LNG-powered ships currently in operation and more than half - 240 - are tankers or combination LNG/LPG. Most of these ships have multi-engine main propulsion, making the number of engines 810 out of a total of 1274 units (Figure 1.3).

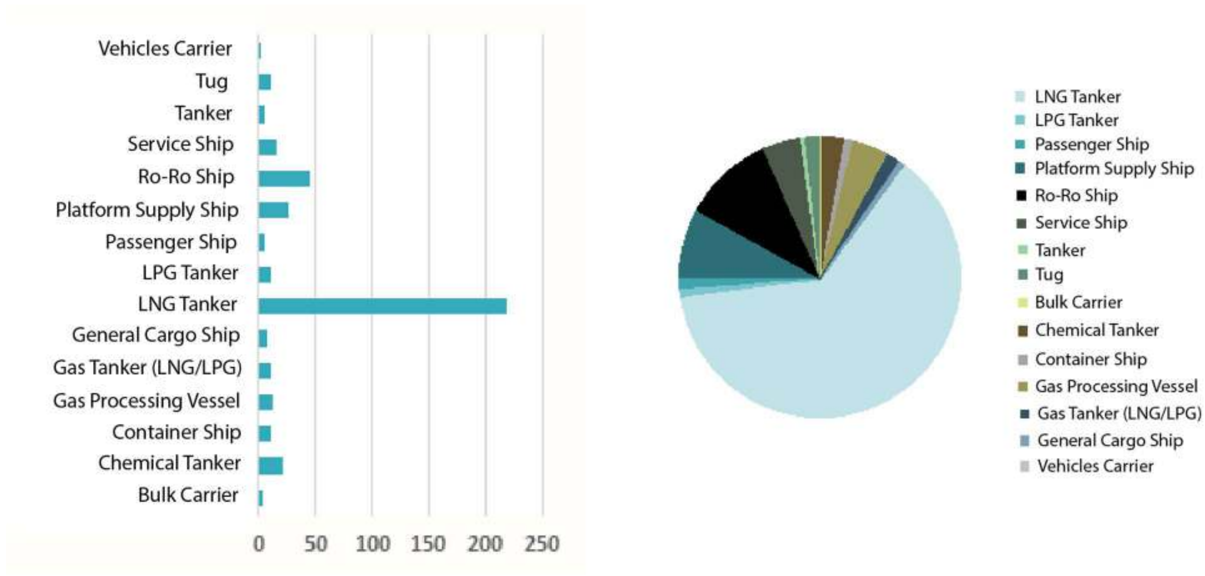


Figure 1.3 Number of LNG fuelled ships (left) and relevant engine amount distributions (right).

Similarly, Ro-Ro ships (Roll-on/Roll-Off) are equipped with multi-engine main propulsion systems, usually four-stroke, medium-speed engines.

Diesel-electric

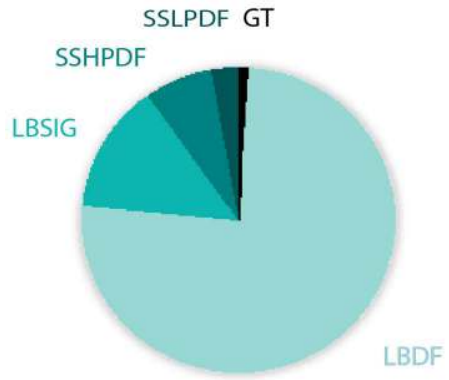
There has been a noticeable increase in the number of ships with multi-engine diesel-electric (D-E) propulsion systems. In general, the advantages of D-E propulsion can be listed as follows:

- Lower fuel consumption and emissions. Generators can run on high loads with high engine efficiency. This applies specifically to ships that have a large variation in power demand.
- Better hydrodynamic efficiency of the propeller. Usually D-E propulsion plants operate FPP-propellers via a variable speed drive.
- High reliability and multiple engine redundancy.
- Efficient performance resulting from high electric motor torques at low speed.

Further development in the area of electric power and dual-fuel engines is likely for a large number of ships.

The most common LNG engine

So far, the use of 4-stroke, medium-speed, gas and dual-fuel engines has been predominant - 1134 of 1274 units (Figure 1.4). Due to the method of combustion initiation there are two types of engines in this category - spark-ignited and liquid fuel pilot injection. The Finnish company Wärtsilä is the most common manufacturer, providing 840 units, as shown in Figure 1.4.



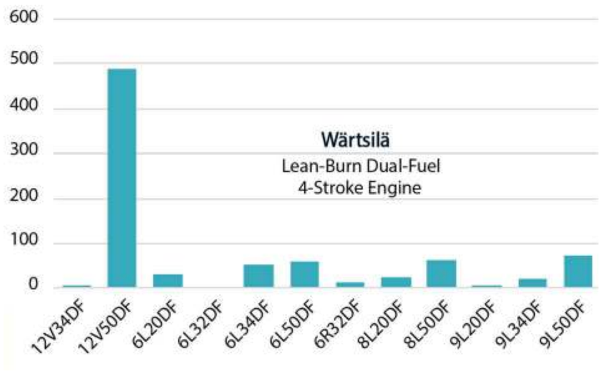


Figure 1.4 Quantitative relations of different types of LNG engines (left graph) and Wärtsilä dual-fuel engine family (right graph). Abbreviations: LBSIG (Lean Burn Spark Ignited Gas), LBDF (Lean Burn Dual-Fuel), SSHPDFD Slow Speed High Pressure Dual-Fuel), SSLPDF (Slow Speed Low Pressure Dual-Fuel), GT (Gas Turbine)

The 12V50DF engine was chosen for the EnviSuM measurement programme as the most representative of the entire dual-fuel engine population currently installed on LNG-fuelled ships. Sea service tests were conducted on a ship with a diesel-electric propulsion system containing four engines. An important aspect of the research was to determine the energy efficiency of the ship's main propulsion (Zahradníček 2018). As an example, Figure 1.5 presents a comparison of actual (service) specific natural gas consumption (SNGC) standardised to ISO conditions (including fuel LHV of 42 700 kJ kg), with the new ship performance (after the completion of construction - sea trial).

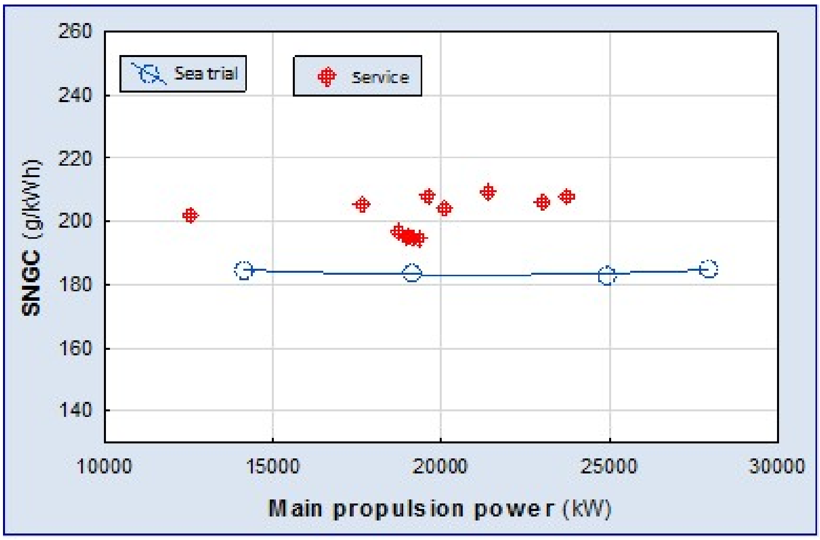


Figure 1.5 The comparison of specific natural gas consumption (SNGC) for LNG fuelled ship on a sea trial and at service.

There are currently no regulations regarding methane slip from gas engines and measurements of methane are not included in regulation and certification requirements. For LNG-fuelled engines, methane slip from incomplete combustion should be included when evaluating the total effects on greenhouse gases.

To obtain methane emission data from gas engines in operation, measurement tests were carried out on a testbed engine at a manufacturer's premises as well as on an engine standing in an industrial heating plant. Methane-specific emission factors were determined using measurements and calculations of fuel and emission data in accordance with ISO 8178 (Figure 1.6).

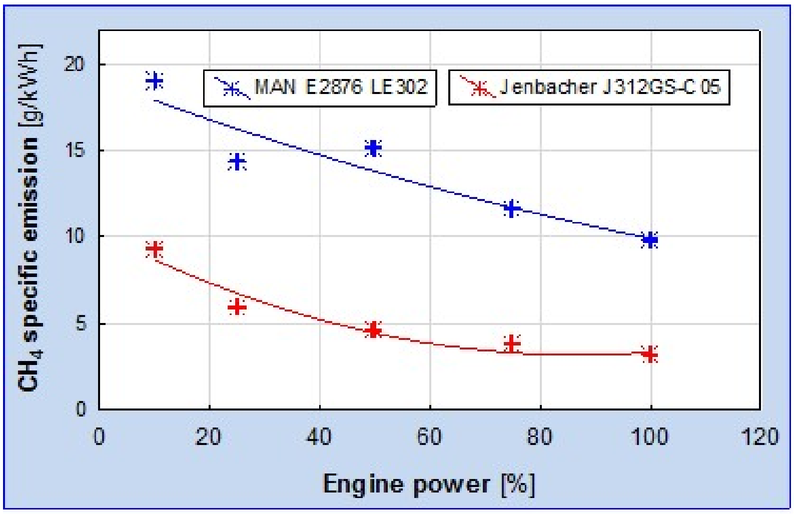


Figure 1.6 Methane specific emissions from spark ignited gas engines.

LNG - an easy solution?

The switch to LNG as an alternative fuel involves more than just ship arrangements and vessel specifications. It is a long process that requires significant investment in areas such as transport and supply of the fuel itself. Appropriate port infrastructure, especially LNG bunkering systems, is vital for the expansion of new technology. Currently, four different ways of vessel fuelling are used

- Bunkering barge, Ship-to-Ship (STS)
- Trucks, Truck-to-Ship (TTS)
- Shore terminal, Port-to-ship (PTS)
- LNG tanks containers loaded on board, Container-to-ship (CTS)

As of July 2018, there were only 15 ports in the SECA zone with onshore terminals for LNG bunkering, most of them on the North Sea coast. In the Baltic Sea Region (BSR) TTS technology remains most common. There are only a few ports with onshore LNG terminals: Hirtshals, Klaipeda, Pori and Stockholm (Table 1.1). On figure 1.7, we present the small scale of LNG infrastructure in the BSR.

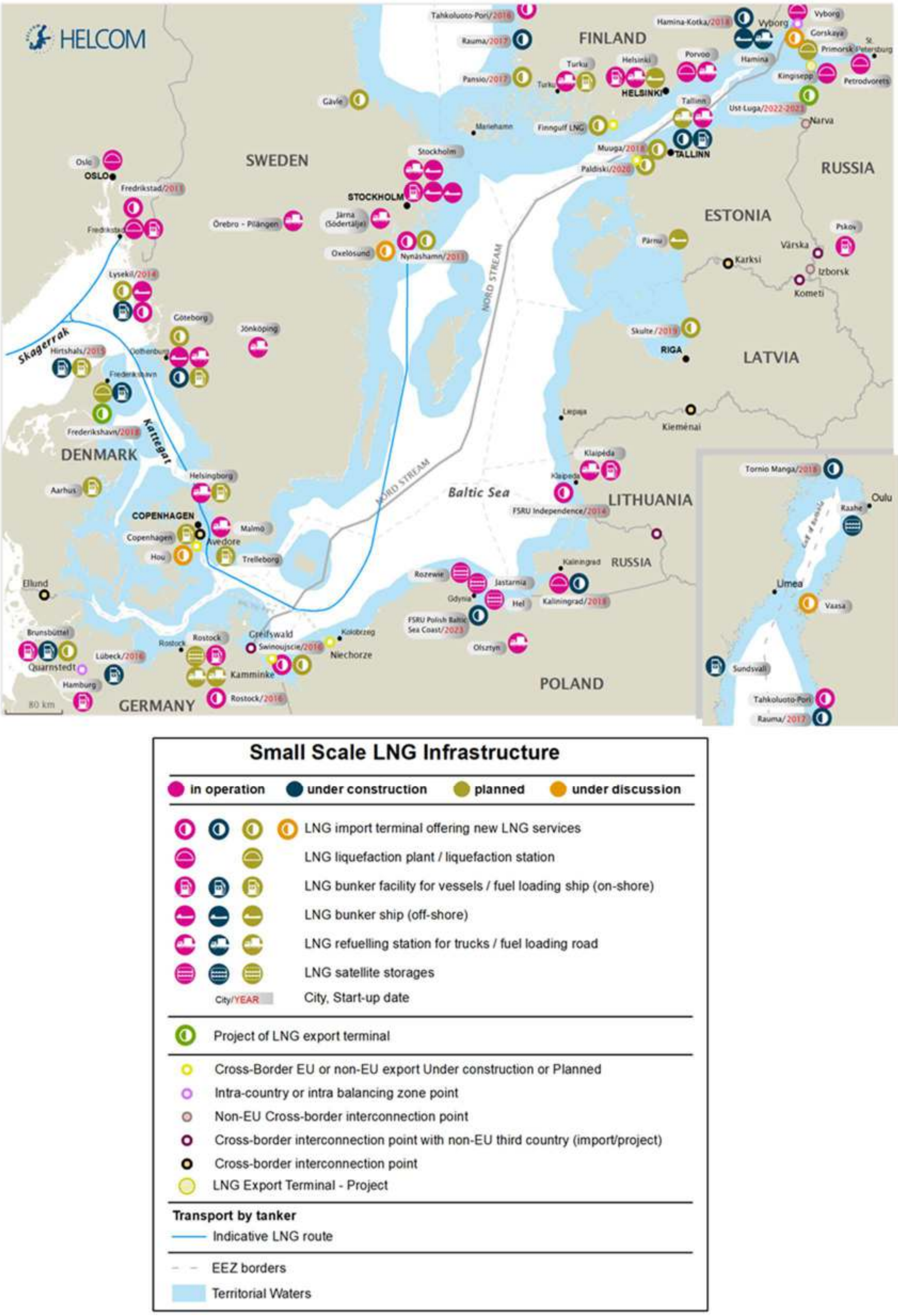


Figure 1.7 HELCOM map on the small-scale LNG infrastructure in the BSR. (Source: HELCOM report Alternative Fuels for shipping in the Baltic Sea region).

Table 1.1 List of ports in North-Baltic Sea SECA with LNG bunkering infrastructure. Source: DNV-GL

Port	LNG Tanks capacity [m^3]	Bunkering rate [m^3/h]	Truck loading rate [m^3/h]	Method	Bunker barge capacity [m^3]
Dunkirk	600.000	-	-	TTS, STS	
Zeebrugge	560.00	-	75	TTS, STS, CTS	5000
Isle of Grain	1.200.000	-	80	TTS, STS	
Rotterdam	720.000	-	100	TTS, STS	6500
Risavika	30.000	350	50	PTS, TTS, STS	5600
Hirtshals	500	210	-	PTS	
Nynãshamn	20.000	-	75	TTS, STS	167
Pori	30.000	300	50	PTS, TTS, STS	
Klaipeda	5.000	500	100	PTS, TTS	
Świnoujście	320.000	-	90	TTS	

Abatement technology - further options for emission compliance

Apart from switching from high-sulphur heavy fuel oil to LNG, there are two further options that enable ship operators to comply with emissions regulations. The first is the use of low sulphur fuels, such as ultra-low sulphur fuel or hybrids that the ship can use without making many changes.

The second option requires more significant financial investment and would entail the installation of technology that treats emissions after they have been made, known as scrubbers or catalysts.

Both methods have cost and energy implications that need to be considered for comparison with LNG. It is apparent that there are significant potential impacts on the WtW analysis of a given option when technology is adopted. If these impacts are not fully accounted for in an analysis, total emissions of the considered method will be underestimated.

Scrubber measurements

In order to gather information on the performance of exhaust after-treatment options, the particle composition, physical properties and concentrations of selected gaseous compounds were measured on a large RoRo passenger ship equipped with an open loop scrubber and a diesel oxidation catalyst (DOC). See Teinilä et al. 2018.

Measurements showed the scrubber reduced SO_2 from the exhaust gas effectively (more than 99 per cent) and the concentration of NO_x was slightly reduced. CO and volatile organic hydrocarbon (VOC) concentrations were reduced by the DOC, which was located before scrubber.

Particulate matter (PM) consisted mainly of sulphate, organics and black carbon (BC). During open sea cruising (with 65 per cent engine load), the major particulate measured after scrubbing was sulphate. At 17 per cent engine load, markedly lower sulphate concentrations were measured, as a result of lower engine temperature and reduced conversion of SO_2 to SO_3.

About one third of measured PM was organic matter and only about 4 per cent of PM was BC. At 17 per cent engine load, however, larger concentrations of black carbon were measured, which can be explained by the incomplete combustion when lower engine load is used (Fig 1.8).

The DOC reduced concentrations of measured metals and polycyclic aromatic hydrocarbons (PAH) in the particulate phase after the fuel has burned and smoke is produced.

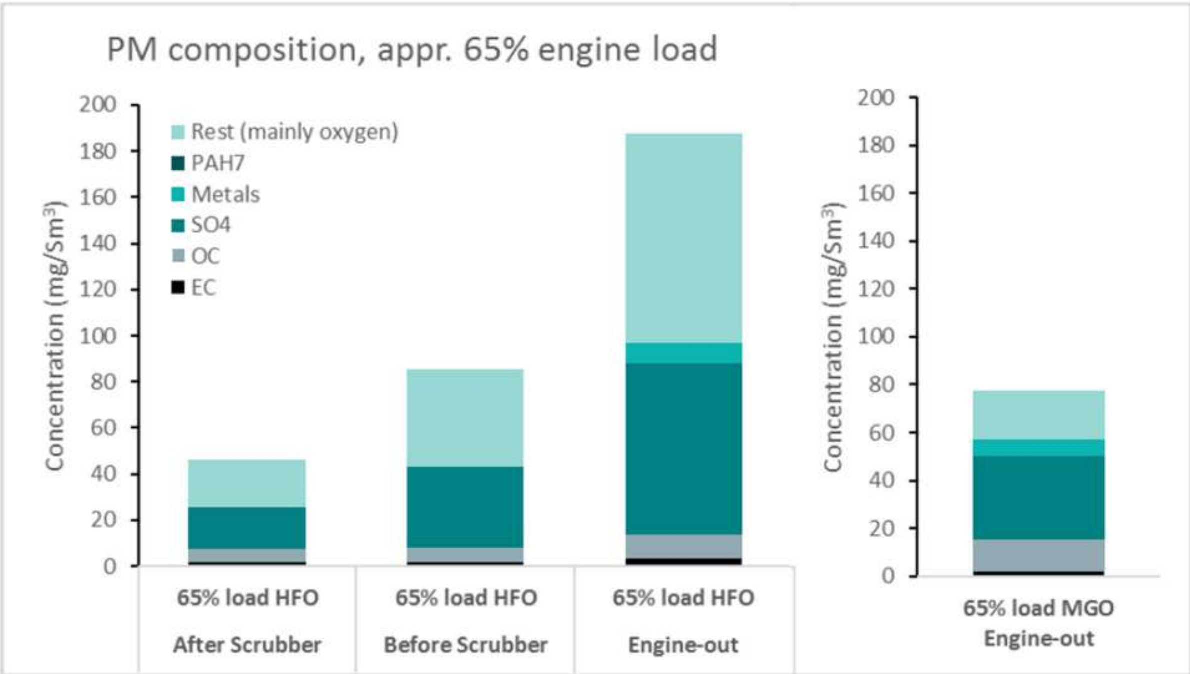


Figure 1.8 Chemical composition of primary PM emissions with and without SOx scrubber. PAH7 = Seven species of polyaromatic hydrocarbons, SO_4 = particulate matter sulphate, OC = Organic Carbon, EC = Elementary Carbon. Engine-out represents exhaust before any after-treatment, Before Scrubber is measured after DOC and After Scrubber is measured after DOC and scrubber.

The removal efficiency of a scrubber on primary PM was around 50 per cent at 65 per cent engine load. Gaseous sulphur components were effectively removed from the emissions, but some of the PM SO_4 remained.

The DOC effectively removed heavy metals from the exhaust by oxidizing these to metallic oxides (Fig 1.9). Also, VOCs were significantly reduced by the DOC, which reduces secondary particle formation in the atmosphere and helps to mitigate harmful impacts of PM on human health.

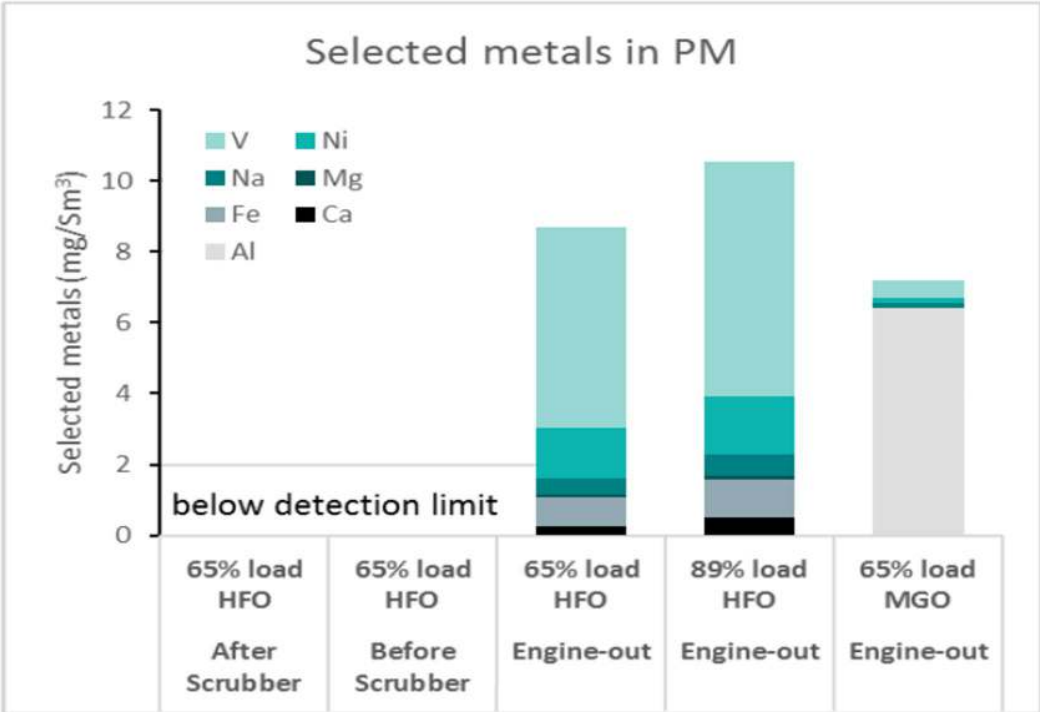


Figure 1.9 Emissions of various heavy metals in PM.

Additional power requirements, such as for pumping water and chemicals, were considered for scrubbers. It should be noted that scrubbers are not very efficient in primary PM removal, but they can reduce gaseous sulphur emissions, which contribute to secondary formation of particulate matter in the atmosphere.

Open loop scrubbers, however, use seawater to wash out air pollutants that are then released to the sea. Estimated volume of wash water released to the sea is roughly 600 million cubic meters, but it is difficult to estimate how many vessels in the Baltic Sea fleet will adopt scrubbers by 2030.

Switching fuel oils

The introduction of fuel sulphur content regulation has resulted primarily in changes to the way ship fuel systems are operated. The basic means of meeting the emission limits has been to use low sulphur fuels, including distillate and hybrid fuels.

Hybrid fuels have not been used in shipping worldwide before, but their share in the marine fuel market is expected to increase as an alternative to distillate fuels. Trials conducted on ships using hybrid fuels have been successful, encouraging ship-owners to use them.

New regulations require the proper maintenance of sulphur content in bunkered fuel. Therefore, any mixture of low sulphur fuel with high sulphur fuel must be avoided. Such requirements, together with the incompatibility of some grades of fuels, especially hybrid ones, mean the bunkering, storage and even supply of fuel systems must be adapted (Tuński 2019).

On existing ships, fuel system retrofit should reduce operating costs, even if the initial cost is high. Retrofitting, however, leads to changes in operational procedure. These pose additional challenges for the crew – when routines are broken, there is a higher risk of accidents. Appropriate training and familiarisation should be provided by ship owners, especially during the initial period.

The process of changing fuel inevitably brings some level of hazard, as the exact properties and compatibility of fuels is not fully known on-board and so the properties of the resulting blend can vary. There are a number of parameters that have to be observed and controlled at the same time: viscosity, temperature, pressure and engine load. Engine manufacturers recommend carrying out the change-over in a safe area, away from intense traffic and ports.

There are different risks when entering and leaving SECA. When switching to distilled/hybrid fuels, there is a risk of low viscosity, fuel leaks and filter blockage (Figure 1.10). When leaving SECA the highest risk is damage to fuel injection system components due to thermal expansion.

Figure 1.10 Heavily stained and blocked fuel filter of the fuel transfer pump.

The MARPOL convention requires vessels to use low sulphur fuel when entering SECA. That means the entire fuel supply system has to be flushed from high sulphur fuels in advance of entering the zone. The amount of time this takes varies depending on the fuel supply system volume, actual fuel consumption and sulphur content. Effective and safely executed fuel operations help to reduce the time and cost of flushing. The ship's crew can significantly contribute to the economic and environmental costs of this process.

All activities related to fuel oil management on-board, however, are very time consuming. This is an additional burden, mainly for engine crew, and the time sacrificed for fulfilling SECA regulations has to be derived from other routines.

Compliance monitoring

New, innovative, observational methods were applied in different locations in the Baltic sea to investigate the real-world emission of SO_2, NO_x and particles (PM, PN, BC), from ships in different modes of operation. From these measurements it was possible to calculate the fuel sulphur content (FSC) of ships and check if individual ships were complying with SECA limits. In addition, NO_x emissions in gram per kWh could be derived to check compliance with the future NECA standard coming into effect in 2021 in the Baltic Sea (Tier II and Tier III).

Measurements were carried out from fixed stations, harbour vessels and from an aircraft. The locations studied as part of the project are shown in Fig. 1.11 and correspond to Göteborg (fixed site Älvsborg), Gdansk/Gdynia in Poland (campaign) and St Petersburg in Russia (campaign). We also carried out an airborne campaign in the Baltic Sea, in the vicinity of Isle of Gotland. In addition to the main activities, some campaign measurements were carried out at Great Belt bridge, complementing fixed site FSC measurements by the Danish Environmental Protection Agency with particle and NOx measurements.

Fixed measurements in Götenborg and Great Belt, 2016-2018

Airborne campaign in middle of Baltic Sea September 2017

Campaign TriCity October 2017

Campaign St. Petersburg September 2018

Figure 1.11 Measurement activities carried out during the ship emissions study.

Individual ship measurements were compared with ship emission models run by FMI (STEAM) and MUS used for the air quality modelling in EnviSuM Project. From the measurements we also tried to investigate the effectiveness of new abatement and alternative fuel techniques, such as scrubbers, LNG and methanol.

The measurements are based on the ratio of various pollutants to CO_2 in individual ship plumes, using aircraft or measuring plumes as they drift across sensors on fixed stations or harbour vessels. In Figure 1.12 an example of several individual ship plume measurements is shown. It can be seen that the various pollutants (SO_2, NO_x, PM, PN, BC) correlate well with CO_2.

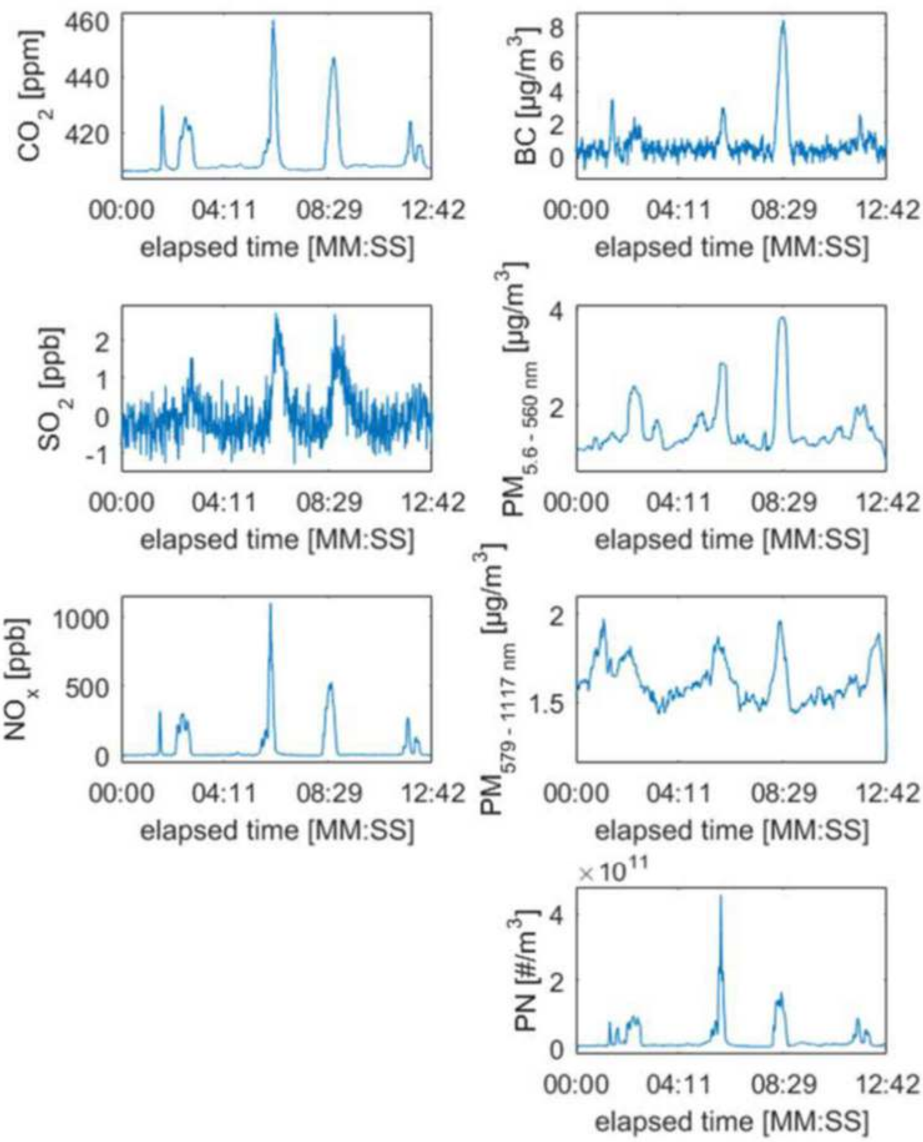


Figure 1.12 Emission factors in g/kg fuel are obtained for different species X from the ratio against CO2. This includes SO2, NOx, BC, PM and PN. Here an example of measurements is shown where each peak corresponds to a ship plume. From these measurements the emission factors in g/kg can be derived and g/kWh.

From these measurements the fuel specific emission factor is derived in g/kg_{fuel}, as well as the power specific emission factor in $g/kWh_{axial\ power}$. For the latter a fuel efficiency (specific fuel oil consumption) of 200 g fuel per kWh was assumed. The instruments used were based on UV-florescence (SO_2), chemiluminescence (NO_x), cavity enhanced laser spectroscopy (CO_2), electro-mobility (particles with size 5 nm to 500 nm, EEPS) and filter light absorption for BC for particles up to 10 µm. The technical approach is explained in detail elsewhere (Beecken et al., 2014; 2015, Mellqvist et al. 2017c,). The results of these measurements will be presented in a separate scientific paper (Mellqvist, 2019a, b).

The Table 1.2 shows how well individual ships comply with the EU sulphur directive. The EnviSuM data is compared to similar data from other sites in projects run by the Danish EPA and an EU CEF project CompMon.

Table 1.2. The main sulphur compliance results obtained in EnviSuM based on the IMO annex VI and EU sulphur directive. For comparison we also show some other sites with data obtained by the Danish EPA and within the EU CEF project CompMon using the same equipment.

	Time period	**Non compliance**	**Threshold**	**Ships**	**Project**
Göteborg harbor, inlet	2016-2017	1-2%	>0.18%	~8000	CompMon, Swedish EPA, EnviSum
Öresundbridge	2016-2017	1-2%	>0.18%	~150	CompMon
Great Belt bridge	2016-2017	5 %	>0.18%	~8000	Danish Epa, EnviSum
Denmark, near coast	2015-2016	6-8 %	>0.2 %	~1000	Airborne by Danish EPA
SECA border English Channel	Sep 2016	13 %	>0.2%	~75	CompMon
Middle Baltic Sea	Aug 2017	2 % 6%	>0.3% >0.15%	~112	EnviSum
Tri-city	Sep 2017	0 %	>0.18%	134	EnviSum,
St Petersburg	*Oct 2018*	*5 %* *3 %*	*>0.18%* *>0.3%*	*175*	*EnviSum*

As can be seen, EnviSuM data is compared to similar data from the Danish EPA (Mellqvist 2018) and the EU project CompMon (Mellqvist 2017a, 2017b; 2017c). The compliance rate in Göteborg and Gdynia was good (> 98%) while somewhat worse in St Petersburg, 95-97 %. In the middle of Baltic Sea the compliance rate was 94 %, which is comparable to measurements around Denmark and better than at the SECA border 87 %. In Figures 1.13 and 1.14 the fuel sulphur compliance measurements on two of the campaigns is shown with high FSC marked in yellow or red.

Figure 1.13 Shipborne Measurements of the Fuel Sulphur Content of individual ships in Neva bay, outside St. Petersburg. The limit for detected non-compliance is here 0.15%, taking into account the measurements error.

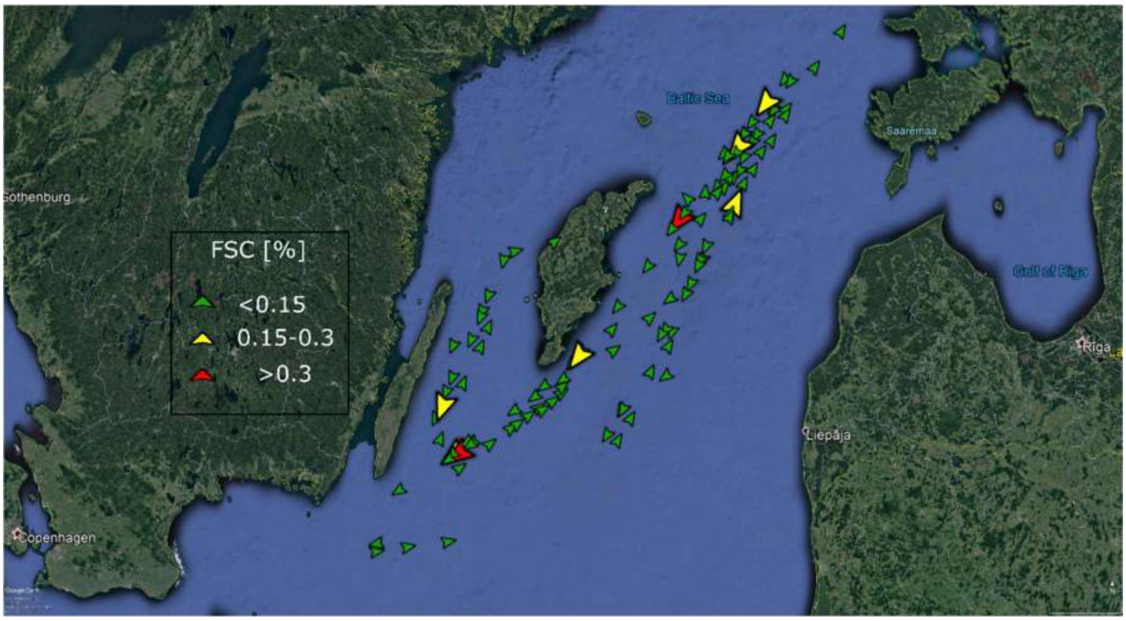


Figure 1.14. Airborne measurements of the Fuel Sulphur Content of individual ships in the middle of the Baltic Sea in Aug 2017. The limit for detected non-compliance is here 0.15%, taking into account measurement error.

In Fig. 1.15 to Fig.1.17 the emission factors of NO_x measured in Göteborg and Gdansk/Gdynia are shown. The data are shown in the units g/kg, g/kWh and as the ratio between measured g/kWh and Tier limit value (either I or II – see Notes section for more information about Tiers), based on when the ship was built. In addition are the emission factors shown for ships at berth and in operation. These measurements show that 10-20 % of the ships are above their respective Tier limits. The used methodology seems to be a useful tool for NO_x compliance measurements with respect to the introduction of the Tier III rules in 2021. However, it should be noted that the remote measurements are a snapshot of a certain engine operation mode while the IMO regulation states that the limit should be obtained as a weighted average of 4 engine operation modes with different engine load, with most weight on the 75 % load, for most engine types. A sensitivity analysis is therefore needed in the future to assess what uncertainties are created due to this fact.

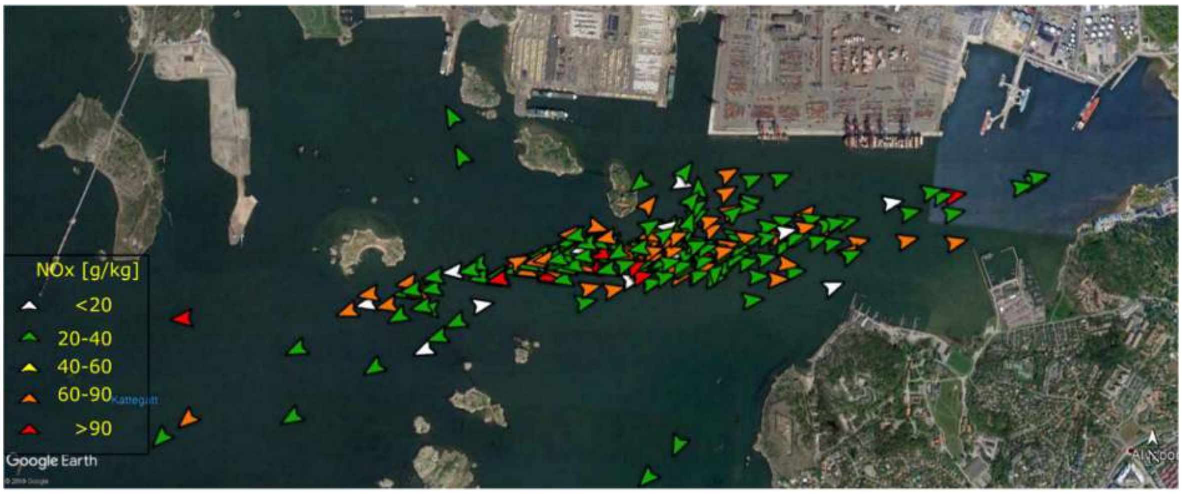


Figure 1.15. Fixed NO_x emission factor measurements (g/kg_{fuel}) at the Älvsborg site in Göteborg of individual ships.

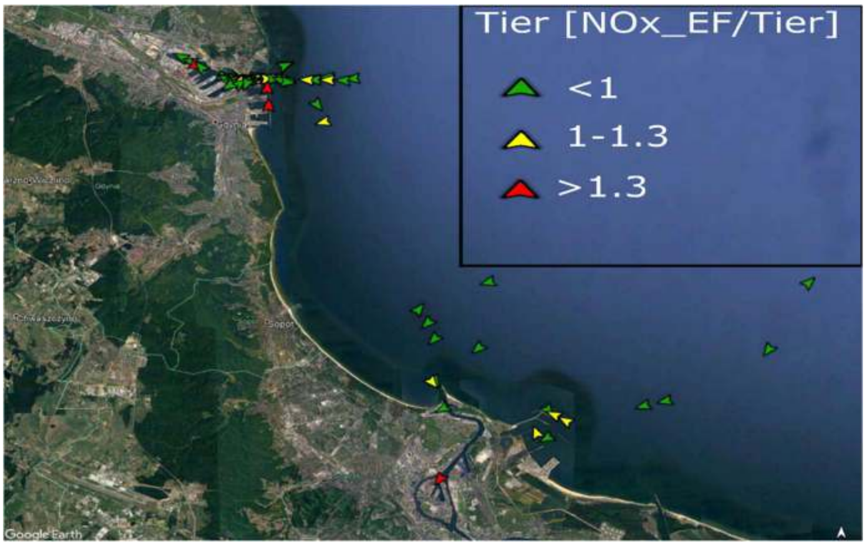


Figure 1.16. Shipborne NO_x emission factor measurements in g/kWh divided by the Tier I and Tier II limits for individual ships in the Tricity area. Red means 30% above the limit.

In Fig. 1.17 to Fig. 1.19 the emission factors of particles measured in St Petersburg and Tricity are shown. The data are shown in the units g/kg for both BC and PM0.5 (particles smaller than 0.5 µm). The data is divided into different ship types and are also shown as a function of ship speed. Here it can be seen that service ships, such as river barges, are dominant particle emitters and that the BC emission are reduced at higher speed on average.

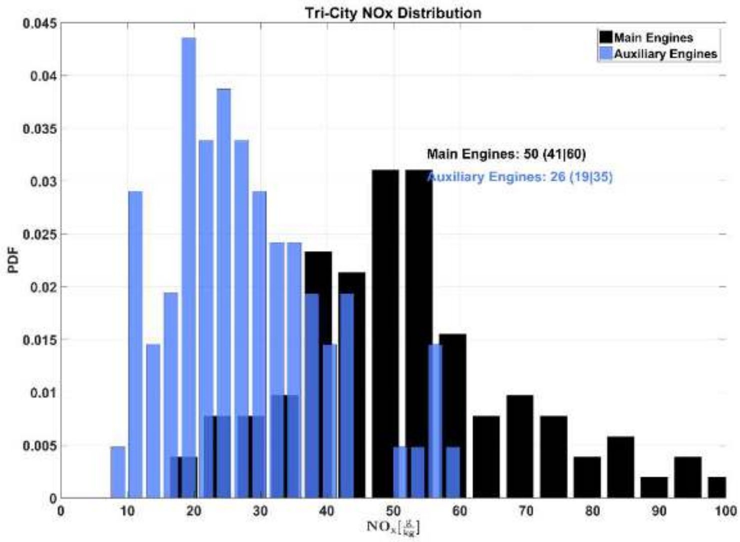


Figure 1.17. Shipborne NO_x emission factor measurements in g/kg for individual ships in the Tricity area, showing the probability density distribution for ships in operation (main engine) and ships at berth (auxiliary engine).

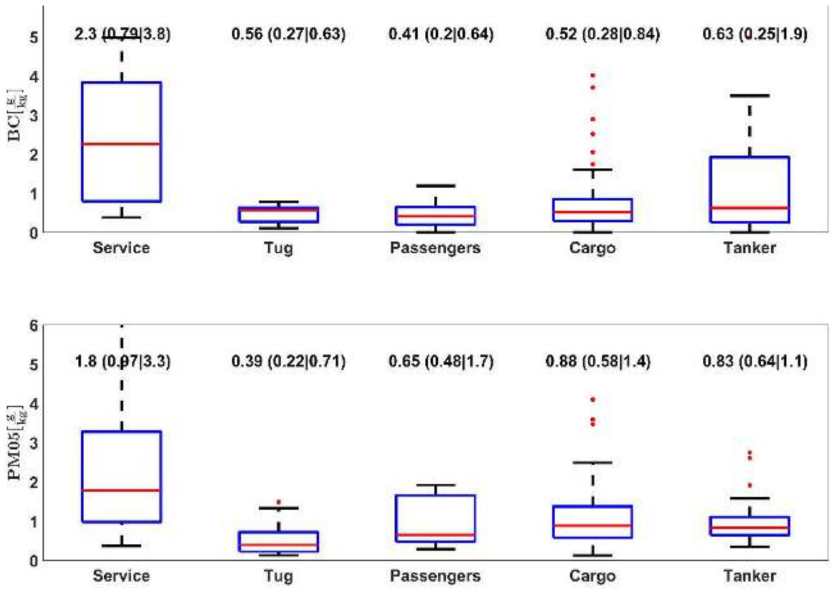


Figure 1.18. Shipborne particle emission factor measurements in g/kg of BC and PM_0.5 (diameter < 0.5 µm) in the St Petersburg area. The data is divided into different ship types. Service ships includes locally operating ships like river barges and pilots. The data correspond to median (red), 25th and 75th percentile (blue), 10th and 90th percentile (black) and outliers as red dots.

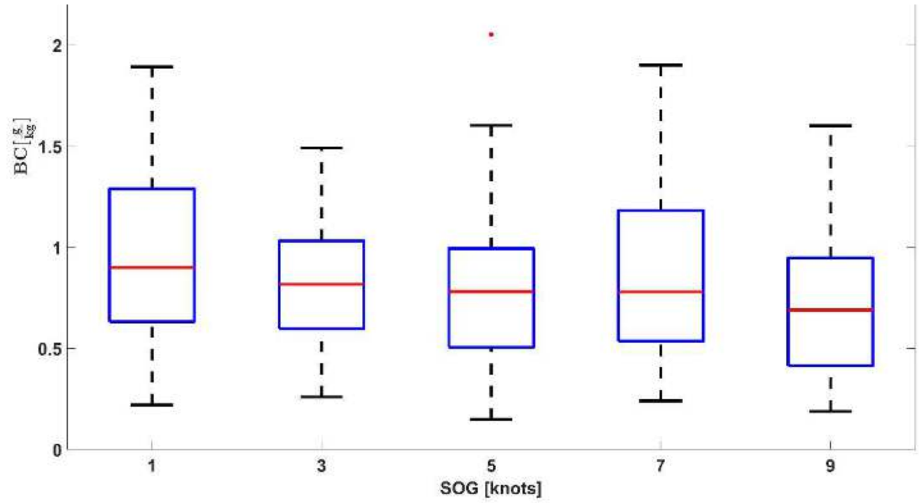


Figure 1.19. Shipborne particle emission factor measurements in g/kg of BC in the Tricity area as a function of ship speed. The data correspond to median (red), 25th and 75th percentile (blue), 10th and 90th percentile (black) and outliers as red dots.

In Table 1.3 the fuel specific emission factors are shown for all species in this study and all sites.

Table 1.3 Ship emission measurements carried out during the EnviSuM project from patrol vessels and aircraft. The data corresponds to emission factors in g/kg fuel and the median and 25th|75th percentiles are shown, respectively, for all measured individual ships. A comparison between measurements and model from FMI (STEAM) is shown. In addition is shown measurement results with the same equipment carried out in St Petersburg in 2012 as part of BSR Innoship project. Here GOT is Gothenburg and St.Pb is St Petersburg. Baltic Sea correspond to the waters surrounding the Isle of Gotland.

Ref	**NO_x**	**SO_2**	**PM0.5**	**BC**	**PN**	**Diam**	**No of Ships**	**Comment**
	g/kg$_f$	g/kg	g/kg	g/kg	10^{16}/kg	nm		
Tricity 2017	**50** 41|60	**0.36** 0|0.64	**1** 0.78|1.6	**0.81** 0.61|1.1	**1.2** 0.85|1.6	**50** 47|53	102	Main Eng
Tricity *2017*	***55*** *49|63*	***2.2*** *2.1|2.2*	***2.0*** *1.9|2.1*					Model Main Eng
Tricity 2017	**26** 19|35	**0.22** -0.1|0.6	**1.1** 0.69|2	**1.2** 0.78|1.6	**0.8** 0.58|1.2	**52** 49|53	78	At berth
Tricity 2017	***53*** *44|55*	***2.2*** *2.1|2.2*	***2***** *1.9|2.1*					Model at berth
GOT 2017	**55** 42|67	**0.38** (-0.1|0.6)	**0.47** 0.3|0.6	**0.52** 0.3|0.73	**0.93** 0.5|1.4	**50** 44|53	87	
GOT 2017	**64** 55|75	***2.2*** *2.1|2.2*	***2.2*** *2.1|2.2*					Model
StPb 2018	**62** 51|79	**0.012** -0.34|0.66	**0.88** 0.56|1.4	**0.59** 0.29|0.88	**1.4** 0.84|2.2	**46** 41|52	175	

(Cont.) Table 1.3

<table>
<tr><td>*StPb 2018*</td><td>***64***
55|73</td><td>***2.2***
2.1|2.2</td><td>***2.1*****
2|2.2</td><td></td><td></td><td></td><td></td><td>*Model FMI*</td></tr>
<tr><td>Baltic Sea 2016</td><td>**69**
56|86</td><td>**1.28**
0.45|1.9</td><td></td><td></td><td></td><td></td><td>112</td><td>Airborne</td></tr>
<tr><td>Baltic Sea 2016</td><td>***78***
65|90</td><td>***2.2***
2.1|2.2</td><td></td><td></td><td></td><td></td><td></td><td>Model</td></tr>
<tr><td>StPb 2012</td><td>**57.7**
±20.9</td><td>**11.6**
± 7.3</td><td>**1.72***
± 1.66[d]</td><td></td><td>**1.6**
± 0.8[a]</td><td></td><td>311</td><td>Beecken 2015</td></tr>
</table>

*corresponds to PM 10, ** PM2.5

It can be observed that the NO_x emission factors measurements are rather similar in all studied areas, also when comparing 2012. The highest values are found on the open sea, when the ships operate on design speed while the lowest values are found for ships at berths. The median of the STEAM model generally agrees with the measurement median. This especially true for the measurements on the open sea while there is a considerable discrepancy for ships at berth. In addition, in the St Petersburg case there is a distinct difference in the statistical distribution and when comparing results for individual ships the scatter between model and measurements is rather high. For SO_2 the measured emission factors are occasionally negative due to noise and this is not reflected in the model. Noteworthy is the big change in SO_2 emission factor between 2012 and 2018 due to the FSC IMO limit changing from 1 % to 0.1% during this period.

The particle measurements, both for PM0.5 and Black Carbon (BC) appears to be highest for the ships at berth. Also, the service boats (river barges etc.) shows the highest PM emissions. For BC the measurements were significantly higher in Tricity than in Gothenburg and St Petersburg, possibly because of tugboats accompanying many of the bigger ships in Tricity. The comparison of measurements and model for particles shows that the latter yields higher emission factors by a factor of 2. However, here it should be noted that the model corresponds to PM2.5 particles (size smaller than 2.5 µm), while the measurements correspond to particles below 0.5 µm. This needs further analysis. Noteworthy is also an apparent change in measured PM values between 2012 and 2017 in St Petersburg. However, in 2012 an additional optical instrument was used measuring particles up to 10 µm in size. In 2017, this instrument was noisy and only used in a limited manner.

Ship emission modelling

Ship emissions were modelled on real-time vessel activity recorded by the Automatic Identification System (AIS), which updates vessel location every few seconds and is mandatory for all ships. The data it provided facilitated vessel-specific predictions of fuel used and emissions produced. Further details are available from Jalkanen et al. (2009; 2012) and Johansson et al. (2013; 2017), but the general approach is described in Fig 1.20.

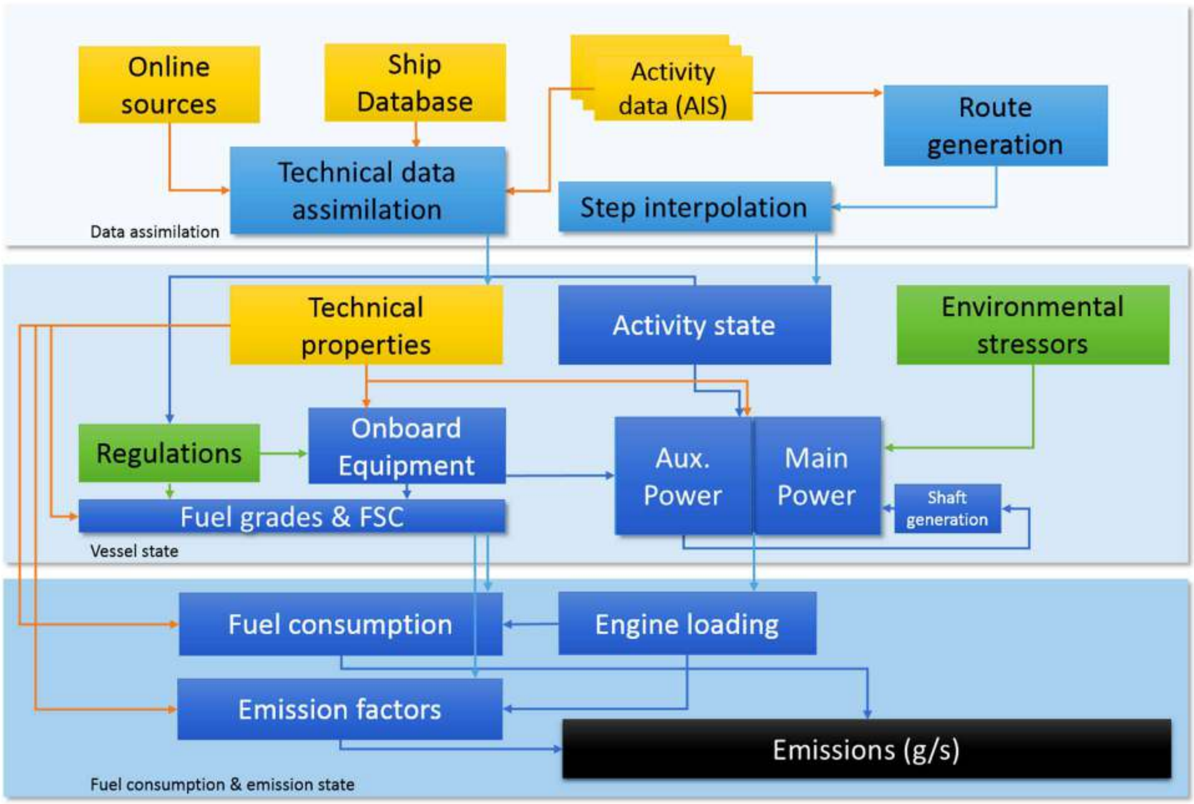


Figure 1.20 Working logic of ship emission model STEAM (from Johansson et al., 2017).

AIS transponder data indicates vessel identity, speed, location and timestamp, which together describe vessel activity as a function of time. The technical description of each vessel, combined with ship activity, enables the prediction of engine power use for both main and auxiliary engines. This facilitates fuel consumption modelling based on predicted power, engine characteristics and fuel properties. When combined with emission factors for marine diesel engines, emitted air pollutants can be estimated.

Emissions from the Baltic Sea fleet were studied for years 2014 and 2016, in order to examine the situation before and after sulphur regulations came into effect for marine fuels. We were able to quantify the reduction in ship emissions following the regulations and their benefits to human health and the environment. The geographical distribution of SOx emissions from ships during the year 2016 is given in Fig 1.21.

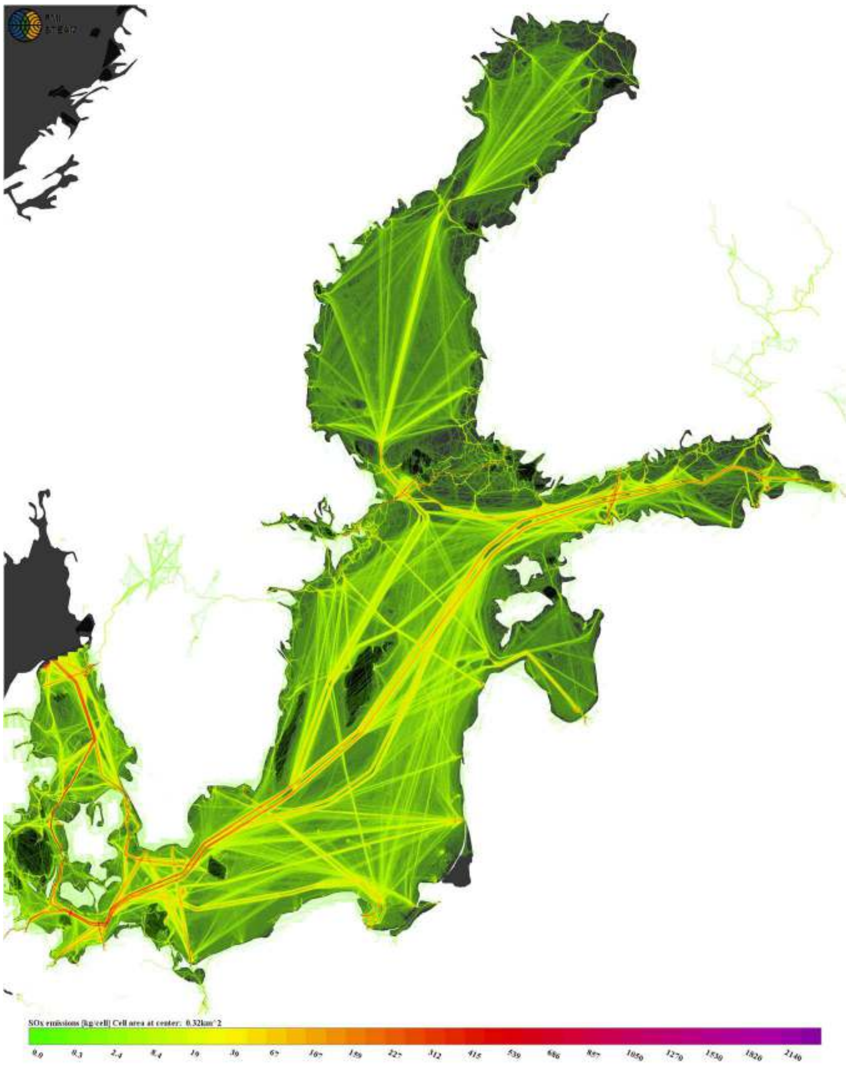


Figure 1.21 Emissions of SO_x from ships sailing the Baltic Sea during 2016.

Scenarios

Future scenarios were constructed to describe ship emissions in 2030, taking into consideration energy efficiency gains, vessel and fleet size growth rates as well as the already agreed regulations to reduce NOx emissions that will be applied from 2021 onwards in the Baltic Sea and North Sea areas.

Annual energy efficiency gains were based on the atmospheric emissions projections in Kalli et al (2013), where the efficiency gains are approximately three times larger as what is currently required by IMO through the Energy Efficiency Design Index (EEDI).

It should be noted that EEDI alone will be an insufficient tool to meet greenhouse gas reduction targets in the Baltic Sea area, which compel the shipping sector to find low or zero carbon fuels.

In the Table 1.4 we compare the emissions from Baltic Sea Ships before SECA, after SECA and future scenarios.

Table 1.4 Emission totals from Baltic Sea ships. Emissions from inland waterway traffic are excluded.

Year	CO2 (million tonnes)	NOx (103 tonnes)	SOx (103 tonnes)	CO (103 tonnes)	NMVOC (103 tonnes)	PM2.5 (103 tonnes)
2014	14.4	314	75.1	21.1	2.56	15.0
2016	15.0	323	9.98	22.2	2.65	9.62
2030 (BAU)*	12.7	171	8.45	18.2	2.29	8.28
2030 Scrubbers*	12.8	171	7.78	18.2	2.29	6.91

* Includes annual efficiency gains as described in Kalli et al. (2013), fleet and vessel size growth rates, NOx and SOx Emission Control Areas and additional energy needs for scrubber pumps.

Sanctions

The risk of getting caught and sanctions for using non-compliant fuel vary between states. SECA compliance monitoring is mainly based on fuel samples taken by authorities when the vessel is at port. However, it is difficult to determine whether a fuel switch has been done when entering the SECA area, and bunker delivery notes can be counterfeited making it possible to evade detection.

Each Baltic Sea coastal country independently decides on the administrative and criminal sanctions of breaking maritime regulations. Even if maritime authorities detect a non-compliant vessel in their territorial waters, the penalty may be small, or there is no penalty at all.

The usual sanction for breaking SECA rules are fines, but port state control authorities can also detain a vessel if it is not seaworthy (CompMon 2018). According to OECD (2016, 42), penalties for non-compliance have typically been smaller than the cost savings a ship-owner would make by using a noncompliant fuel.

Compliance rates and compliance culture

Contrary to pessimistic expectations, the overall compliance rate with SECA rules has turned out to be very good: more than 90 per cent of vessels sailing in the Baltic Sea follow the rules. Some maritime actors were rather sceptical as to ship-owners willingness to comply, mainly because the costs of low-sulphur fuel at that time made the use of non-compliant fuel a more economically attractive option. The share of fuel costs in total operating costs is high, typically 25 - 45 per cent.

Our interviews with ship-owners (chapter 4) revealed there are also moral reasons behind the high compliance rate. Although fines for SECA non-compliance are negligible, shipping companies seem to think that they would face negative economic and social consequences if they do not comply. Following the rules is seen as the “right thing to do”, and non-compliance is not considered an option if a company wants to continue in the shipping business. There is a strong compliance culture among shipping companies in the region (Lähteenmäki-Uutela et al. 2019).

Overall, shipping companies operating in the Baltic Sea agree with the goals of sulphur emission reduction and see that the societal benefits of better air quality as a result of the regulation exceed the costs.

Conclusions

The reduction of sulphur-related emissions between 2014 and 2016 is clearly evident meaning that the SECA regulation was successful in achieving its main goal. There has been an 87 per cent reduction in gaseous emissions of SO_2 and a 36 per cent reduction in fine particle emissions in the Baltic Sea Region following the introduction of SECA. Particulate matter (PM) emissions are not reduced as much as gaseous emissions because PM consists of various chemical species that do not all contain sulphur.

There are several methods to comply with the regulation that all have their own good points and challenges. They all fulfil their purpose, however. There will not be just one solution but a combination of methods, and further development and innovations will improve the performance of the compliance methods.

EnviSuM data on compliance monitoring is comparable to other data that gives creditability to the results. The used methodology seems to be a useful tool for NO_x compliance measurements with respect to the introduction of the Tier III rules in 2021. However, it should be noted that the remote measurements are a snapshot of a certain engine operation mode while the IMO regulation states that the limit should be obtained as a weighted average of four engine operation modes with different engine load, with most weight on the 75 % load, for most engine types. Therefore we conclude that a sensitivity analysis is needed in the future to assess what uncertainties are created due to this fact.

CHAPTER 2

AIR QUALITY

Introduction

The aim of this part of the project was to assess the effects of ship emissions on air quality, before and after the sulphur regulations that entered into force in 2015, in order to help analyse the impact on public health and the environment

Model calculations using estimates of air pollutant emissions were made on a regional European scale, but with a focus on the Baltic Sea region.

In addition, model calculations for three urban regions were carried out - in Gothenburg in Sweden, the Tri-City (Gdansk, Sopot and Gdynia) in Poland and St. Petersburg in Russia.

Existing routine measurements were used to validate model calculations of air pollution from ships. Additional measurements within port areas were used to supplement the urban model calculations. Data on concentrations and depositions for present and future (the year 2030) conditions were included in the regional calculations.

Regional calculations

Regional model calculations have been made using the EMEP MSC-W (Meteorological Synthesizing Centre West) model (hereafter the EMEP model) on a 0.1 x 0.1 degrees resolution, and for the domain between 30 degrees W, 45 degrees E and between 30 and 75 degrees N. A detailed description of the EMEP model can be found in Simpson et al. (2012) with later model updates being described in Simpson et al. 2018 and references therein.

The EMEP model is available as an open source online, and is regularly evaluated (see Gauss et al. 2016, 2017, 2018).

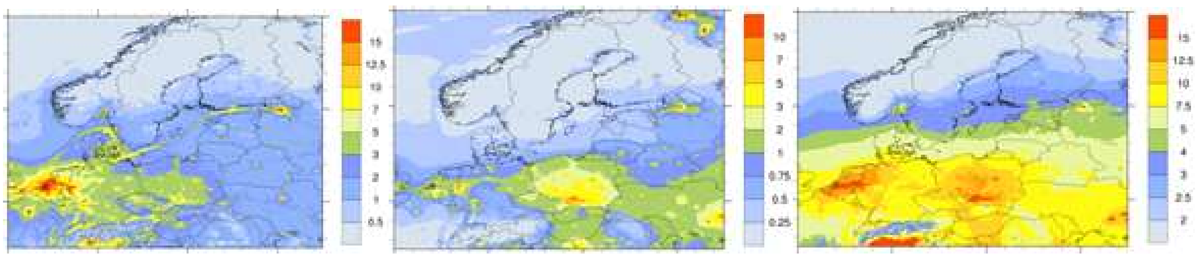
Using these models, it was possible to distinguish emissions originating from land (traffic and industry) and originating from sea traffic. Three sets of regional model calculations have been made

1. AllEm_2016: 2016 Baltic Sea ship emissions. All other emissions as in 2015.
2. NoShip_2016: As AllEM_2016 but excluding Baltic Sea ship emissions
3. HiSulphur: As AllEm_2016 but with Baltic Sea ship emissions as they were in 2014, prior to sulphur regulations.

In addition, emission projections have been calculated for 2030 with (Future_AllEm) and without (Future_NoShip) Baltic Sea emissions. Furthermore, the source receptor calculations in the 2018 EMEP report (EMEP, 2018) have been made with 2015 ship emissions from FMI.

All model simulations were done with meteorological data for three different years - 2014, 2015, and 2016 - and then averaged. This approach was chosen in order to filter out interannual variability in meteorological conditions, which could partly mask the effects of policy measures being studied here.

Figure 2.1 shows the levels of SO_2, NO_2 and $PM_{2.5}$ calculated as an average for the three meteorological years 2014, 2015 and 2016 for AllEm_2016. The highest concentrations of all three pollutants were calculated in western and central parts of Europe and decrease from south to north.



a) SO_2 in µg(S)/m3 b) NO_2 in µg(N)/m3 c) $PM_{2.5}$ in µg/m3

Figure 2.1 Concentrations of SO_2, NO_2 and $PM_{2.5}$ calculated with 2016 (post 2015 SECA) ship emissions. Figures from Jonson et al. (2019).

Concentrations of SO_2

As shown in Figure 2.2.a concentrations of SO_2 are up to 75 per cent higher in the HiSulphur scenario (pre stricter SECA) compared to the AllEm_2016 calculations.

This is also seen in the comparison with measurements in Figure 2.5 (left panels) where measured SO_2 levels are substantially overestimated in the HiSulphur calculations.

The average concentrations for individual countries shows that for smaller countries in particular, the 2015 SECA regulations give marked reductions in SO_2.

SO_2 levels and sulphur depositions in individual countries (Figure 2.4d) are hardly affected when Baltic Sea emissions are removed (NoShip_2016) as ship emissions of sulphur are already low in the Baltic Sea. The latter is also the case for the future (2030) calculations.

Concentrations of NO_2

Baltic Sea ship emissions of NO_2 remain high in both HiSulphur and AllEm_2016 scenarios. The difference in the calculations with (All_2016_2016) and without (NoShip_2016) ship emissions are shown in Figure 2.2.b. At sea, the calculated differences are large, and even though the lifetime of NO_2 in the atmosphere is short, substantial effects (increases between 20 and 40 per cent) are also seen in some coastal regions.

The right panels of Figure 2.5 show that at several coastal sites the model substantially underestimates measured NO_2 concentrations when Baltic Sea ship emissions are excluded from the calculations.

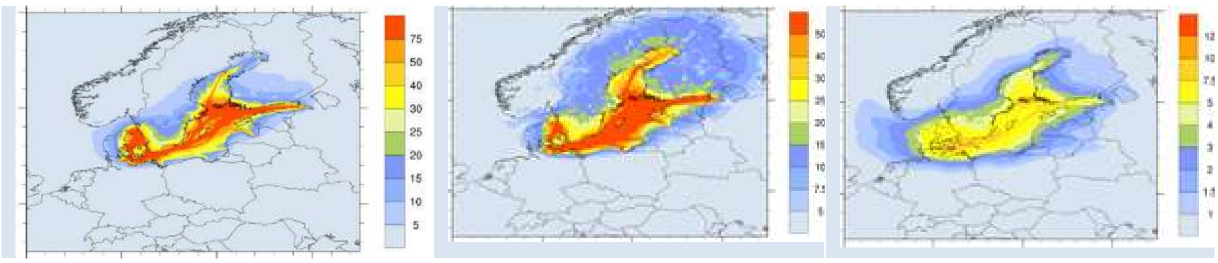
When averaged (Figure 2.4b) there are marked contributions from Baltic Sea shipping particularly in the smaller countries. The fractional reductions of future concentrations, attributed to (mainly) land-based and to ship emissions, are roughly in the same range.

Particulate matter (PM)

$PM_{2.5}$ is a mixture of many chemical substances of both natural and anthropogenic origin. It is either emitted as a 'primary pollutant' or formed in the atmosphere, known as a 'secondary pollutant'. In many coastal regions the calculated contribution to $PM_{2.5}$ from ship emissions is between 5 - 10 per cent (Figure 2.2c).

Averaged for individual countries (Figure 2.4c), the contribution to $PM_{2.5}$ levels from Baltic Sea shipping are relatively smaller than for NO_2, both in the present and in the future.

Country-to-country source receptor calculations (Figure 2.3b) show that Baltic Sea shipping is among the largest anthropogenic contributors to $PM_{2.5}$ in Denmark. There is also an equally or larger contribution from North Sea shipping here.



a) HighS - AllEm_2016 SO_2 b) AllEm2016 - NoShip NO_2 c) AllEm2016 - NoShip $PM_{2.5}$

Figure 2.2 Percentage change in SO_2, NO_2 and $PM_{2.5}$. (a) percentage difference in SO_2 between HiSulphur (2014 Baltic Sea ship emissions) and AllEm_2016 (2016 Baltic Sea ship emissions). (b) and (c) show the percentage differences calculated as AllEm_2016 - NoShip_2016. Figures from Jonson et al. (2019).

Depositions of oxidized sulphur and nitrogen

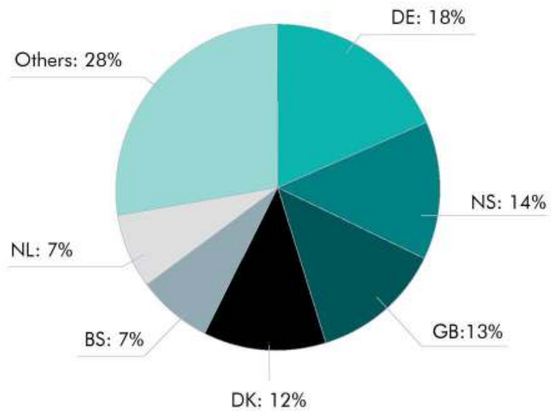
The effects of Baltic Sea ship emissions on depositions of oxidised sulphur and nitrogen in neighbouring countries are shown in Figures 2.4d and 2.4e. As for SO_2 in air, present emissions have virtually no effect on oxidised sulphur depositions in neighbouring countries.

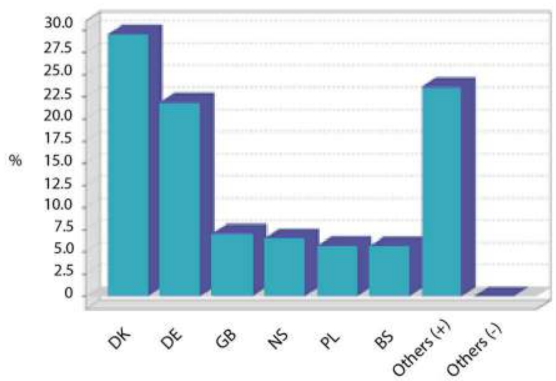
There are, however, marked contributions when calculations are made with HiSulphur emissions, which are representative of 2014 conditions (Figure 2.4d).

Figure 2.4e shows that depositions of oxidised nitrogen are not affected by the implementation of the 2015 SECA regulations. It also shows that a substantial portion of the depositions can be attributed to ship emissions, exemplified by source receptor calculations for Denmark where the calculated anthropogenic contribution is 7 per cent from the Baltic Sea (and 14 per cent from the North Sea).

Ozone

Annual ozone levels in the Baltic Sea region are in the 33 to 37 ppb range. The effects of Baltic Sea shipping on ozone are shown in Figure 2.4f. Ozone levels change throughout the year, with increases mainly in summer and decreases (due to ozone titration) in winter. As a result, net ozone production and titration effects partially cancel out resulting in only small changes on an annual-average basis. A moderate increase in annual ozone is calculated for Estonia, Latvia and Lithuania. In Denmark additional emissions from shipping result in reductions in annual ozone. Figure 2.4f also shows that annual ozone levels are expected to decrease in most of the coastal countries of the Baltic Sea in the future.





a: Depositions of reduced nitrogen in percent b: $PM_{2.5}$ in per cent

Figure 2.3 The six main contributor countries/regions to a: depositions of reduced nitrogen and b: concentration of $PM_{2.5}$ in Denmark. BAS is the Baltic Sea, NOS the North Sea, DE Germany, GB Great Britain, DK Denmark, NL The Netherlands and PL Poland. Figures adapted from EMEP country report for Denmark. http://emep.int/publ/reports/2018/Country_Reports/report_DK.pdf

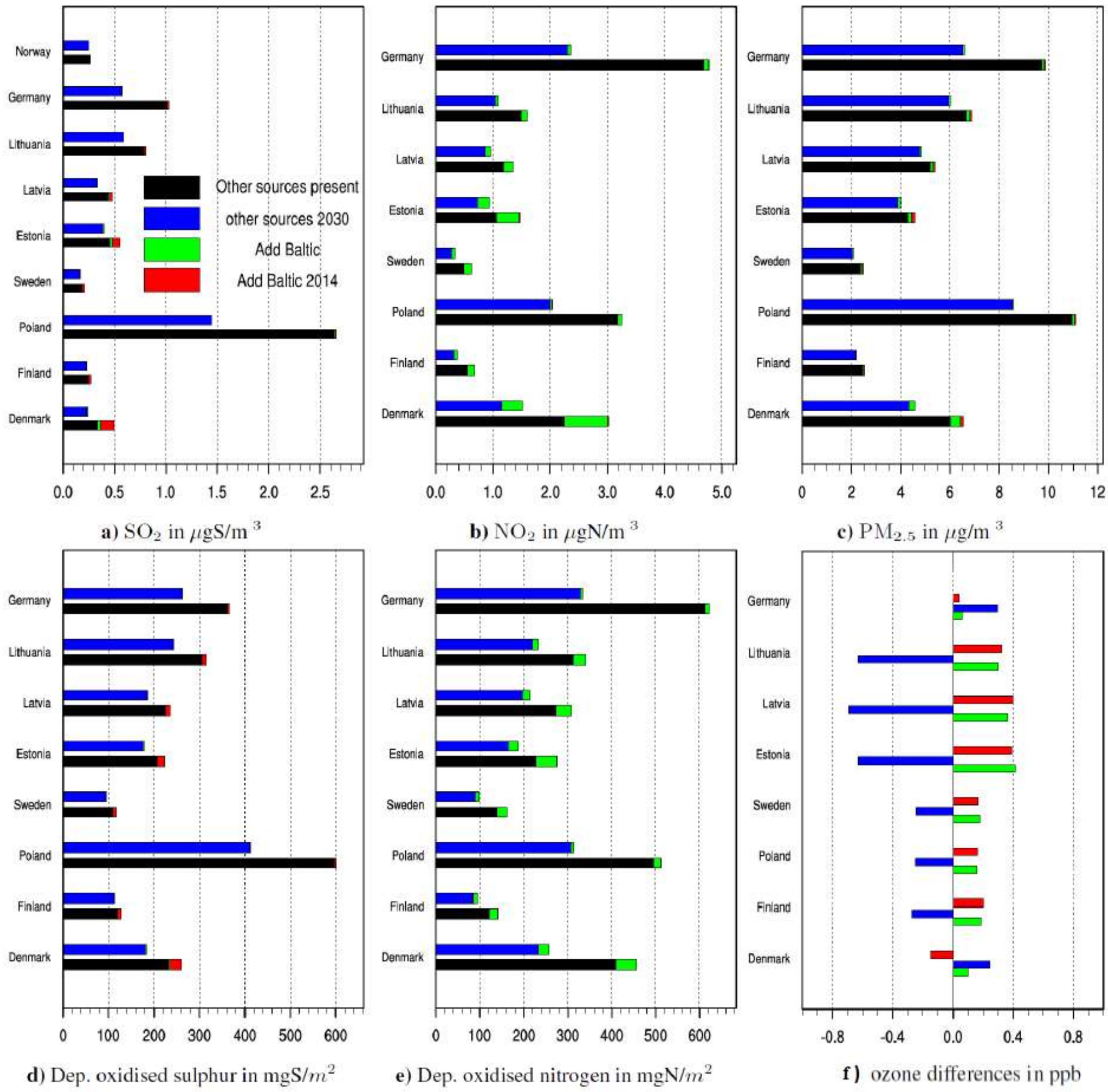


Figure 2.4 For each country, in panels (a) to (e) the black and blue bars represent the NoShip_2016 and NoShip_Future country average depositions respectively. The additional contributions from the Baltic Sea are shown in green and the additional effect assuming high sulphur fuel emissions in red. Panel (f) shows the changes in annual ozone in ppb (annual average ozone is in the 30 - 35 ppb range) where red bars represent contributions from the Baltic Sea with 2016 emissions and green bars contributions from the Baltic Sea with future (2030) emissions. Blue bars represent the calculated effects of future versus 2016 European emissions. Figures from Jonson et al. (2019).

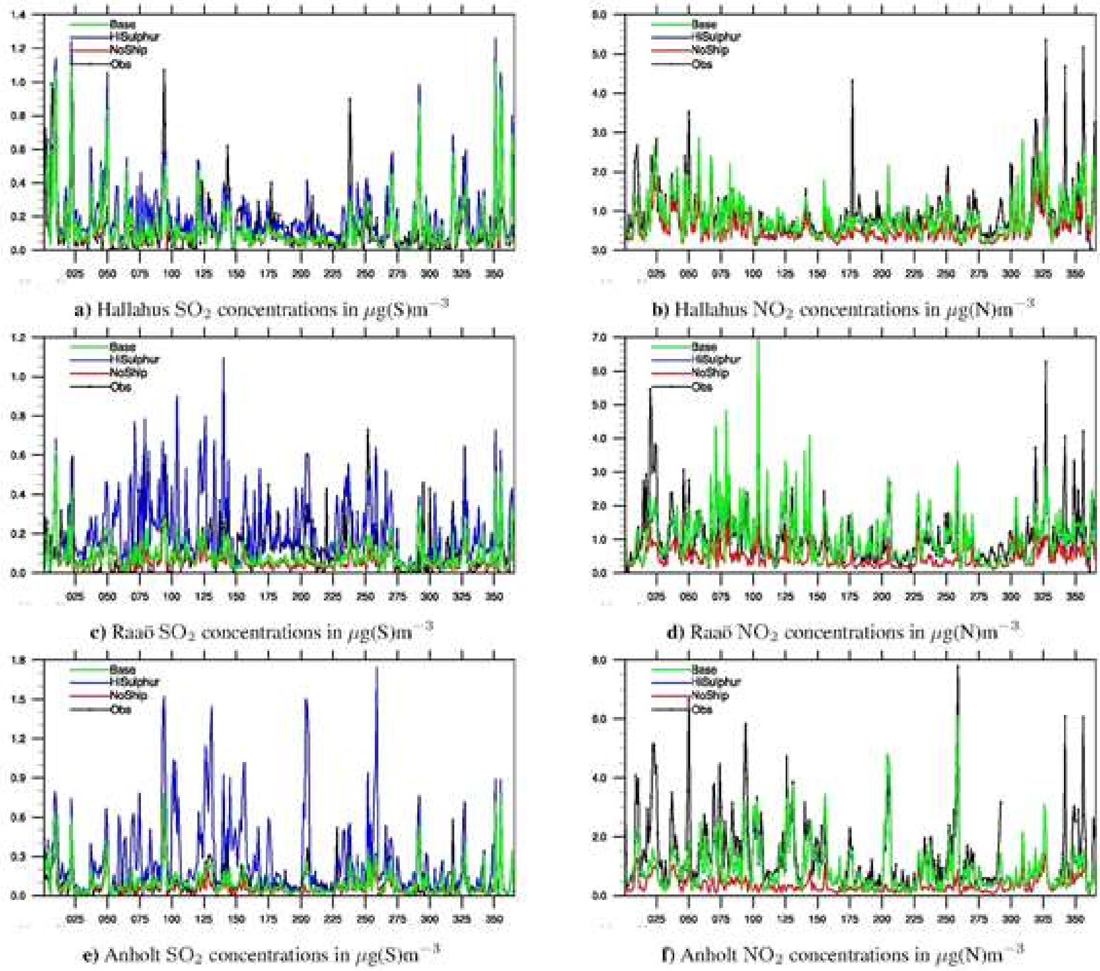


Figure 2.5 Measured (Obs) and model calculated SO_2 (left) and NO_2 (right) at coastal sites in the Baltic Sea region. In the HiSulphur scenario 2014 ship emissions are used in the Baltic Sea. In the NoShip_2016 scenario Baltic Sea ship emissions are excluded. Figures from Jonson et al. (2019).

Conclusions

Ship emissions of SO_2, NO_X and PM in the Baltic Sea lead to increased air pollution especially over the sea, but also in the coastal regions of its littoral states. PM and SO_2 are increased, while ozone is either increased or decreased depending on the region and the season.

The 2015 sulphur regulations resulted in a substantial reduction of these negative effects, especially in terms of SO_2 and PM concentrations. PM concentrations will be further reduced by reductions in nitrogen oxides until year 2030.

The results calculated here were used in the local studies described in the next section and in the health impact assessments. We can conclude that sulphur regulation was a success story for regional air quality. Tighter regulation for PM and nitrogen, however, are still needed.

URBAN AIR QUALITY - A TALE OF THREE CITIES

The aim of the project was to spread best practice on air quality modelling methodology in three target cities in the Baltic Sea Region.

St. Petersburg and its harbour

St. Petersburg is the second largest Russian city with population about 5.4 million people. Covering an area of 1,403 km^2, average population density is approximately 3,800 persons per km^2. The city of St. Petersburg is located in the eastern part of the Gulf of Finland, in the delta of the Neva River. The main port of St Petersburg is made of up several separate ports. It was once the largest Russian port in the eastern part of the Baltic Sea. Nowadays, however, the city of Ust-Luga is home to the largest amount Russian freight, accounting for approximately 40 per cent of the total Russian cargo of 250 million tonnes on the Baltic Sea. St. Petersburg port accounts for 20 per cent of this figure. The main shipping routes through the Finnish Gulf to or from the port are shown on the Fig. 2.6.

Figure 2.6 The map of St. Petersburg with environs and main shipping routes in and out of the Big St. Petersburg Port (dashed blue line). Yellow lines are major roads and highways; the curve crossing the Gulf of Finland via Kronshtadt indicates the Ring Road.

As one of Russia's major industrial and transportation centres, there are many sources of air pollution. Official data on total emissions in 2016 are shown on Fig. 2.7. It is clear from this picture that total SO_2 emissions are comparatively small because local power stations are fuelled mainly by natural gas, with fuel oil used only as a reserve during severe frosts. Emission data includes both stationary and mobile sources of air pollution, but there is no certainty that shipping emissions are also included.

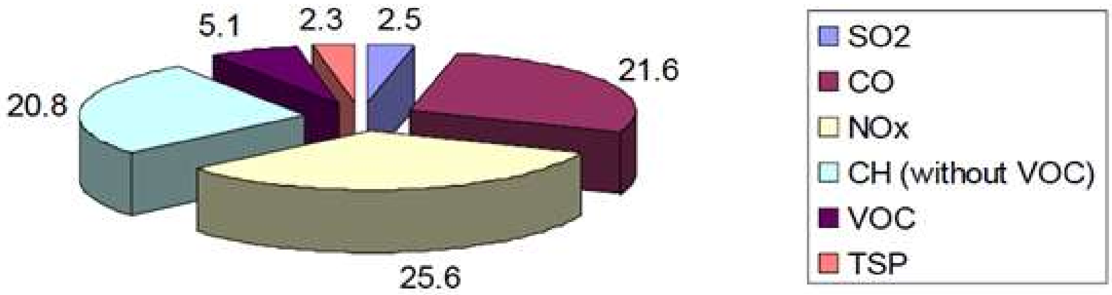


Figure 2.7 Total emissions (in kt) of atmospheric pollutants in St. Petersburg in 2016 (here, NOx – sum NO oxidized to NO2 and NO2, CH – hydrocarbons with no account for VOC, VOC – volatile organic compounds, TSP – total suspended particles).

Modelling air pollution in the St. Petersburg region

Air pollution in St. Petersburg was modelled using a Chemical Transport Model developed at the Voeikov Main Geophysical Observatory (MGO). Further details of the modelling methodology can be found in the Notes section at the end of this report.

Challenges with the data

Complications were experienced with data describing the emission sources. A request for data on recent emissions was unexpectedly refused by the city administration, which had initially expressed support for this project. As a result, the dispersion calculations were carried out using a previous emission inventory, supplemented with more recent data from two newly constructed major highways, the Ring Road (RR) and the Western Speedway Diameter (WSD). Only data for the northern part of WSD, however, is currently available at the moment.

Another problem related to the absence of data on important components of the chemical composition of emissions, in particular, volatile organic compounds (VOC). Our previous attempt to reconstruct them artificially using SNAP classes (Selected Nomenclature for Sources of Air Pollution, in Guidebook B, 2016) was not successful enough. It could be seen from our results that concentrations of chemically reactive pollutants were emitted from cars or from other sources, which are shown on Fig. 2.8.

Given this situation, our estimates in this project of CO, SO_2 and NO_x concentrations are conservative approximations.

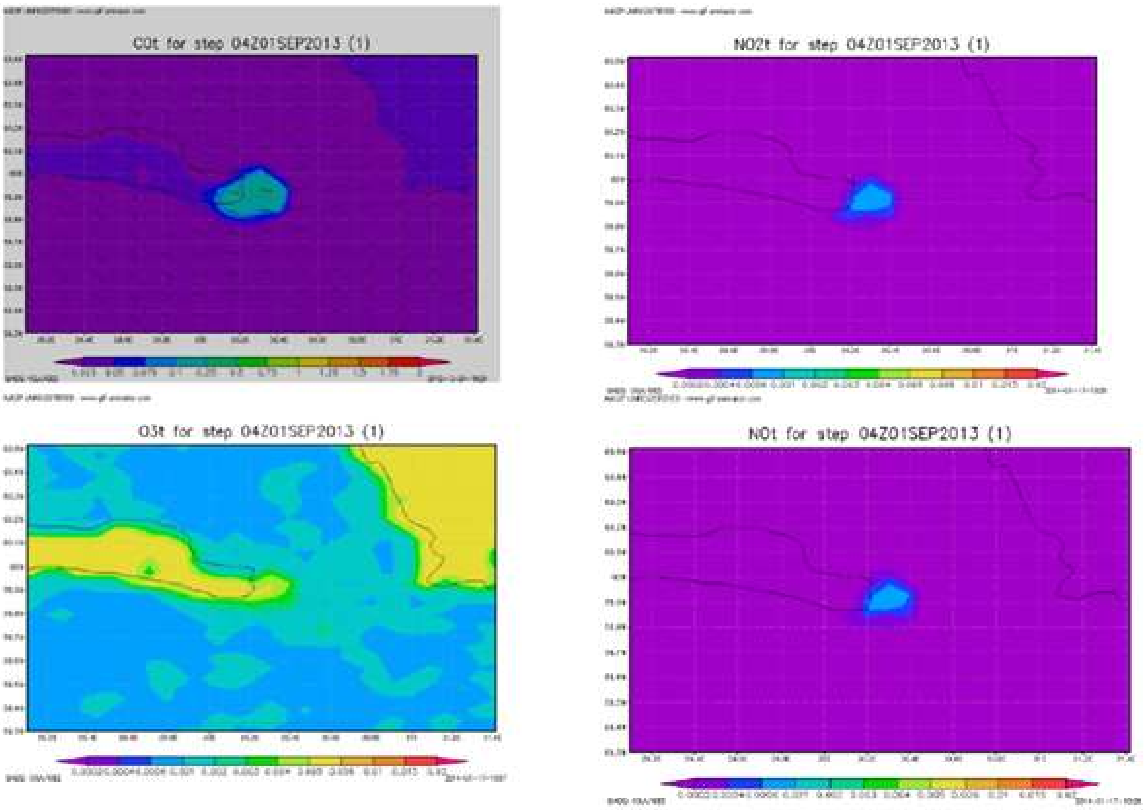


Figure 2.8 Air pollution in St. Petersburg related to the traffic emissions

Our findings

Using emission data for the year 2011, the annual average concentration of different atmospheric pollutants for St. Petersburg was calculated using a non-Gaussian dispersion model of the source-receptor type, which was developed at the Voeikov Main Geophysical Observatory (later on, this model was included into the official Russian national guideline called Methods (2017)).

The map of ship emissions inputted into the total field of NOx concentrations, which had been published in Breitzmann, Hytti (2013), is reproduced here as Figure 2.9. These calculations indicated that in St. Petersburg in 2011, the contribution from shipping to total NOx emissions concentrations could be as high as up to 10 per cent.

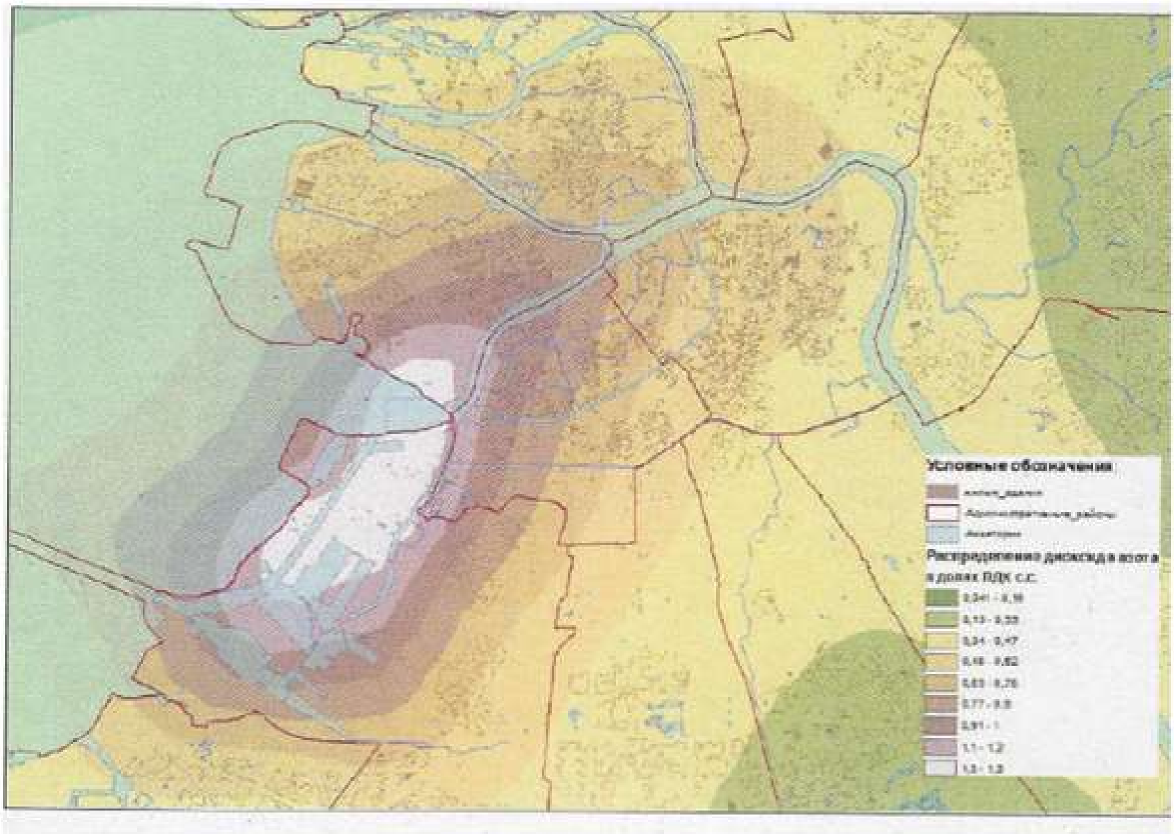


Figure 2.9 Annual average concentrations NOx emitted by ships in 2011. The concentration values are given in fractions of the maximum permissible concentration (MPC) equal to 0.2 mg/m3 (Breitzmann, Hytti, 2013).

Future work

Modelling the impact of SECA requirements on air pollution levels in the St. Petersburg area requires the following

- Analysis of available data on emissions of urban sources of pollution
- Analysis of provided data on ship emissions for the years 2014 - 2016
- Analysis of provided data of instrumental monitoring of air pollution in 2016
- Analysis of data transferred from the MSC-W results to the EMEP model in order to estimate background concentrations for the St. Petersburg area
- Aggregation of emission data for their usage with the grid CTM model "CTM-MGO"
- Numerical simulation over 2016 of fields of meteorological elements using WRF model
- Numerical CTM calculations of fields of concentrations of CO, SO2 and NO2 with met fields for 2016, available urban emissions and ship emissions for 2014
- Numerical CTM calculations of fields of concentrations of CO, SO2 and NO2 with met fields for 2016, urban emissions for 2016 and ship emissions for 2016
- Dispersion calculations of fields of mean annual concentrations of pollutant considered using the national regulatory guideline MDC-2017 (if corresponding fields are also calculated by partners too)

Tri-City - Gdańsk, Gdynia and Sopot

The Tri-City agglomeration covers an area of 414.4 km^2 and includes three interconnected cities: Gdańsk, Gdynia and Sopot. It is located in the northern part of Poland on the Bay of Gdansk. The city centres are mainly characterized by dense multi-family buildings (tenement houses) and newer, high-rise buildings of both residential and commercial use.

The main industrial infrastructure of the Tri-City agglomeration are its ports. The ports of Gdynia and Gdansk, with more than 11,000 ship calls per year and intensive tugboats movements, are the Poland's largest seaports and the Southern Baltic's busiest container ports. In addition to specialist transhipment bases, there are terminals for the growing industry of passenger transport. The port industry sector is mainly composed of shipbuilding, oil and gas and chemical companies. In 2016, the population of the Tri-City agglomeration was 747,594 inhabitants with population density of 1.8 persons/km^2.

Within the boundaries of the Tri-City, a significant part is Landscape Park, made up of mostly forested areas. These forests are an important element of land use in the Tri-City agglomeration, occupying an area of about 12,000 hectares, about 29 per cent of its total size. Urbanised land covers about 15,000 hectares, 36 per cent of the agglomeration area. Wasteland constitutes 2.4 per cent (969ha).

The area lies on the Gdansk Coast and in the East Pomeranian Lakeland. The cities of Gdynia, Sopot and the northern part of Gdansk lie within the mesoregion area of the Kashubian Lakeland and the Kashubian Coast, while the south-eastern part of the agglomeration lies within the mesoregion of the Vistula Spit. This location has complex terrain, with hills and valleys with an altitude difference up to 230m (Figure 2.10).

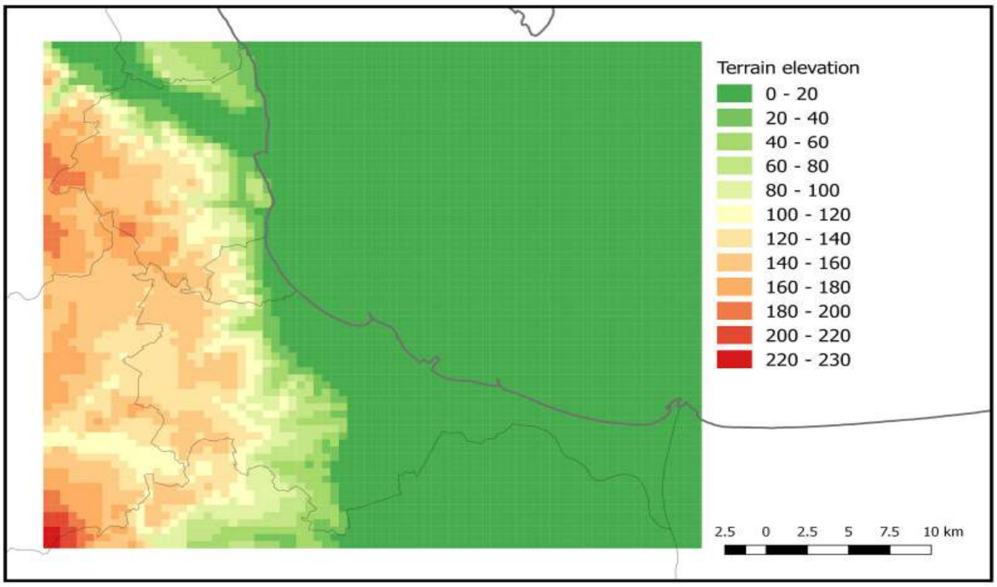


Figure 2.10 Terrain relief in the Tri-City agglomeration.

Modelling air pollution in the Tri-City region

To ascertain the effects of SECA regulations, the contribution of shipping emissions on air quality and health of the inhabitants of the Tri-City agglomeration was modelled in the ports of Gdynia and Gdansk. Air pollution modelling was carried out in a spatially limited domain. In order to account for the inflow of pollutants from the outside the grid, information on concentrations at the edges of the grid - boundary conditions -was introduced into the model. This information was provided by the Norwegian Meteorological Institute and contained hourly concentrations of SO_2, NO_2, NO and particulate matter pollutants in both primary and aerosol form (sulphates, nitrates) – Figure 2.11. Further details on air pollution modelling can be found in the Notes section at the end of this report.

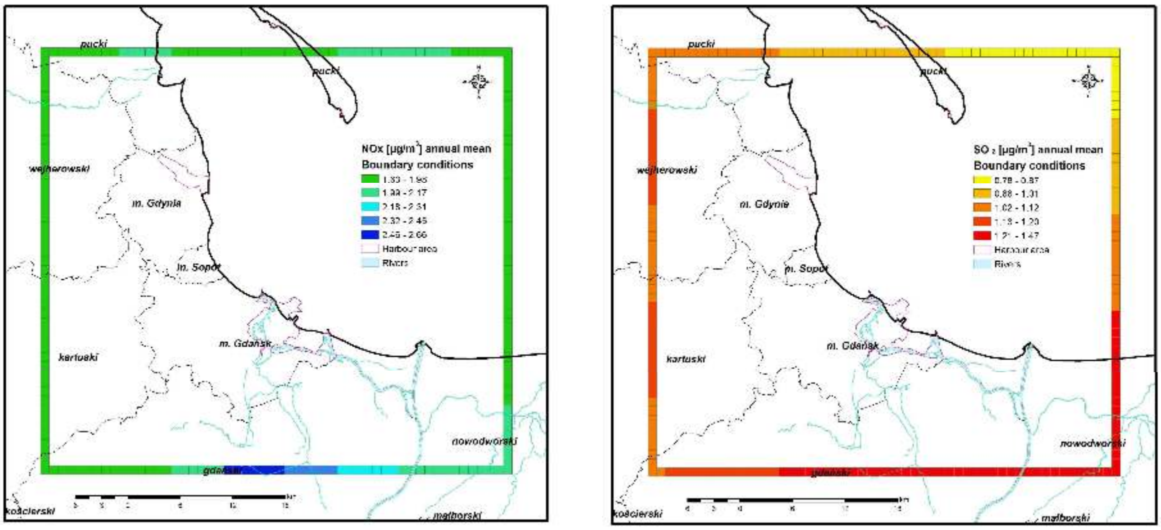


Figure 2.11 Boundary conditions for NO_X and SO_2 for the Tri-City agglomeration in 2016.

Emission sources

In this study calculations were based on three types of sources:

- point sources, in the form of emitters with given technical parameters - height, diameter, speed and temperature of exhaust gas discharge,
- surface sources, in the form of emission cadastre with a mesh size of 250 m and given emission height
- linear sources, i.e road transport.

The source of information on point emitters were databases of the Marshal's Office of the Pomorskie Voivodeship and the National Centre for Balancing and Emissions Management (KOBiZE, Polish). Each emitter had technical data of the exhaust gas channel, or stack, and the hourly variability, resulting from the SNAP category (SNAP- Selected Nomenclature for sources of Air Pollution). The concentrations were calculated for the whole year. The Figure 2.12 shows the exemplary distribution of point emitters (industry) with the assigned emissions of NO_2 and SO_2.

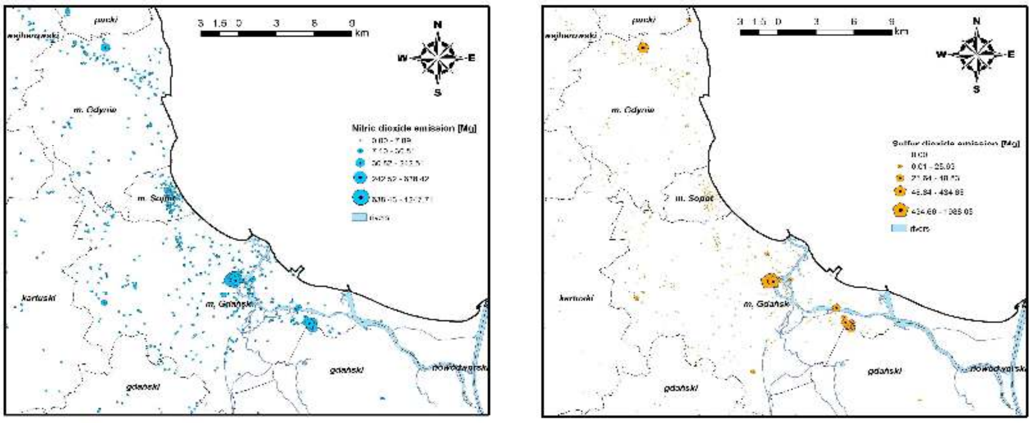


Figure 2.12 The distribution and loads of NO_2 and SO_2 point emissions in the modelling area in 2016.

Shipping emissions were determined using the emissions inventory made by the Maritime University of Szczecin in cooperation with the Maritime Port Authority in Gdynia and the Port Authority in Gdansk. It was divided into the stage of entering the port and the stage of berthing. The approach routes were presented with the use of substitute surface sources with the area of testing ranges selected from the computational domain.

The vessels were divided according to stack heights and for each group a separate calculation pass was made. Calculations were carried out in a daily cycle with emissions calculated for each source and each hour, on the basis of the time spent by the vessel within the respective replacement emitter. Ships at berth in ports are presented as point emitters, each with its own technical parameters. For the area of the Gdansk Bay, which was not included in the inventory mentioned above, data from model calculations of the Meteorological Institute in Helsinki was used. This information was linked to the meshes of the computational domain and counted in a daily cycle with emission values for each hour.

Findings

On the basis of the data obtained, significant emissions are assessed to have originated from industry rather than from other sources (Table 2.1).

Table 2.1 The comparison of emissions in 2014 and 2016 for Tri-City.

Emissions (tons/yr)	**Industry**		**House heating**		**Road transport**		**Ships**	
	2014	**2016**	**2014**	**2016**	**2014**	**2016**	**2014**	**2016**
SO_2	19 860	5 660	2 178	2 206	8	8	1 632	177
NO_2	8 149	4 146	509	517	4 507	4 214	3 664	4 562
PM	1 094	610	2 280	2 311	2 044	2120	264	210

In 2016, the year following the introduction of sulphur limits, SO_2 emissions from ships decreased by approximately 92 per cent for traffic and by approximately 89 per cent for berthing, as compared to 2014. However, due to an increase in the number of bigger ships serviced by the ports of Gdansk and Gdynia, NO_X emissions increased.

There are 10 air quality monitoring stations in Tri-City and several are located in the vicinity of ports as shown in Figure 2.13. For all stations, the model quality criterion of 90 per cent is met, and the differences between the modelling results and the measurements are greater than the measurement uncertainty.

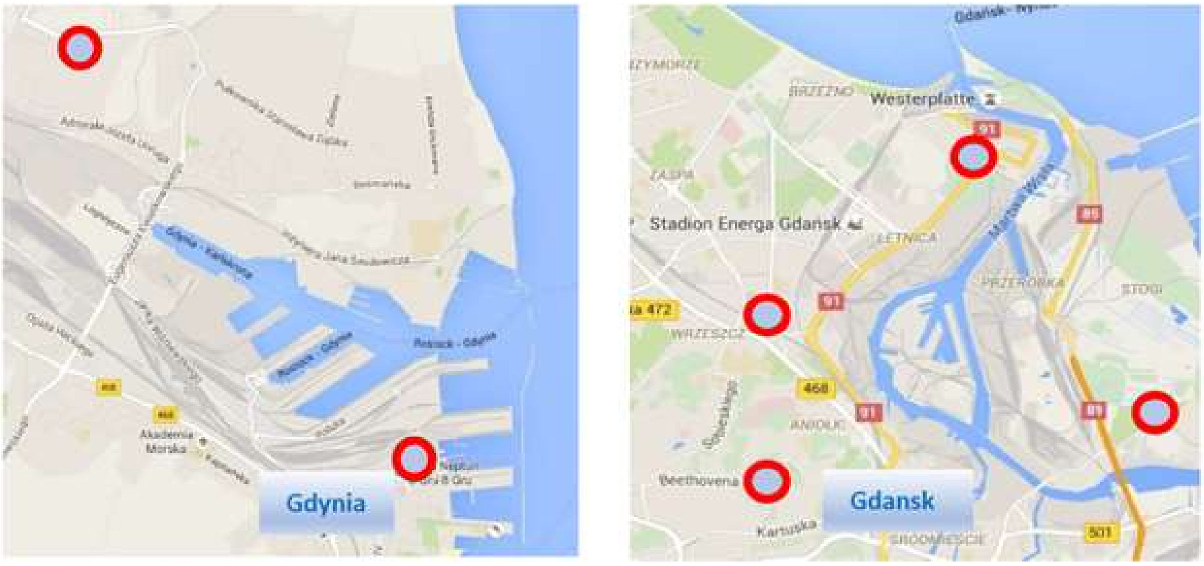


Figure 2.13 Air quality monitoring stations location in ports vicinity.

Impact of air quality on health in TriCity

Polish law defines air quality standards with regard to human health using concentration levels of certain substances.

Analysis of air quality was based on the identification of all sources of emissions and the relevant share that originated maritime transport. We also assessed the effectiveness of sulphur limits by comparing data from 2014 and 2016. Model calculations of yearly average pollutant concentrations are presented in Figures 2.14, 2.15 and 2.16.

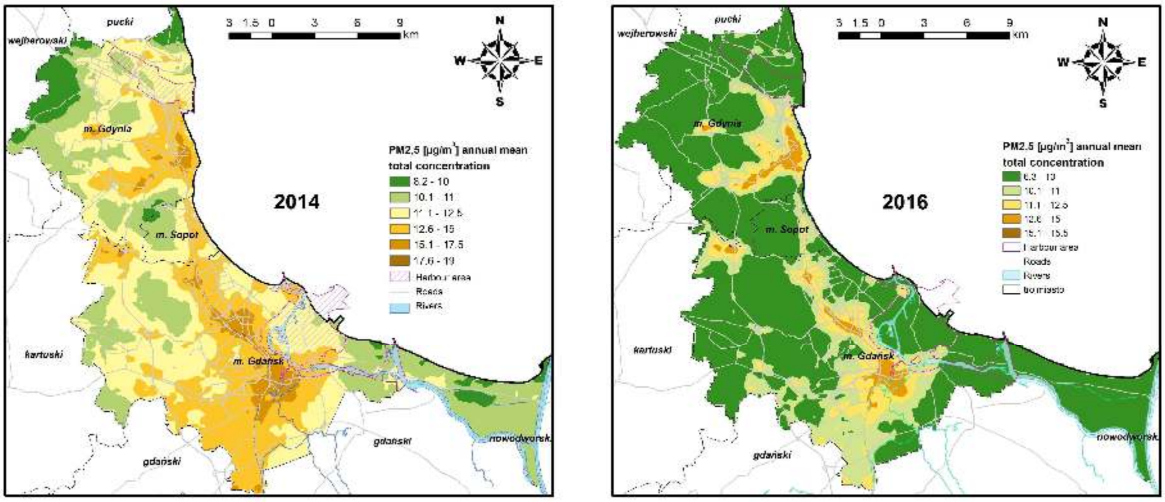


Figure 2.14. The comparison of annual average concentrations of PM2.5 in the port of Gdynia.

NO_2 concentrations from road transport dominate practically all receptors in the TriCity. However, annual average concentrations of NO_2 did not exceed national limits.

In 2014, ship traffic was the main source of SO_2 concentrations along the coast of Gdansk Bay and its ports. In 2016, however, in the entire Tri-City area, SO_2 concentrations were predominantly as a result of house heating.

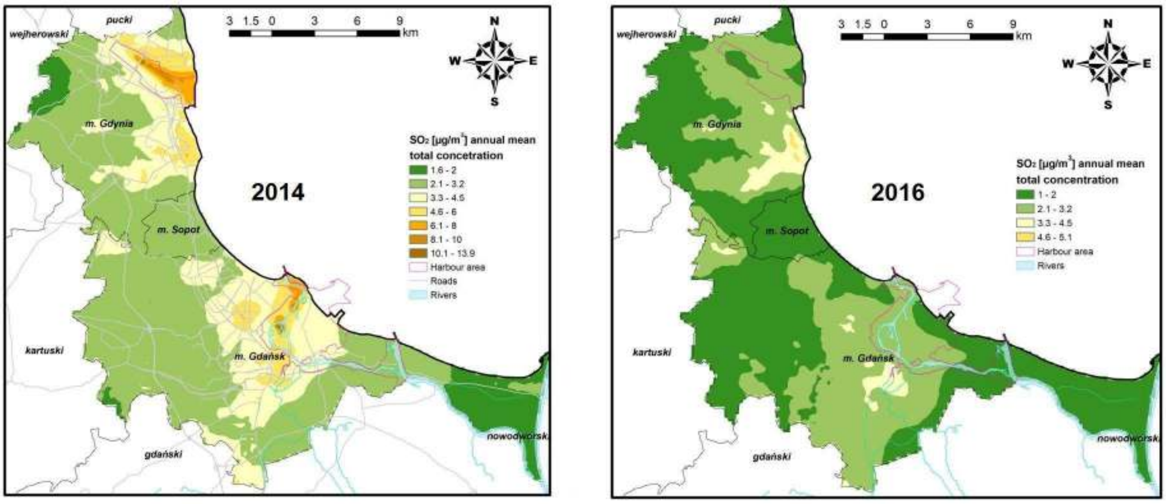


Figure 2.15 The comparison of annual average concentrations of SO_2 .

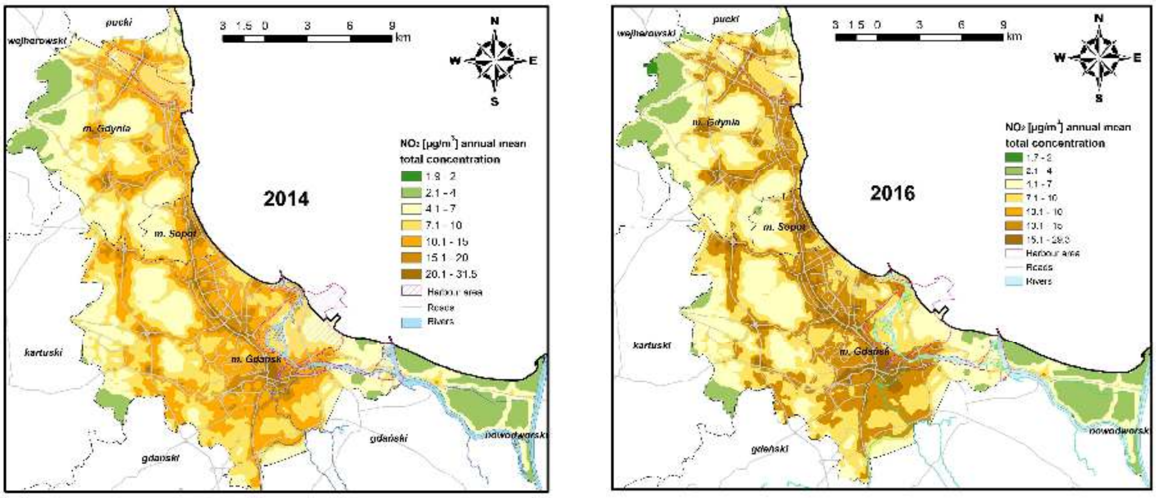


Figure 2.16 The comparison of annual average concentrations of NO_2.

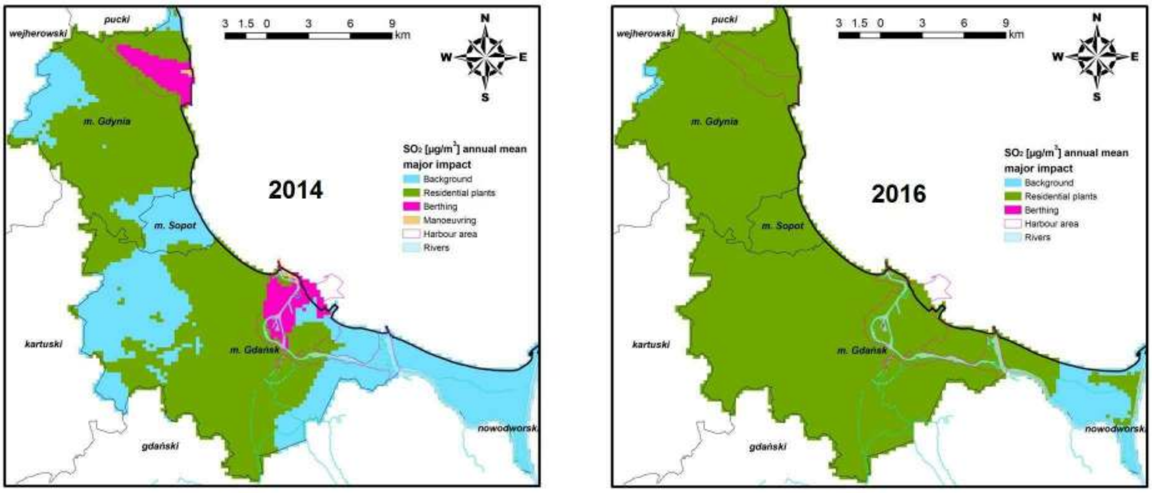


Figure 2.17 The comparison of share of maritime transport in total pollutant annual average concentrations.

Analysing average annual concentrations of SO_2 reveals there was a significant reduction in the share of emissions from maritime transport between 2014 and 2016. Similarly, national limits were not exceeded in 2014, nor in 2016.

In terms of all pollutants, the main sources affecting air quality in the Tri-City are road transport and house heating. The impact of maritime transport related to the ports of Gdansk and Gdynia is relatively small (Fig. 2.17).

Gothenburg

Gothenburg is the second largest city in Sweden, with about 1 million inhabitants in the metropolitan area. The economy was traditionally based on manufacturing industry and shipping, but it has diversified gradually. The port of Gothenburg, the largest in Scandinavia, has an advantageous location with about 70 per cent of industry and the population of Scandinavia within a radius of 500 km, including three capital cities - Copenhagen, Oslo and Stockholm (Table 2.2).

Table 2.2. Port of Gothenburg in figures.

Containers	644 000 TEU*
Ro-ro units	593 000
Cars	295 000
Passengers	1.7 million
Oil	23.5 million tonnes
Freight in tonnes	40.8 million

* Calculated as twenty-foot equivalent units – TEU. Source: Administration of Port of Gothenburg.

Due to emissions of air pollutants from industry, road traffic and shipping, air quality has been a long-standing problem in Gothenburg. The city centre is low-lying and surrounded by hills (figure 2.18). The valleys leading into the city all have major roads located in them. Low level temperature inversions occur frequently in winter and spring. Due to a range of policies being implemented, air quality has been significantly improved in recent years. The most problematic air pollutant at the moment is nitrogen dioxide.

Figure 2.18 Topographic map of Gothenburg.

The harbour and shipping activities are main contributors to emissions of nitrogen dioxide in the municipality of Gothenburg. Until regulations were implemented, the port was also a main emitter of sulphur dioxide.

The main berths of the port are however separated from the low-lying central city (5 – 8 km away) by hills, decreasing their contribution to the concentrations of air pollutants in the city centre. Ships do use ports located further up the River Göta Älv, however, which do involve passing through the city centre.

In this project, we have combined results from the EMEP MSC-W model runs described earlier in this report with Gaussian dispersion model calculations. The Gaussian model is one module in the Airviro system. The calculations utilised a detailed local emission database where all known sources of air pollutants are included. Meteorological data came from local measurements. The EMEP data is projected on to the finer grids (50 x 50 m) of the Gaussian calculations using linear interpolation.

We have calculated concentrations of SO2, $PM_{2.5}$ and NO_2 for 2016 with known real emissions, and for 2016 with sea traffic emissions from 2014. From here we can compare the real 2016 with a hypothetical 2016 where SECA was not implemented. The calculated concentrations were quality controlled using measurements from sites in Gothenburg.

For sulphur dioxide, the effect of regulating sea traffic emissions is significant (figure 2.19). Absolute concentrations were low, however, even before SECA, from both a historical and international perspective. Since there are no large land-based emitters of sulphur dioxide in the Gothenburg area, the concentrations are highest close to heavily trafficked seaways. The concentrations are far below European Union air quality standards, both for the real 2016 and for the hypothetical 2016 with higher sulphur dioxide emissions.

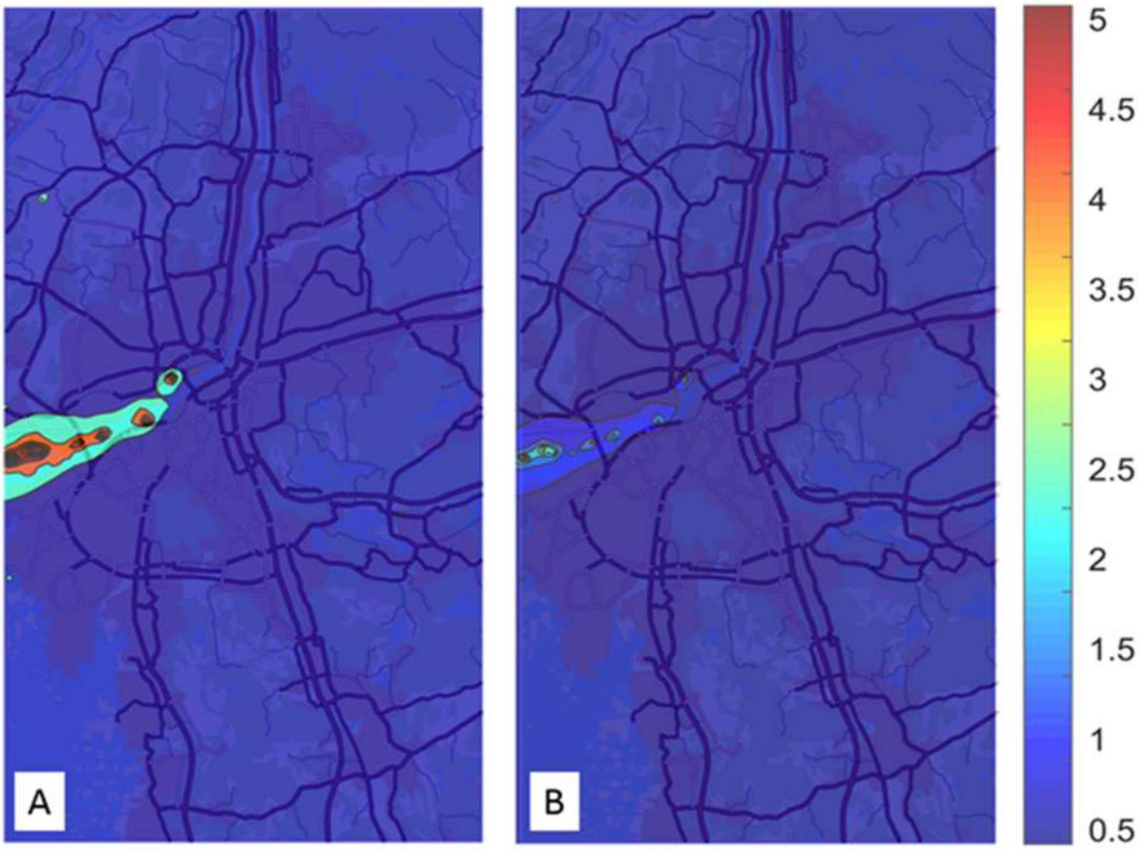


Figure 2.19. The calculated concentrations of sulphur dioxide in µg/m³ in 2016. Panel A shows the scenario where SECA was not implemented and panel B shows the actual concentrations.

The effect of SECA emission regulations was evident for $PM_{2.5}$, but less than for sulphur dioxide, as seen in figure 2.20. The highest concentrations occur in the harbour area, but there is also a significant local contribution to the concentrations.

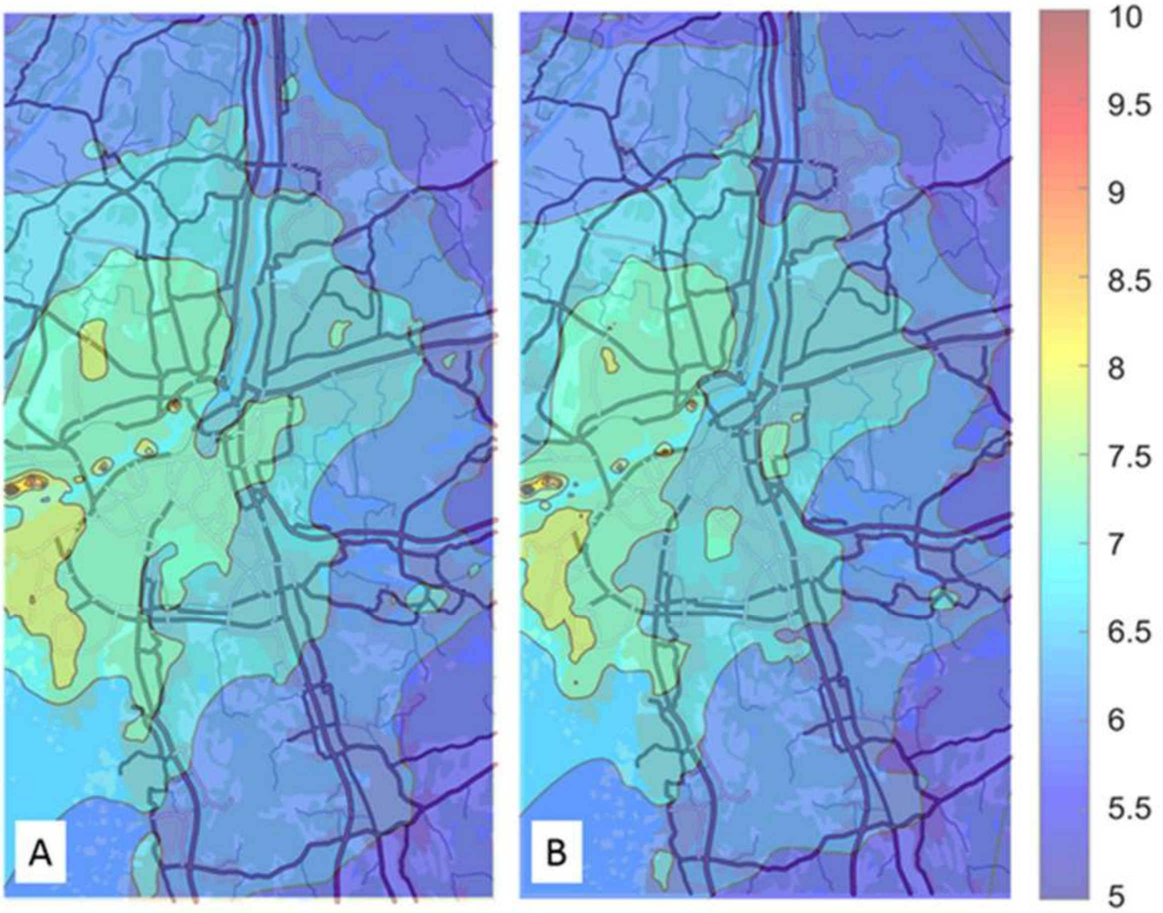


Figure 2.20 The calculated concentrations of $PM_{2.5}$ in µg/m3 in 2016. Panel A shows the scenario where SECA was not implemented and panel B shows the actual concentrations.

In our calculations, the effect of sulphur regulations on the concentrations of nitrogen oxides were minimal. That is likely due to both low and possibly unknown changes in nitrogen oxides emission, and the fact that road traffic is a large emitter. The changes in concentrations are not visible in the maps, and hence no scenario comparison is shown. In figure 2.21 we instead show the calculated concentrations of nitrogen oxides and the derived concentrations of nitrogen dioxide using an empirical formula.

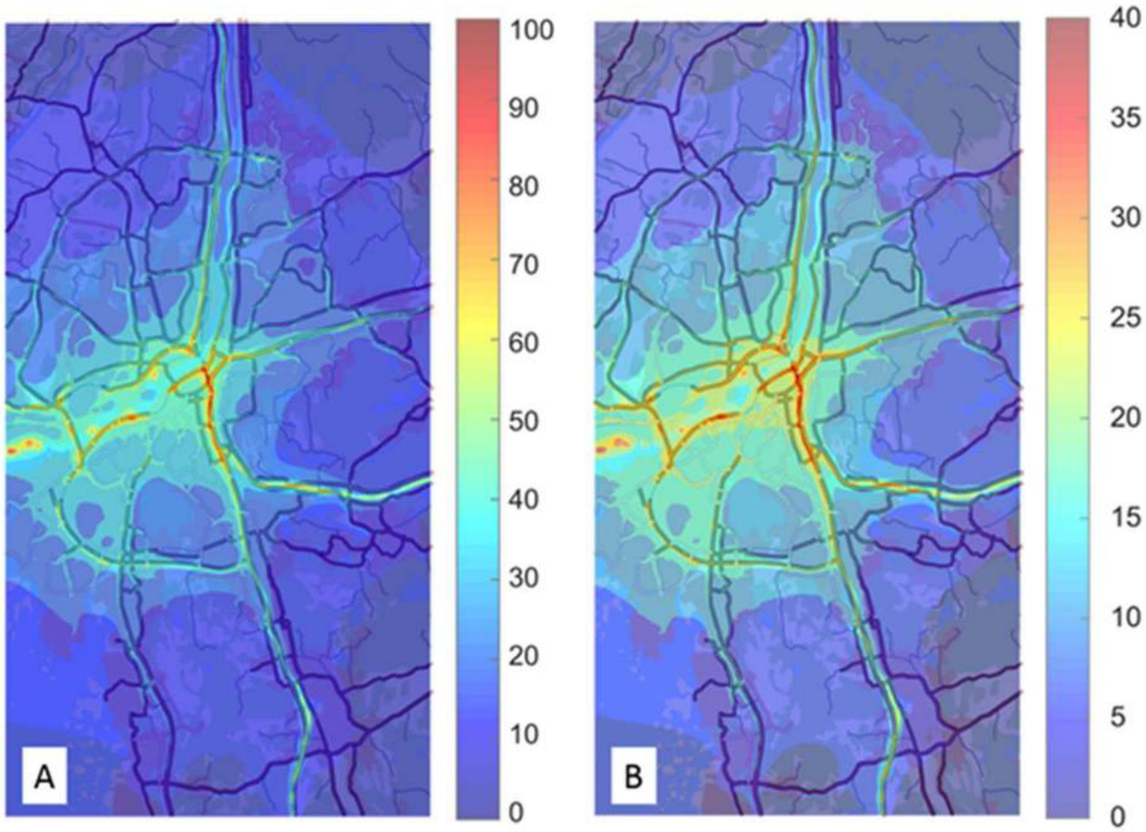


Figure 2.21 The calculated concentrations of NO_x (panel A) and NO_2 (panel B) in µg/m3 in 2016. Note that the colour scales are different between the panels.

Comparing air quality across three cities

Air quality measurements in Europe are conducted in order to have knowledge on the level of concentrations of air pollutants, to demonstrate the effect of abatement strategies and to assess public health effects.

Comparability of measurements across Europe is, therefore, very important and a lot of effort has been put in legislation, standardization, quality management systems, reference laboratories and their accreditation, defining the reference methods, interlaboratory comparisons, traceability of measurements and estimation of uncertainty of measurement results.

In this study, our aim was to demonstrate the comparability of air quality measurements within the pilot cities. This included the comparison of particulate matter measurements against the reference method defined by the EU directive, and also the comparison of calibration of the analysers for gaseous compounds in the pilot cities.

The quality management system (QMS) of the network in the pilot cities was audited in order to demonstrate the existence and functioning of the QMS, as well as to check if the QA/QC procedures conducted in the field follows the requirements set up in the relevant EN-standards. This provides a way to assess how well quality control procedures ensure the accuracy of the measurement results. Findings on the comparability of air quality measurement results in the pilot cities can be used to evaluate the model results obtained in the cities investigated (Waldén et al. 2019).

Comparison studies for PM_{10} and $PM_{2.5}$ were conducted using the EU air quality directive as a reference against the PM-analyser at selected sites in the three pilot cities. The study ran over a two-month period per city in order to verify the performance of the site PM-analyser against the reference method run by the Finnish Meteorological Institute (FMI).

Calibration of the analysers for gaseous air pollutants (NOx, SOx, CO, O3) was conducted at the selected site in Gothenburg and in the TriCity (Gdansk). Calibration did not succeed in St. Petersburg due to problems with Russian customs authorities. Instead, we inspected the operation and the facilities of the laboratory responsible for providing the calibration of the analysers to the whole air quality network in St. Petersburg.

A protocol for the comparison was prepared and it was followed during all the measurements in order to reach consistent results. Figure 2.22 shows a time series of daily averages for the site analyser for PM_{10} and $PM_{2.5}$ measurements, the reference method and the optical analyser of the FMI from Gdansk, St. Petersburg and Gothenburg.

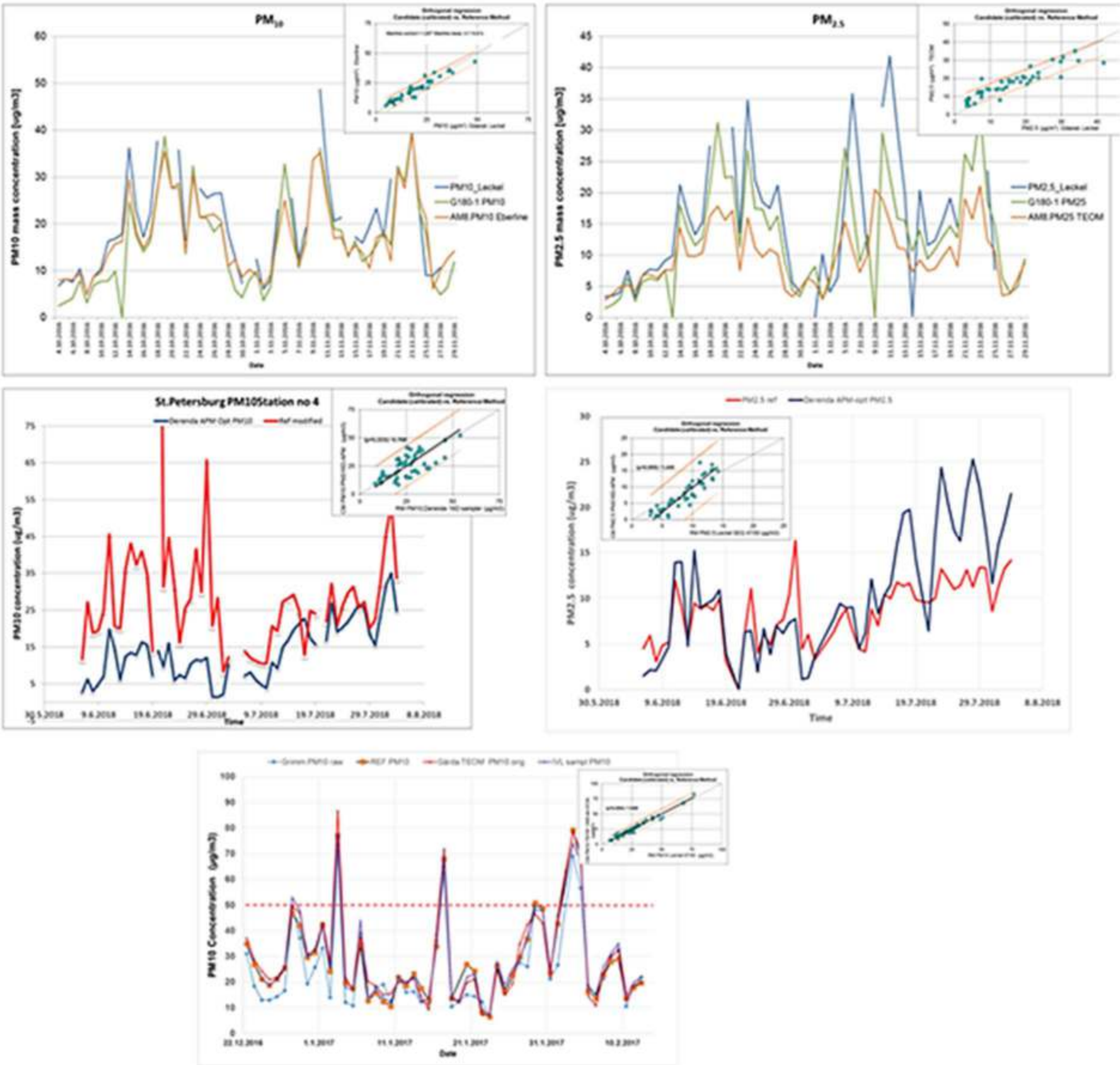


Figure 2.22 The daily average values of PM10 and PM2.5 mass concentration for site analyser and the reference method. The orthogonal regression analysis of the site analyser against the reference method is also presented in the small graph. The results from Eberline (PM10), TEOM 1400ab (PM2.5), optical analyser (PM10 and PM2.5) by Grimm and reference method at station AM8 in Gdansk (uppermost graphs). Results from Derenda APM (PM10), Derenda APM (PM2.5) and reference method (PM10 and PM2.5) at station no. 4 and no. 24 in St. Petersburg (middle graphs). Results from TEOM 1400ab (PM10), optical analyser (PM10), IVL-sampler (PM10) and reference method (PM10) at station Gårda in Gothenburg (lowermost graph).

In Figure 2.23 calibration results of the gaseous analysers from Gdansk and Gothenburg is presented. As mentioned earlier, calibration was not achievable in St Petersburg.

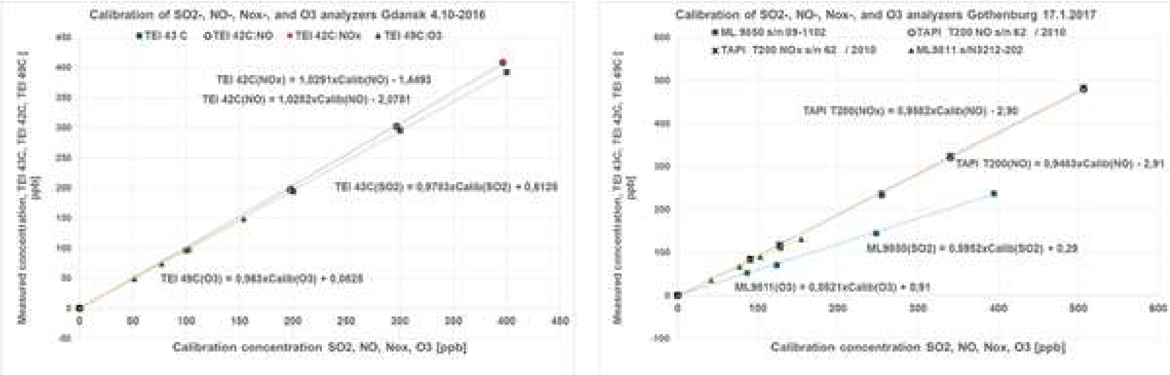


Figure 2.23 Calibration results for SO_2, NO-NOx and O_3 analysers in Gdansk (left) and in Gothenburg (right). In the x-axis the calibration concentration provided by FMI and injected into the site analysers for each gas compounds. The regression equations are also shown in the graphs.

A summary from the correction factors based on the comparison results for the particulate matter and gaseous compounds is presented in Table 2.3.

Table 2.3. Summary of comparison results from PM_{10}, $PM_{2.5}$ and from gaseous compounds of NO, NO_X, SO_2 and O_3. Correction factors are for the slope for PM-measurements and for the slope and intercept for gaseous compounds. ND means no data.

	Gdansk			**Gothenburg**			**St. Petersburg**		
	Slope	Intercept	Expanded uncertainty	Slope	Intercept	Expanded uncertainty	Slope	Intercept	Expanded uncertainty
PM 10	1,227y		13,8%	0,962y		13,3%	1,712 y		40,2%
PM2.5	1,864y		31,7%	ND		ND	0,694 y		69,7%
NO	0,973	2,021	11,9%	1,055	3,069	ND	ND	ND	ND
NOx	0,972	1,408	11,9%	1,044	3,027	ND	ND	ND	ND
SO2	1,022	-0,626	9,7%	1,680	-0,487	ND	ND	ND	ND
O3	1,038	-0,086	9,7%	1,174	-1,068	ND	ND	ND	ND

A more detailed explanation of this table can be found in the Notes section at the end of this report.

The comparison results for particulate matter fulfilled the requirements for the data quality objectives (DQO) set up by the EU directives in case of PM10 measurements in Gdansk and in Gothenburg. In case of PM2.5 measurements it was difficult to pass the DQO at the site investigated in Gdansk. In Gothenburg, lack of local PM2.5 measurements occurred at the selected site; therefore, the only PM2.5 measurement at the site investigated was conducted with the analyser that was delivered by FMI. In case of St Petersburg, performance of both PM_{10} and $PM_{2.5}$ measurement results did not fulfil the DQO requirements by EU, but passed Russian national standards.

Calibration of the air quality analysers for gaseous compounds succeeded extremely well at ARMAAG network in Gdansk, as shown in Figure 2.23. Good results were also detected in the cases of NO-NOx and O_3 measurements in Gothenburg but not for SO_2 measurements.

The purpose of the audit was to demonstrate existence of the QMS and whether it was used. We checked if the QA/QC procedures defined by the relevant EN-standards for the reference method were respected at the measurement sites.

It turned out that in Tri-City the quality system by ARMAAG was accredited according to EN ISO/IEC 17025 standard for the field measurements of gaseous compounds (but not for particulate matter). In general, the QMS was well-documented, including the plans for calibration and maintenance of the equipment. The QA/QC activities followed the requirements by the EN-standards. A few nonconformities were observed during the audit survey and were reported to those responsible for the network.

Gothenburg maintained the QMS that covered the activities in the field and fulfilled the requirements by the EN-standards. The QMS used was a “light version” of a quality system with some documentation such as instructions, logbooks and calendars but the network does not have a Quality Manual and it does not utilize EN ISO/IEC 17025.

In St Petersburg, the QMS maintained by SC-MINERAL followed the requirements of the national legislation and national standards. It includes defined QA/QC activities for field measurements that were similar but not exactly the same as those defined by EN-standards.

At each network the traceability of measurement results were arranged to the national or international standards as required by the Air Quality Directive (AQD).

CHAPTER 3

Health and environmental impacts of SECA

Introduction

This chapter summarises the impacts of emissions from shipping in the Baltic Sea on health and environment in the region. The impacts on health are based on modelled concentrations of pollutants from shipping described in Chapter 2. The impacts on environment are based also on modelled deposition of pollutants.

Health

In the year 2014, Baltic Sea shipping made a significant contribution to PM2.5 and sulphur deposition (Figure 3.1). As shown in Chapter 2, the stricter SECA regulations in 2015 resulted in marked reductions of the contribution to air pollution from Baltic Sea shipping. For health, concentration of fine particles (particles with a diameter <2.5 µm, $PM_{2.5}$) is the most important part of the air pollution mixture. Following SECA, PM2.5 from shipping in the Baltic Sea decreased in 2016 – on average by about 35 per cent in the countries close to the Baltic Sea.

The population exposure in a country depends both on the size of the population and the levels of air pollution. The mean exposure per person from Baltic shipping is highest in Denmark (about 0.5 µg/m3 $PM_{2.5}$), followed by Sweden, Estonia, Finland, Latvia, and Lithuania, while the total population exposure (in µg/m3 x persons) is highest in Germany and Poland due to their large populations.

Premature deaths

Many studies have examined the relation (“exposure-response functions”) between air pollution levels and the risk of premature death, for example how much mortality increases due to a certain increase in levels of $PM_{2.5}$. There is, however, still some uncertainty on the relation between $PM_{2.5}$ and premature death. EnviSuM, therefore, used two alternative exposure-response functions from literature.

With the first one, emissions from Baltic shipping are estimated to have caused about 1,500 premature deaths across 10 countries in 2014, decreasing to about 1,000 in 2016. With the second one premature deaths were about 3,400 in 2014, and 2,300 in 2016. In both cases the average reduction was 37 per cent.

The increased mortality can also be expressed in terms of years of life lost (YLL). The death of children will result in a larger number of YLL than the death of elderly people. In the EnviSuM case, the number of YLL is approximately 10 times the number of premature deaths.

Risk of non-fatal disease

In addition to premature mortality, air pollution also increases the risk of certain diseases. The most established causal relations are for “ischemic heart disease” (IHD, mainly myocardial infarction) and stroke. Using recent exposure-response functions for IHD and stroke, the estimated number of non-fatal disease cases “saved” due to due to decreased PM2.5 from Baltic shipping is about 500 each for IHD and stroke.

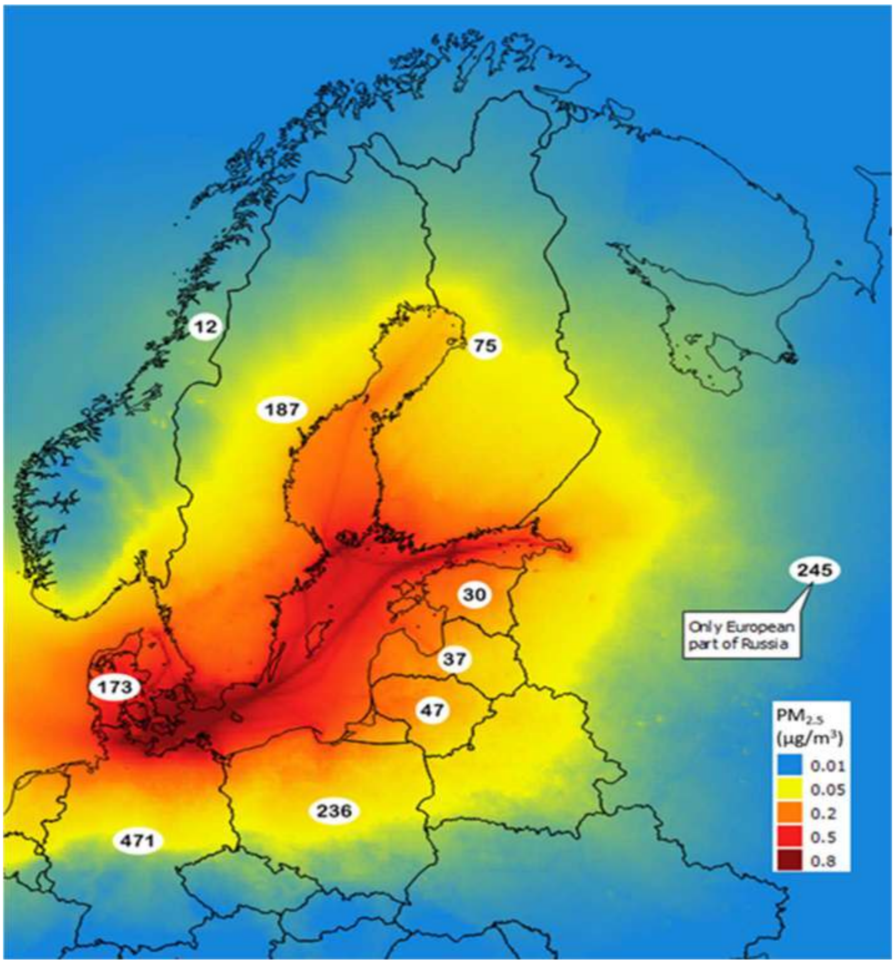


Figure 3.1 Estimated contribution to $PM_{2.5}$ from Baltic shipping in 2014 (before SECA) and number of premature deaths in each country due to this. Meteorology: average for 2014 – 2016. The estimate is based on an increase in mortality of 0.62% per μg/m3 of $PM_{2.5}$. With another exposure-response function (1.4% increase per μg/m3 of $PM_{2.5}$) the numbers are about two-fold higher.

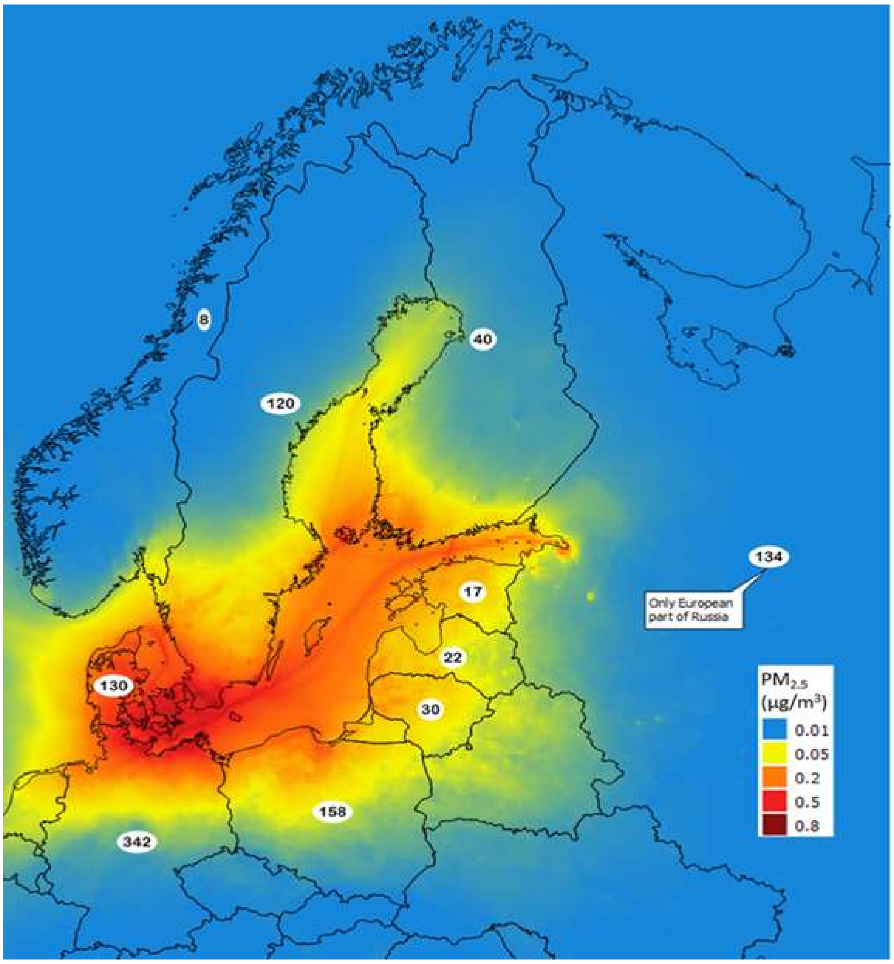


Figure 3.2 Estimated contribution to $PM_{2.5}$ from Baltic shipping in 2016 (after SECA) and number of premature deaths in each country due to this. Meteorology: average for 2014 – 2016. The estimate is based on an increase in mortality of 0.62% per µg/m3 of $PM_{2.5}$. With another exposure-response function (1.4% increase per µg/m3 of $PM_{2.5}$) the numbers are about two-fold higher.

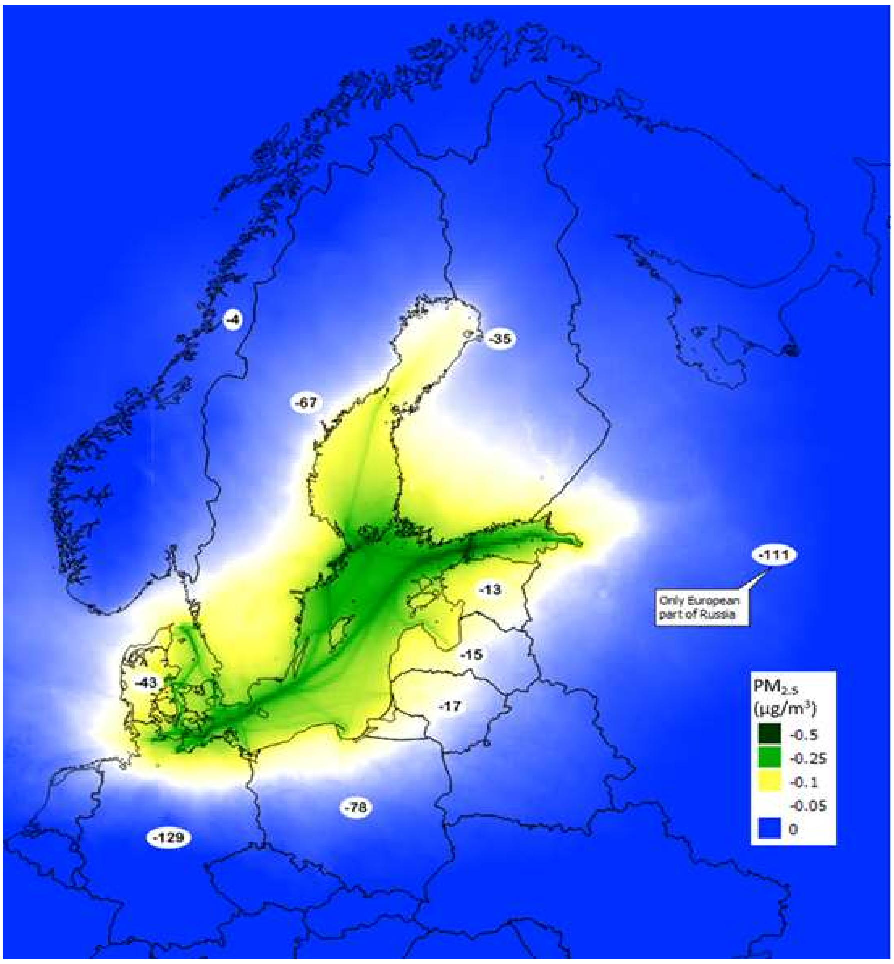


Figure 3.3 Estimated decrease in contribution to $PM_{2.5}$ from Baltic shipping between 2014 (before SECA) and 2016 (after SECA) and number of premature deaths in each country "saved" due to this. Meteorology: average for 2014 – 2016. The estimate is based on an increase in mortality of 0.62% per µg/m3 of $PM_{2.5}$. With another exposure-response function (1.4% increase per µg/m3 of $PM_{2.5}$) the numbers "saved" are about two-fold higher.

Regional health impacts in monetary terms

The environmental policy-making in the European Union emphasizes the "internalizing externalities" which requires also the valuation of human life (van der Kamp & Bachmann. 2015). According to Desaigues et al. 2011, the mortality due to air pollution was mainly calculated by multiplying number of premature deaths with the value of prevented fatality, i.e. "value of a statistical life" (VSL) until the end of 1990's. This approach has been widely used. However, it has pointed out that the changes of life expectancy are more suitable for valuation of mortality due air pollution and thus the value of a life year (VOLY) is suitable for monetary valuation.

We used two estimates based on these approaches to value the decrease in mortality in terms of life years lost from 2014 to 2016. The first is based on "value of a statistical life" (VSL) which is "translated to life expectancy by looking at accidental mortality and assuming this to be randomly distributed in the population at risk" (Steen 1999). The original value of average life expectancy produces €85,000 for willingness to pay (WTP) for one YLL, but as the OECD average life expectancy in 2015 has been extended from 75 to 80.6 years, the original value was modified accordingly to inflation-adjusted value of €111,000.

The second value was one of the estimates from European studies which have developed health-related cost assessment methodology since 1990's (van der Kamp & Bachmann 2015). These estimates are based on contingent valuation methodology and measure changes in life expectancy due to air pollution. Inflation-adjusted Value of a Life Year (VOLY) $40{,}000_{EUR2005}$ from NEEDS project was used for estimation of mortality due to the long-term exposure to air pollution (Desaigues et al 2007, 2011; van der Kamp & Bachmann 2015, see Table 3.1.). While there are considerable uncertainties in these methodologies and wide confidence intervals (lower bound $25{,}000_{EUR2005}$ and upper bound $100{,}000_{EUR2005}$ for VOLY of the NEEDS project), the selected value has been intended for the use of EU member states.

Table 3.1. The monetized values of the changes in life years lost (YLL) from 2014 to 2016. The decrease of the number of YLL has lead to gains in monetary values. The values have been calculated for both exposure-response functions. A. The inflation-adjusted WTP for one YLL modified from Steen 1999. B. The Value of a Life Year (VOLY) from Desaigues et al. (2007, 2011) is inflation-adjusted for 2018 (1 VOLY = $49{,}000_{EUR2018}$). The monetary values are presented in millions of Euros.

	A. Monetized values based on VSL, MEUR	B. Monetized values based on VOLY, MEUR
Sweden	**72 – 162**	**32 – 71**
Norway	**5 – 12**	**2 – 5**
Denmark	**52 – 118**	**23 – 52**
Finland	**40 – 90**	**18 – 40**
Germany	**145 – 327**	**64 – 145**
Poland	**105 – 237**	**46 – 105**
Estonia	**17 – 39**	**8 – 17**
Latvia	**18 – 41**	**8 – 18**
Lithuania	**20 – 46**	**9 – 20**
Russia*	**150 – 339**	**66 – 150**
Sum, Mean	**625 – 1412**	**276 – 623**

The total value of health benefits from SECA is €276-1412 million depending on the exposure–response function used, which corresponds to 5,633-12,719 years of life gained. Russia benefited the most, according to a more conservative estimate of €66-339 million and Germany close to that. This can be explained by the large population and proximity to heavily trafficked Baltic shipping lanes.

Morbidity

For estimates regarding morbidity, we used data on baseline incidence of ischemic heart disease and stroke from the Global Burden of Disease (GBD) project (ref IHME ghdx). We also used exposure response-functions from the ESCAPE-study for acute coronary events (Cesaroni et al. 2014) and stroke (Stafoggia et al. 2014).

The relative risk was 1.026 (95% CI 1.00 – 1.06) per µg/m3 of annual mean PM2.5 for IHD and 1.038 (95% CI 0.98 – 1.12) for stroke. To avoid double counting with mortality estimates we subtracted the numbers of deaths due to ischemic heart disease and stroke from the incidence, using data from the GBD project and assuming that half the deaths were from new (incident) cases of IHD/stroke.

The number of extra cases of morbidity in IHD and stroke due to $PM_{2.5}$ emissions from Baltic shipping are highest in Germany and Poland, mainly due to large exposed populations (Table 3.2). They are also relatively high in Denmark and Sweden due to higher exposures of $PM_{2.5}$ from shipping, and in Russia, again due to population size.

The number of IHD and stroke cases due to PM from Baltic shipping decreased by around 500 each after 2015, a decrease of roughly one third.

Table 3.2 Estimated number of premature cases of ischemic heart disease and stroke due to $PM_{2.5}$ emissions from Baltic shipping in 2014 and 2016.

	Extra cases of IHD 2014	**Extra cases of IHD 2016**	**Reduction (n)**	**Extra cases of stroke 2014**	**Extra cases of stroke 2016**	**Reduction (n)**	**Reduction (%)**
Sweden	208	134	74	180	116	64	35%
Norway	13	8	5	18	11	7	39%
Denmark	210	158	52	169	127	42	25%
Finland	93	50	44	100	53	46	47%
Germany	521	379	142	465	338	127	27%
Poland	231	155	76	254	170	83	33%
Estonia	34	19	15	36	20	16	45%
Latvia	28	17	11	47	28	19	40%
Lithuania	44	29	16	58	37	21	36%
Russia*	166	91	75	228	125	103	45%
SUM/MEAN	1 548	1 039	510	1 555	1 026	528	37%

Environmental impacts

In the Baltic Sea Region, environmental degradation such as acidification and eutrophication, are causing scientific and public concern. Regulations to reduce airborne emissions have been successful in lowering sulphur deposition. Reductions in deposition of oxidised nitrogen are expected in the future.

Sulphur deposition

In 2014, total deposition of sulphur in the study area was approximately 1751 kt in 2014 (Table 3.3), with 2.2 per cent of this originating from Baltic Sea shipping. The European side of Russia received one fifth of ship-originated SO_X deposition (8,445 kt).

Sweden received around 10 per cent and Finland around 7 per cent of sulphur deposition from Baltic Sea shipping, which was approximately 5-6 per cent of the total SO_X deposition that fell to these countries.

The remaining countries received 16.5 per cent of ship-originated SO_X deposition. In Poland the share of SO_X deposition from shipping was only 0.62 per cent of the total deposition, but in Denmark and Estonia, shipping accounted for more than 7 per cent of the total.

Table 3.3. Atmospheric deposition of sulphur (SO_X) in the study area in 2014 and 2016 calculated with average meteorology of the years 2014-2016. TOT is total of dry and wet depositions. Depositions from Baltic Sea shipping is included in TOT, but the share is also shown separately as SHIP. SHIP/TOT is the share of the ship-originated SO_X deposition of the total deposition.

	SO_X DEPOSITION IN 2014				SO_X DEPOSITION IN 2016			
Country	**TOT, kt**	**TOT, %**	**SHIP, kt**	**SHIP, %**	**TOT, kt**	**TOT, %**	**SHIP, kt**	**SHIP, %**
Denmark	12.902	0.7 %	0.982	2.6 %	10.802	0.7 %	0.099	2.3 %
Estonia	10.841	0.6 %	0.776	2.0 %	9.344	0.6 %	0.084	1.9 %
Finland	47.501	2.7 %	2.666	7.0 %	42.455	2.6 %	0.293	6.7 %
Germany	139.157	7.9 %	1.25	3.3 %	129.152	8.0 %	0.148	3.4 %
Latvia	17.046	1.0 %	0.771	2.0 %	14.968	0.9 %	0.093	2.1 %
Lithuania	22.732	1.3 %	0.572	1.5 %	20.14	1.2 %	0.061	1.4 %
Norway	55.911	3.2 %	0.692	1.8 %	54.473	3.4 %	0.098	2.3 %
Poland	203.261	11.6 %	1.259	3.3 %	183.611	11.3 %	0.03	0.7 %
Russia*	1 076.243	61.4 %	8.445	22.2 %	1 022.069	63.0 %	1.028	23.7 %
Sweden	56.951	3.3 %	3.786	9.9 %	50.163	3.1 %	0.436	10.0 %
Baltic Sea**	109.299	6.2 %	16.869	44.3 %	86.106	5.3 %	1.975	45.5 %
Total	1 751.844	100.0 %	38.068	100.0 %	1 623.283	100.0 %	4.345	100.0 %

*European side of Russia. **The sea areas of the Baltic Sea.

In 2016, after SECA regulations came into force, total deposition of SO_X in the study area decreased by 7.3 per cent. The share of SO_X deposition originating from shipping, however, dropped by more than 88 per cent, to 4,345 kt.

In Denmark, Estonia, Latvia and Sweden, where in 2014 the share of ship-originated deposition was higher than in other countries, total deposition of SO_X decreased the most.

In all countries in the study area, SO_X deposition from Baltic Sea shipping decreased by approximately 85-90 per cent. In Poland, the reduction was more than 97 per cent.

In both 2014 and 2016, the marine area of the Baltic Sea received 44-45 per cent of ship-originated SO_X deposition (Table 3.3).

In 2014, ship-originated SO_X deposition was 15 per cent of total SO_X deposition. In 2016, the share of deposition on the sea surface that originated from ships dropped to 2.29 per cent of total.

Shipping is an important source of local atmospheric SO_X loading in the marine area. The spatial patterns of ship-originated SO_X deposition followed the busiest shipping lanes and the area around them (Figure 2.2).

In 2014, the extent of SO_X deposition in land areas was much greater than in 2016, reaching far into land areas. In the vicinity of the busiest shipping lanes, the highest depositions were approximately 100 times higher than in 2016. Following the decrease in SO_X from shipping, the distribution was far less extensive in 2016. This can also be seen in the decrease of ship-originated deposition in land areas of adjacent countries (Table 3.3.).

Nitrogen deposition

In 2014 total deposition of NO_X from the Baltic Sea shipping in the study area was 3052 kt (Table 3.4). This amounts to 2.6 per cent of total atmospheric deposition. The European side of Russia received almost half the total NO_X depositions that fell in the study area (46 per cent / 1429,36 kt), Germany almost 20 per cent and Poland around 12 per cent.

However, the share of deposition that originated from shipping was very low, 2 per cent or less.

The picture is different in Estonia, Finland and Sweden. In 2014, these countries together received 8 per cent of total NO_X deposition in the study area, but the share that originated from shipping was 7-9 per cent of total NO_X deposition in these countries.

In 2016, total NO_X deposition on land areas was almost the same as in 2014 (Table 3.4). This includes ship-originated NO_X deposition, which changed very little in this time, less than 1kt in each country and the sea area. In Lithuania and Norway, the amount of NO_X deposition from Baltic Sea shipping even increased slightly in 2016.

Spatial patterns of ship-originated NO_X deposition were rather similar in 2014 and 2016 (Figure 3). This is probably because the amount of atmospheric NO_X deposition was almost the same and modelling was performed with averaged meteorological conditions.

There is a similar picture in sea areas. While sea areas received only 7 per cent of total NO_X deposition in the study area, the share that originated from shipping was almost 8 per cent of total NO_X marine deposition.

Deposition of NO_X was highest in the narrow zones on the landward side of the coastlines. There were slightly elevated deposition in the central Baltic Sea and the Gulf of Finland, where ship traffic is heaviest.

Table 3.4 Atmospheric deposition of nitrogen in the study area in 2014 and 2016 calculated with average meteorology of the years 2014-2016. TOT is total of dry and wet depositions. Depositions from Baltic Sea shipping is included in TOT, but the share of it is also shown separately as SHIP. SHIP/TOT is the share of the ship-originated NO_X deposition of the total deposition.

	NO_X DEPOSITION IN 2014				**NO_X DEPOSITION IN 2016**			
Country	**TOT, kt**	**TOT, %**	**SHIP, kt**	**SHIP, %**	**TOT, kt**	**TOT, %**	**SHIP, kt**	**SHIP, %**
Denmark	48.627	1.6 %	1.822	2.3 %	47.391	1.6 %	1.804	2.3 %
Estonia	24.167	0.8 %	2.193	2.8 %	23.605	0.8 %	2.102	2.7 %
Finland	84.801	2.8 %	7.171	9.1 %	82.505	2.7 %	6.871	8.9 %
Germany	588.236	19.3 %	2.655	3.4 %	577.506	19.1 %	2.586	3.3 %
Latvia	41.334	1.4 %	2.365	3.0 %	40.455	1.3 %	2.311	3.0 %
Lithuania	54.368	1.8 %	1.764	2.2 %	53.384	1.8 %	1.770	2.3 %
Norway	67.491	2.2 %	2.022	2.6 %	67.761	2.2 %	2.059	2.7 %
Poland	376.426	12.3 %	4.590	5.8 %	366.571	12.1 %	4.560	5.9 %
Russia*	1 429 .360	46.8 %	29.156	36.9 %	1 428.733	47.4 %	28.207	36.4 %
Sweden	132.100	4.3 %	9.387	11.9 %	129.422	4.3 %	9.323	12.0 %
Baltic Sea**	204.659	6.7 %	15.947	20.2 %	199.914	6.6 %	15.801	20.4 %
Total	3 051.569	100.0 %	79.072	100.0 %	3 017.247	100.0 %	77.394	100.0 %

*European side of Russia. **The sea areas of the Baltic Sea.

Evaluating emission changes in monetary terms

Sulphur and nitrogen depositions were monetarised using coefficients found in literature.

We chose to use the method of Ecovalue08 for acidification from Ahlroth et al (2011) and omitted health effects as they were calculated separately. This method was decided on as it is developed for northern parts of Europe. It is quite conservative, however and equalled a value of 3.4 €/kg.

For nitrogen deposition we used a coefficient (c. 1.5 €/kg) consisting of values from agriculture, buildings, ecosystems and fertilization effects from Turner et al. (2004) and Weidema (2009).

Environmental savings from sulphur deposition

The decrease in ship-orignated sulphur deposition from 2014 to 2016 reduced the value of environmental impacts by at least €109 million in the entire study area.

The European side of Russia gained the highest benefit, at nearly €24 million, followed by Sweden with €11 million and Poland as well Germany with €4-3.5 million of reduced environmental impacts. In Lithuania and Norway, where the share of sulphur from Baltic Sea shipping was low, the decrease was lowest, €1.6-1.9 million.

Environmental savings from nitrogen deposition

The small 2.1 per cent decrease in ship-originated nitrogen deposition from 2014 to 2016 returned a reduction of €2.3 million in the study area. In the European side of Russia, the decrease was highest, €1.33 million.

For most countries, the return ranged from €25,000 to €422,000. In Lithuania and Norway, where nitrogen deposition increased, environmental costs increased from €8,000 and €52,000.

Critical loads

A critical load (CL) is defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge'. CLs are another way to evaluate the environmental effects of pollutants.

CLs are calculated for terrestrial or aquatic ecosystems, and a 'sensitive element' can be any part of an ecosystem, such as fine roots in forest soils or fish in a lake. CLs were originally derived in the context of acidification limits for sulphur and nitrogen deposition. Limits for the eutrophying effect of nitrogen depositions have also since been derived.

No methodology for CLs yet has been established to derive critical loads for marine ecosystems. In contrast to deposition, a critical load for a site is an ecosystem property and so does not change over time.

If a deposition is higher than the CL at a site, the CL is said to be exceeded. To obtain a single exceedance number for a grid cell (or any other region) the so-called average accumulated exceedance (AAE) is used, defined as the weighted mean of the exceedances of all ecosystems within the grid cell, with the weights being the respective ecosystem areas. In this paper the current European CL database for acidity and eutrophication CLs was used.

Calculations on whether critical loads have been exceeded were made for all three meteorological years using the following emission scenarios:

_ AllEm 2016: All emissions with 2016/2015 emissions.
_ No Balt: No Baltic Sea ship emissions. Elsewhere 2016/2015 emissions
_ Balt 2014: 2014 Baltic Sea emissions. Elsewhere 2016/2015 emissions

For acidification, the clear difference in sulphur deposition from shipping between years 2014 and 2016 can be seen as a slight decrease on critical load exceedances (Table 3.5). The difference remains slight as the situation of general acidification has improved already in the past in the area due to regulations of land-based sources. This is understandable as most shipping depositions are in the Baltic Sea itself and there are no established methods for assessing critical loads on sea water.

For critical loads of eutrophication there is more influence from shipping emissions. This situation has not changed since 2014 because the regulations have not changed.

Table 3.5 Exceedance (AAE; in eq/ha/a) and exceeded area (Exarea; in percent of the total ecosystem area given in column 2) for critical loads of *acidification* for the 3 deposition scenarios in the countries bordering the Baltic Sea (including Norway).

	Scenario:	**AllEm 2016**		**NoBalt**		**Balt 2014**	
	Ecoarea (km^2)	Exarea (%)	AAE (eq/ha/a)	Exarea (%)	AAE (eq/ha/a)	Exarea (%)	AAE (eq/ha/a)
DE	106870.5	44.1	246.5	43.9	244.1	44.2	247.4
DK	5692.3	11.9	14.3	6.7	9.1	13.7	18
EE	27229.7	0.1	0.1	0.1	0.1	0.1	0.1
FI	286	0.7	0.4	0.6	0.3	0.7	0.4
LT	22197.8	28.4	83.2	27.9	78.1	28.6	84.6
LV	36630.2	3.7	3.4	2.8	2.8	3.8	3.6
NO	320449.3	11.3	20.2	10.9	19	11.4	20.6
PL	96845.7	32.9	120.2	32.3	117.6	33.1	121
RU	624631.4	1.6	1.7	1.4	1.7	1.7	1.8
SE	395225.1	5.2	3.6	5.1	3.2	5.7	4.1
All	1636058	9.4	30	9.1	29.2	9.6	30.3

Conclusions

Reducing sulphur emissions will benefit the world's health and environment. For countries bordering the Baltic Sea, the EnviSuM project estimates that 500 – 1,000 premature deaths every year have been prevented as a result of Baltic Sea SECA regulations.

In addition, a large number of non-lethal cases of heart attacks and stroke have been prevented, and reduced shipping emissions in the Baltic Sea have also improved the environment and health in countries further away.

The health impacts were estimated to be at least M€670 annually, although valuing human life is controversial. It is common to use cost-benefit analyses of this kind when evaluating regulations, which is why we chose to make it part of this discussion.

Our estimate on human health is rather conservative, as only the effects of $PM_{2.5}$ were considered and were in line with calculations before the regulations were introduced.

Some other studies have also included the direct health effects of SO_X. Our results are also still lacking the effects on morbidity, however mortality usually accounts for around 90 per cent of health effects.

The changes were significant even in the cities that already had good air quality and that already had regulations in place to limit sulphur emissions - this is quite remarkable.

The 0.1 per cent sulphur limit was already in place in port areas before our health analysis started.

The monetarised value of environmental effects was less than that of human health but was not insignificant. This was a first attempt at including environmental effects in the debate. The analysing the critical loads shows a minor effect of SECA.

CHAPTER 4

ECONOMIC IMPACTS

Three years of sulphur regulations have led to many changes in the maritime sector. Many vessels in the Baltic Sea have been the first in the world to implement these changes.

An aim of the project was to create "Economic Guidelines for SECA", and, having assessed the costs and benefits of SECA regulations, provide political and maritime market stakeholders with recommendations.

This included evaluating emission abatement costs, administrational burdens, changes in modes of transport as well as socio-economic impacts related to public health and environment.

Here we present the approach of the European maritime industry to complying with SECA regulations, as well as impressions of the economic impact on their businesses. This input helps give a clearer picture as to the status quo as well as highlighting where the focus of future regulation should be.

Investment analysis

We evaluated investment relating to SECA regulation on a micro and macro level, based on previous studies, a Baltic Sea Region-wide survey and a number of business case studies. The timing of the project was a great opportunity to compare the situation before SECA regulations came into force in 2015. Data from 2014 and 2017 was used to assess the effects of the regulation (Olaniyi 2017; Olaniyi et al. 2018; Atari et al. 2019).

Our aim was to identify and evaluate key SECA-related economic activities in both the public and private sector. This included planned and already-executed investments, as well as changes in business processes for the most affected sectors - ports, ship operators, shipping industry companies and public sector bodies.

Costs of implementing the SECA regulations include abatement costs, investment costs and other costs, such as loss of income while a ship is being retrofitted. A time series analysis method was used to analyse this in more detail.

The overall results have been used to create a web-based visualised economic decision tool, that will help companies estimate costs related to SECA regulations and decide which investments to make in order to comply.

Our findings

Compliance with SECA requires significant investment decisions by maritime stakeholders. Research showed that low bunker prices have alleviated the some of the costs of SECA but the economic effects are spread unevenly.

Compliance in the BSR region is high. The effects on growth and cohesion, however, are slightly negative in smaller regions, where some maritime companies are very closely linked to the economic well-being of the area.

Some traditional fuel companies are not able to cope with the decreasing demand for heavy fuel oil because their major product is no longer competitive in the market (Olaniyi et al. 2018).

A BSR-wide survey assessing the economic impact of SECA regulations from the view of maritime stakeholders was conducted. A scale from showing the degree to which a SECA impact is very negative to very positive was used, as shown in table 4.1.

Table 4.1 Factor dimension of economic impact of SECA regulations

What is the impact of SECA regulations on the maritime businesses and the BSR?
Overall economic impact on the BSR
Impact on blue growth in the BSR
Impact on your product/service costs
Impact on your pricing
Economic impact on your company development
Impact on innovation of maritime sector in the BSR
Impact on attractiveness of the BSR for foreign direct investments (FDI)
Change of cargo flows within Europe
Change on transport modal split within the BSR
Reputation/branding of the BSR

Nearly all mean results for all the questions were close to zero, suggesting that views on the impact of SECA are relatively homogenous among the maritime sector.

The impact on economic parameters such costs, pricing, foreign direct investment (FDI), cargo flow and modal split, where other forms of transport are used instead of shipping, are considered negligible. Significant positive SECA impacts were attributed to bringing innovation to the sector and enhancing the reputation of the BSR.

Response outcomes are sector specific - ports, for example, feel slightly negative about modal split while ship-owners are positive. Responses are also country-specific - Danish maritime stakeholders, for example, are more positive about the overall impact of SECA regulations compared to their Estonian counterparts.

Economic development of maritime sectors, known as 'Blue Growth', cargo flows and branding/reputation of the Baltic Sea Region are the most important factors linked to the "overall impact of SECA". This suggest a positive perception on these factors will improve the perception on SECA.

The future development of oil markets is uncertain but currently, fuel prices are around the 2014 annual average. This suggests that the shipping companies that did not investment in abatement technology could end up falling into a strategic trap where an increase in oil prices would ramp up their costs. This situation can force an increase in transport prices that weakens their competitiveness in the maritime industry. On the other hand, ship-owners who decided to invest in SECA-compliant abatement technologies earlier on may enjoy increasing benefits of higher margins from using cheaper HFO.

A new business model for small/medium fuel producing companies

Compliance with SECA regulations requires investment decisions by maritime fuel producers as well as ship-owners, particularly in the case of scrubber installation.

The concept of a Maritime Energy Contract is a dynamic market instrument designed to deliver emission reductions and competitive advantages for both the ship-owner and the fuel company. The Maritime Energy Contract model (MEC, MEC Price = Energy supply + scrubber costs + adjustments) is a synthesized conceptual and empirical mapping tool that offers a balance between regulatory demands and compliance.

In a new proposed model, the Energy Supply Contract (ESC) concept is transferred to the maritime sector using scrubber technology - whereby fuel producers supply heavy fuel oil to contracted ships directly, pre-financing the scrubber project for a particular vessel in order to ensure SECA compliance. This creates a win-win situation for both ship-owners and fuel producers.

The MEC shows how the implementation of a new business model can increase the capacity of private companies to make profitable investment decisions related to clean shipping.

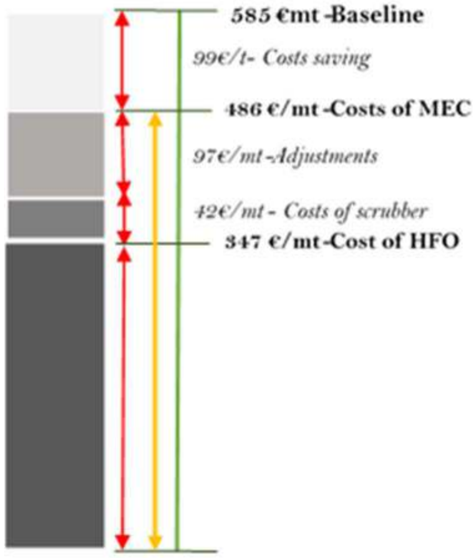


Figure 4.1 Cost savings in MEC model

The model further facilitates collaborative problem-solving and flexible investment management among companies, helping them to adjust to shifting market demands and new production technologies.

Developing the SECA investment decision tool

The study considered incentives for maritime companies making investment decisions related to clean shipping and maritime fuel management.

The Value-at-Risk model was used to demonstrate the risks associated with a scrubber as an abatement technology for SECA. This produces an estimate of a project's value on a set of random variables to assess the risk associated with it.

Traditionally, financial assessments are based on capital budgeting methods comprising cash flow analyses and net present value calculations. The findings reveal that the Real-Option approach, where the investor has the right to invest in an underlying asset at a specified fixed price during an agreed period of time or at a given date, represents a more realistic, reliable and promising method for the evaluation of abatement projects, especially in markets that are highly volatile.

The results can be applied to the evaluation of all projects in the maritime industry where there is price variation of an underlying asset during a specific period.

The SECA investment decision tool was developed to validate a stochastic approach for assessing real options for compliance with maritime sulphur regulations and to indicate the best short or long-term investment and capital budgeting strategies for the future.

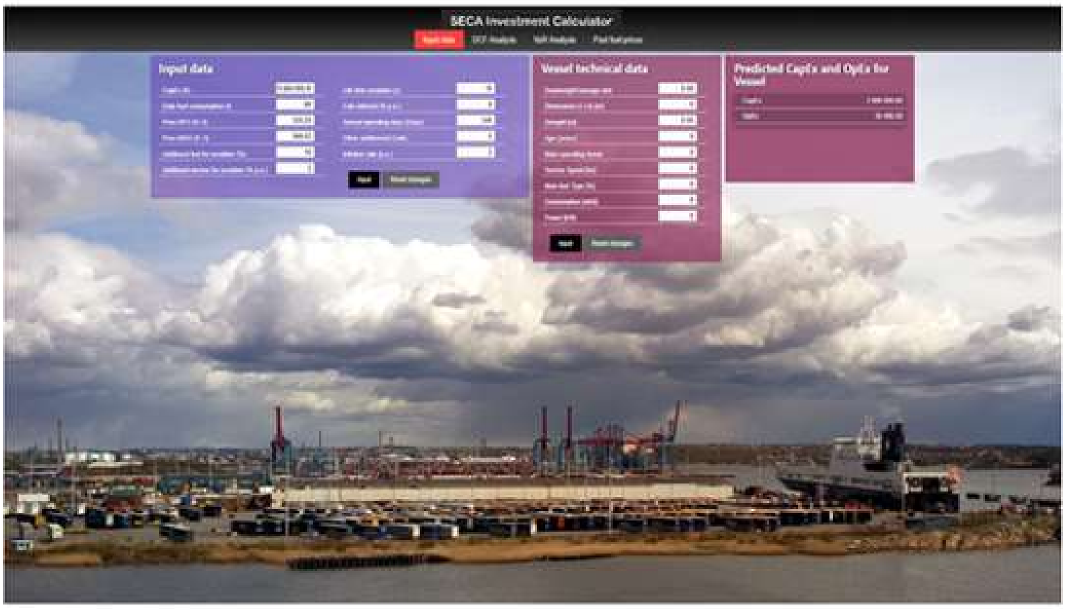


Figure 4.2. Show the economic performance of running a scrubber. A potential investor has the flexibility to re-evaluate the scrubber project and redefine a new strategy if necessary.

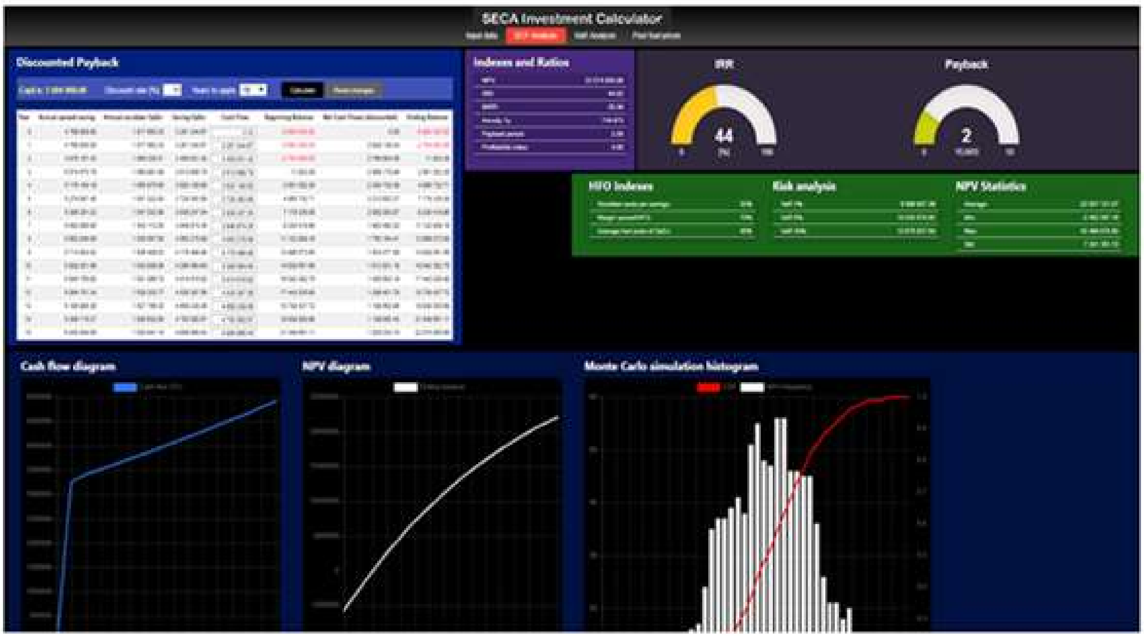


Figure 4.3. Show risk analysis from SECA investment by highlighting the value of different fuel and their spread.

Figure 4.4. Simulate fuel price predictions and volatility to predict investment outcomes. This contains critical policy implications for industry operators, Baltic Sea regulatory authorities and the International Maritime Organisation.

Figure 4.5. The different dashboards present clear pictorial outcomes and indications of the imputed data.
http://envisum.ttu.ee/envisum.dash

The administrative burden

Administrative burdens are costs incurred whenever a business is required to provide information as part of new regulations. These are obvious costs, such as materials or services, that can be measured objectively.

The Standard Cost Model (SCM) is generally used for the calculation of administrative burden costs. This defined by Renda et al (2013) as the sum of the costs of all activities necessary to meet the obligation multiplied by the number of repetitions of such activities during the given period.

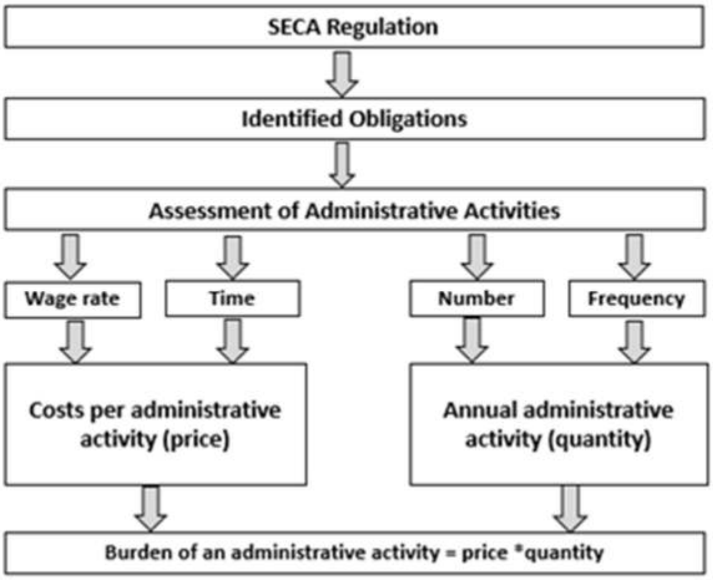


Fig. 4.6 SECA Regulations Administration Burden Analysis Framework. Adapted from Renda et al. (2013)

The use of the SCM usually assumes some estimates. These estimates are, however, carefully quantified to ensure they are comparable with ensuing tasks.

Evaluating the SECA administrative burden involved two phases - identification and then measurement. The identified SECA information obligations for ship-owners are (Olaniyi & Prause 2019):

- recording bunker delivery notes
- time spent recording fuel samples. For ships using scrubber technology, keeping a scrubber emissions logbook & waste disposal logbook
- fuel switchover before entering SECA
- training and awareness of staff, including recruitment
- installation and maintenance days
- time to write applications for subsidies, grant and loans related to SECA investments and other specified obligations.

All maritime stakeholders are quite conversant with their respective information obligations under SECA regulations. Case studies used in this study included the Scandlines Ferry Company, Euroafrica Shipping Line, container ships operating between SECA and Asia/Africa and the Port of Tallinn/Maritime Administration.

The results show SECA-related information obligations that affect ship-owners the most are

(1) Recording in the ship's emission logbook. This takes 10 minutes every day and increased by an extra 2.5 hours, five times a year, i.e. for each bunkering (for intra- SECA traffic).
(2) Extension of staff training programmes on ships, which now take place for one hour once or twice a month - equivalent to about two minutes a day spread evenly across every month.
(3) Recording fuel switchover for intra-SECA travelling ships. This activity takes about two hours for each voyage and happens 4-5 times a year, resulting in about 10 hours of recording on an annual basis.

The costs of the administrative burden relating to SECA regulations were calculated on an assumption of average monthly staff costs of €5,000 in Denmark, Finland, Germany and Sweden, and €3,500 in Estonia, Latvia, Lithuania and Poland.

Findings

The SECA-related administrative burden for ship-owners in the BSR is approximately €2,743, 800 per year (Table 4.2).

Table 4.2. Calculation of SECA–related administrative burden for ship-owners

SECA–related Activities	**Figure / Value**
Daily recording of emission logbook Daily SECA – related additional training	10 minutes +2 minutes
	12 minutes
Hourly rate	
Daily SECA – related administrative burden	x 26.88 €/h = 5.38 €
Number of daily plying ships in BSR Operating days in BSR	x 1500 ships x 340 operating days
Annual administrative burden for shipowners	**2, 743 800 €**

For maritime authorities, the administrative tasks in the BSR are mainly related to compliance checks and fuel sample checks in national ports. The majority of compliance checks are executed by national maritime authorities, which comprise checks of all six MARPOL issues. All port state controls within the European Union are inserted in the THETIS-EU databank at the European Maritime Safety Agency (EMSA) located in Lisbon.

As well as on-board inspections, other activities are part of enforcing SECA regulations. One important measure has been the installation of sniffing stations in special places like the bridges of ports to detect non-compliant vessels. The average price for installing a fixed site sniffing station is about €140,000 but their current number is unknown. Some sites are already well-known, such as Öresund bridge, Great Belt bridge or in the inlet channel in Göteborg. However, expert interviews revealed additional sniffing sites are present at Kiel and at upcoming places such as Rostock.

Overall, SECA-related administrative burden costs for maritime authorities in the BSR is approximately €260,000 per year and can be considered negligible.

Further details on how costs for maritime authorities were calculated can be found in the Notes section at the end of this report.

Additional costs for ship owners

Using Rotterdam daily fuel prices, an average spread per ton was calculated for the years between 2015 and 2018.

The spread between ULSFO and IFO380 HFO was adopted because shipping is a price sensitive business and ships that used HFO prior to the 2015 regulations would prefer switching to ULSFO due to its lower price.

Total consumed maritime fuel in 2015 was extrapolated to 2016, 2017 and 2018 by assuming an annual maritime traffic increase of 1.5 per cent, together with an annual increase in energy efficiency of 2 per cent within the whole BSR fleet.
Thus, the 2016 total fuel consumption in BSR, as well as the fuel consumption of the following years, were forecasted by taking the current fuel consumption and multiplying it by 1,015 * 0,98, i.e. 4 947 = 4973 * 1,015 * 0,98.

The diesel part of maritime fuel consumption was estimated at 20 per cent of total fuel consumption and due to the higher process for MGO/MDO compared to ULSFO, this percentage was assumed to stay stable over the years 2015 – 2018.

Based on the above assumptions, the additional costs of SECA regulations were analysed. For the year 2015 the following figures were achieved (Table 4.3):

Table 4.3. Analysis of additional costs of SECA regulation in the BSR in 2015.

Ship type	2015 fuel t	2015 Diesel t	2015 Scrubber t	2015 LNG t	2015 SECA t
Sum	4973	995	692	153	3 134
Add. Costs per t		€0	€37	€41	€186,26
Million €		€0	€25 604	€6 273	€583 739

These calculations add up to circa €616 million. By dividing additional compliance costs to consumed fuel in BSR in 2015, average additional costs per consumed fuel due to SECA compliance were calculated at circa €124.

Additional SECA compliance costs for 2016 – 2018 were calculated using the same approach, shown in Table 4.4.

Table 4.4. Estimated additional SECA compliance costs for 2016 - 2018.

	2015	2016	2017	2018
Fuel consumption million t	4 973	4 947	4 920	4 894
Mean ULS-IFO380 Spread	€186,26	€150,43	€151,92	€182,83
Annual add. Fuel costs million €	615 616	500 641	502 608	563 940

By taking an average over the years 2015 – 2018, annual additional costs for SECA compliance were about €550 million for the Baltic Sea, equivalent to an additional €110 per consumed fuel ton for shipping in BSR.

Other analysis shows the price spread of maritime fuel was found to be normally distributed, so it is also possible to determine the real additional costs from the estimations with a given error probability.

Shipping versus other forms of transport: the modal split

We investigated the impact of SECA on changes to transport patterns including modal shift, shortening of sea legs and increases in road transport (Wenske et al. 2019). These changes are evaluated by a cost/benefit model, which took into account the calculations of internal and external costs. Statistical analysis of transport flows, freight patterns and interviews for the whole Baltic Sea were carried out.

Compliance with SECA rules can be achieved by burning low sulphur fuel oil or cleaning exhaust gases with scrubbers. These changes involve costs and prior to SECA, it was widely expected that complying with the regulations would lead to a modal shift from sea to land transport, with negative consequences for shipping companies and an additional strain on land transport infrastructure.

Analysis of foreign trade and maritime transport between Baltic Sea countries and Western European countries, however, shows that the much-feared effect on sea transport and subsequent modal split did not happen.

What we measured

In this study, measurable impacts of SECA rules on logistics chains in the Baltic Sea region were analysed. The investigation tried to answer the following question - is there a change in the growth patterns of foreign trade and maritime transport in the Baltic Sea region that could be attributed to the introduction of SECA rules? A shift from sea transport to land transport caused by increasing shipping costs should result in lower growth of sea transport than respective foreign trade flows.

The study analysed a sample of trade flows between the Baltic Sea and Western European countries with intense competition between modes of transport in the period 2015 – 2017, using EUROSTAT statistics on foreign trade and maritime transport.

The selected trade flows comprised 101.3 million tons worth €302 billion (2017), which accounted for 45 per cent of the value and 20 per cent of total trade volume between the countries selected for analysis. Manufactured goods made up for 30 per cent of the tonnage, followed by food (23 per cent) and chemicals (19 per cent). In the period 2005-2017 the average annual growth rate of the selected good flows was 0.9 per cent.

Maritime trade amounted to 23.5 million tons of comparable cargo groups in the same period. Total transport volume increased yearly on average by 0.6 per cent, while exports followed a slightly declining path, with a drop of 0.4 per cent yearly. This is chiefly the result of declining exports of forest products. Average annual incoming traffic growth amounted to 2.7 per cent.

The figure 4.7 shows the relation of sea transport volume to foreign trade volume in the years 2007 - 2017 as well as the respective trend lines.

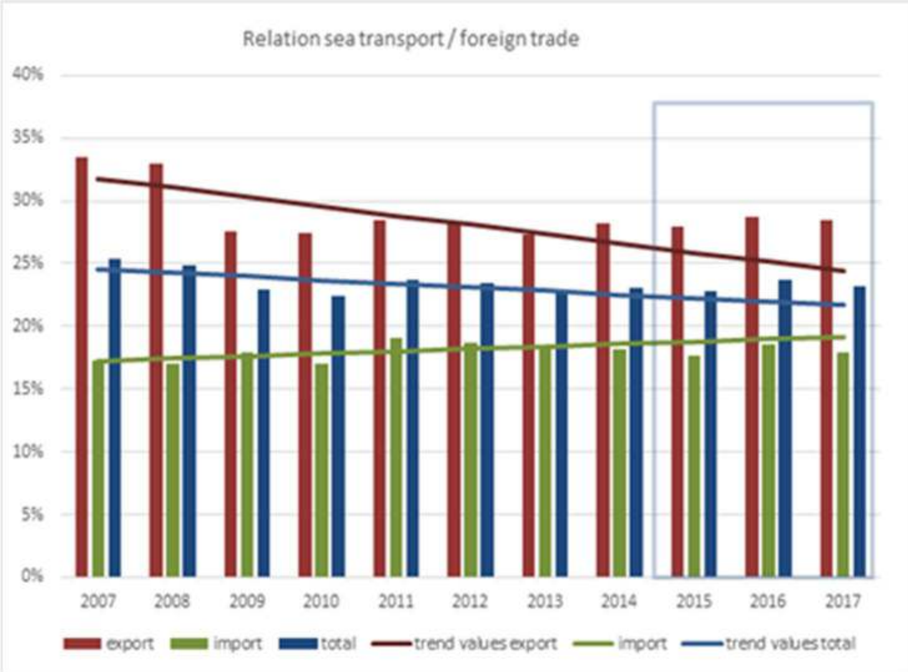


Figure 4.7 Relation of maritime transport to foreign trade - real values and trend values

What we found

Following the introduction of sulphur emission limits, real values in total trade and exports were higher than the estimated trend values. Only import trades showed a lower participation of maritime transport than predicted by the trend function.

The results from the analysis clearly do not support the initial hypothesis - that the cost increase caused by sulphur regulations resulted in a shift from sea transport to land transport. For imports, such a shift could be seen. But the results for exports and total flows indicate an increasing share of maritime transport.

The most obvious explanation for this result is the drastic decline of fuel prices in 2014/15, remaining at a low level until 2017 (figure 4.8).

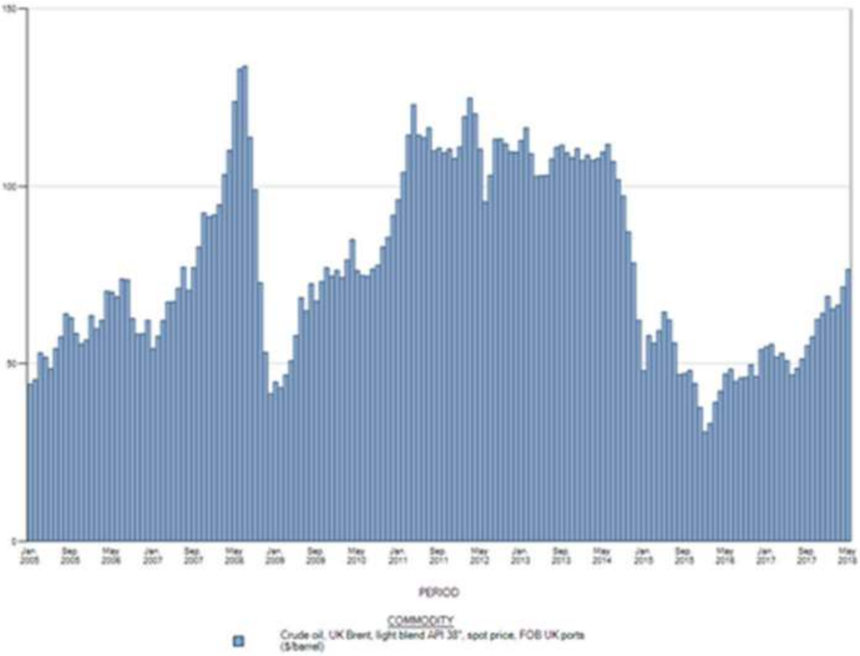


Figure 4.8 Price of Crude oil UK Brent 2005 – 2018.

By employing bigger vessels ship operators take advantage of decreasing unit costs of transport. There is a visible growth trend of average vessel size, accelerating clearly in the years since 2015.

The gross tonnage of vessels <10.000 GT calling at Baltic Sea ports (cargo vessels only, excluding Russia) increased by 0.5 per cent a year between 2006 and 2014. The tonnage of bigger vessels increased by 0.7 per cent a year.

In the years 2015 to 2017 this gap widened considerably: vessels <10.000 GT fell by 1.3 per cent a year, while vessels bigger than 10.000 GT grew at 2.6 per cent a year. The respective average vessel tonnage increased from 15,331GT in 2006 to 16,541GT in 2014, standing at 16,090GT in 2017.

Innovation and investment under SECA

Shipping companies and companies that depend on international transport through the Baltic Sea can suffer from rising costs as a result of stricter emission requirements, at least in the short-term. But at the same time, the regulations can create new business opportunities for shipbuilding and clean-tech industries.

Many strategies can be adopted to adapt to SECA regulations. Here, we examine the impact on innovation and investment strategies for companies operating in globally competitive worlds with legislation that is only regionally binding.

Does regulation drive innovation?

We interviewed six Baltic Sea region clean-tech companies on innovation, targeting companies that presented SECA-related solutions at maritime fairs. The clean-tech entrepreneurs clearly believe the market for sulphur emission abatement was created by SECA - regulation is the main driver for eco-innovation in this field. So in this case, a green regulatory push from the public sector was needed to drive new clean technologies.

> *"We have six or seven different technologies ... they are all related to environmental legislation."*
> *"We are a business because of the regulation."*
> *"If there was not any regulation on sulphur in the marine industry, then no one would want to buy. Because ship owners don't implement green technology, it has to come via global regulations."*
> *"These regulations make our products and innovations possible to market. Without the regulations, no one would buy the tech."*
> *"Before this legislation, we didn't have any of the products. But since it was put into place, we have developed and sold a significant amount. So it is definitely expanding our business."*
> *"When legislation is put into place and enforced, ship owners tend to ask for environmental solutions which are innovative, new, different from what they have seen in the past, and robust."*

In view of the necessary technological innovation system functions listed by Hekkert et al. 2011, sulphur emission abatement has evolved through knowledge development.

In recent years, patents for sulphur emission abatement technologies have been granted to several companies in different countries. Knowledge exchange between science and the industry is represented in projects such as EnviSuM. The size and importance of SECA areas have been large enough to create incentives for entrepreneurial activities. SECA regulation has been the main guidance of the search, leading to market formation. The regulatory push has been particularly critical for take-off phase, as suggested by the theory on technological innovation systems. Innovators have been able to mobilize resources and to counteract resistance to change.

The impact of environmental regulation on innovation may depend on the design and implementation features of the regulation itself, and so understanding context is the key for predicting the impacts of regulation. The shift toward more stringent rules started at least a decade ago - SECA rules are only one of multiple environmental regulations targeting the maritime industry and are a part of a larger international regulatory scheme.

With the case of SECA, many of the design and implementation features (stringency, certainty, timing, flexibility, compatibility, enforcement) seem to have been sufficient to produce markets for low-sulphur fuels, exhaust gas scrubbers and sulphur monitoring technologies. These innovations are more incremental than radical.

These features even in combination with other current and forthcoming environmental rules, however, are not enough to make the shipping industry shift entirely to renewable energy. Radical or systemic innovation would require a different set of regulatory requirements.

“If we didn't do anything to help keep heavy fuel oil as an environmentally-friendly solution to marine propulsion, then all the other equipment we provide to the marine sector would be less attractive, because they are all related to heavy fuel oil.”

Companies that are successful innovators have been able and willing to adopt a proactive approach to regulation by employing their competencies and networks.

Existing businesses have expanded their environmentally-friendly product and service portfolios, and new companies have entered the market to provide new technologies and services.

The market for scrubbers has been created by companies that have invested in research and development and have finally been able to sell their products to shipping companies by overcoming suspicion regarding the reliability of the technology.
“*Our primary function is to develop technologies. We are also persuading the market for scrubbers.”*

Companies that currently sell products related to SECA regulation are potential providers of clean-tech for future regulatory requirements.

“*In addition, they [the scrubbers] reduce particulate matter (PM) emission and black carbon emission although that is not a legal requirement [yet], only the SOX has been specifically mentioned. Thinking one step ahead*.”

In addition to emission innovations, SECA rules may have speeded up the emergence and the adoption of other eco-innovations, such as those related to energy efficiency. There may be also be business model and social innovations.

Assessing the impacts of regulation needs to be in relation to a baseline of what would have happened without it. It is possible technological innovations for reducing ship sulphur emissions may have emerged and disseminated even without any new rules.

For example, increasing pressure from customers or other supply chain members on the shipping business to reduce their environmental footprint may have driven innovation. Motivation to eco-innovate could also have come from within shipping companies. It seems unlikely, however, that market forces and managerial concern alone would have produced improved air quality at the same rate as has been achieved by regulation.

Several new shipping regulations are on the way, and there are reasons to be optimistic about compliance rates for future regulations, although compliance monitoring is more challenging in high seas than in the Baltic Sea region.

The evidence shows it has become legitimate to regulate the environmental impacts of shipping. In order to invest in R&D, clean-tech companies need to know there is demand for their products. Regulations can have a significant impact at the take-off phase of innovation (Lähteenmäki-Uutela et al. 2019b).

EnviSuM study trip to Isle of Samsø

While liquefied methane complies with stricter air emission requirements, it is still a fossil fuel and contributes to greenhouse gas (GHG) emissions. An alternative is to liquify bio-methane from organic materials such as manure into Liquid Biogas (LBG), which abates both air pollutants as well as GHG emission.

A study visit was arranged to the Isle of Samsø (Fig. 4.9), which recently purchased a gas-powered ferry and is working on producing local LBG as part of a goal to create a fossil-free society on Samsø by the year 2050. We wanted to learn about projects carried out on the island by the municipality as well as private stakeholders (Fig. 4.10).

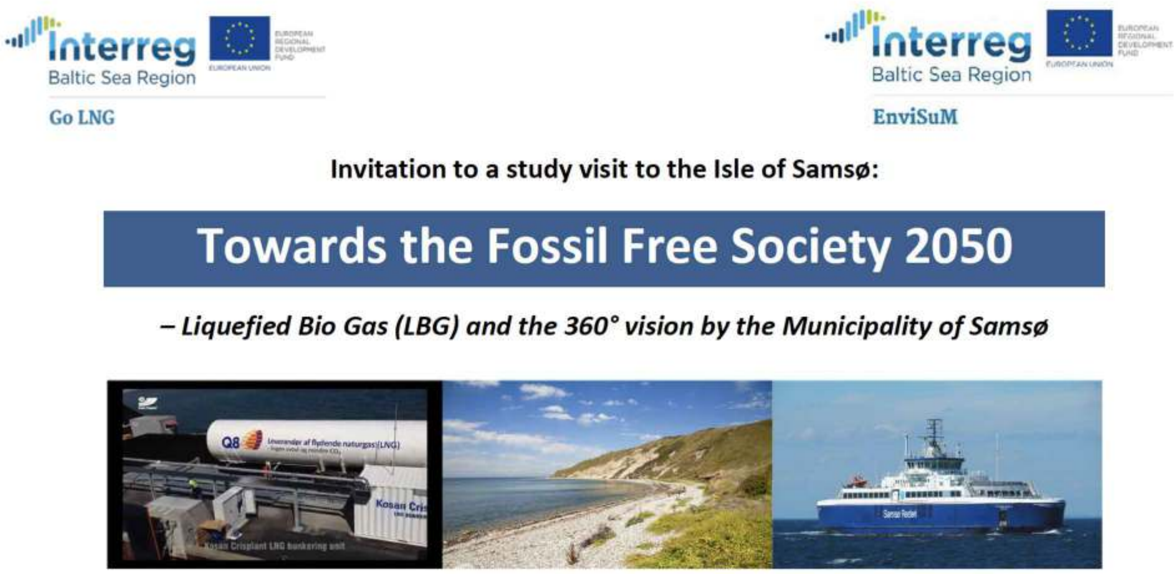


Fig. 4.9. Invitation to the study trip: Towards the Fossil Free Society 2050.

During the visit the municipality of Samsø presented the steps they are taking to produce local LBG involving waste treatment facilities, the island's industries, private farmers/local producers, the public transport sector and its residents. The aim is to create a sustainable value chain – both in terms of the business case for the involved parties, as well as the societal benefits expected from becoming a fossil-free community.

The study trip started with a guided visit to the LNG bunkering station at the port in Hou. The guide was Frej Olsen from Kosan Crisplant, the company that has developed LNG bunkering infrastructure for the island's ferry, MF Princess Isabella. This was delivered in 2014 and is an important milestone towards becoming a fossil-free society. The group also had a guided tour onboard.

Fig. 4.10 Participants at the end of the study trip.

The second day of the study trip started with a welcome from the Mayor of Samsø, Marcel Meijer, who explained the overall reasons for becoming a fossil-free society by the year 2050, as well as the financial and strategic reasons for ordering an LNG ferry.

Søren Stensgaard, the technical director of the municipality, explained how Samsø is building a local supply chain from field-to-ferry that aims to end dependency on imported fossil fuel (Fig. 4.11).

Samsø has been CO2 neutral since 2007, with heating for homes and businesses provided by solar energy and biomass from waste straw and wood chips. Electricity is generated by wind. These achievements have in part been made as a result of local ownership instead of using large companies from outside of Samsø. The focus has been on what locals can do themselves regarding their own utilities.

Søren also presented the reason for choosing LNG as fuel for the ferry, including initial forecasts on operating costs compared to Marine Gas Oil (MGO), as well as how the municipality decided won their own tender in 2013.

The establishment of Emission Control Areas in 2015 was one of the reasons for the decision, as it strengthened the return on investment of the LNG ferry. The forecast price for MGO was relatively high compared to LNG and so a LNG bunkering system was therefore selected.

Fig. 4.11. Slide from the presentation from Søren Stensgaard, Technical Director, Samsø Municipality.

Choosing LNG as the fuel for the new ferry also created the possibility of producing fuel locally. A local supply chain for LBG could be established as an alternative to LNG, which comes on large ships to Rotterdam and is then transported on trucks to the bunkering facility in Hou.

A biogas flow diagram was presented showing how LBG can be produced from vegetable biomass, animal manure and organic wastes. The necessary infrastructure and technologies, such as raw biogas pre-treatment, cooling techniques as well as the operating expenditures of such systems, were presented together with the possibilities for small scale liquefaction.

It was shown that it is technically possible to build a local LBG supply chain from field-to-ferry but that there needs to be political and local willingness to support the project.

Søren was followed by Frej Olsen, who presented the technical details of the LNG bunkering infrastructure that has been installed in the port of Hou, including the tender process, and supply chain for LNG (Fig. 4.12).

Fig. 4.12. Slide from the presentation of Frej Olsen from Kosan Crisplant on the LNG bunkering infrastructure that has been built for the Samsø ferry.

Afterwards the group had a guided tour around Samsø and was shown how district heating is produced by biomass from local agriculture, as well as how local businesses are provided with sustainable energy sources (Fig. 4.13).

Fig. 4.13. Visiting a local district heating production facility.

There followed a second presentation by Søren Stensgaard, who shared knowledge on how to finance a fossil-free society and how to balance costs, sustainability and people. Samsø's energy model was shown, where both energy input from fossil and renewable sources was included together with various output sources such as transport, housing, agriculture, business, electricity export and energy losses.

The flow of bio resources in Samsø was also presented including how wastewater has been turned into a valuable resource through a pilot project on the North Samsø Resource water plant.

Areas such as battery energy storage systems and electrical vehicles will further contribute to establishing a sustainable energy supply where authorities, civil society, business and knowledge institutions collaborate in order to create a fully-circular supply chain on the Island of Samsø.

CHAPTER 5

What can we learn from the Baltic SECA with respect to future environmental regulation for shipping?

The EnviSuM project has reached its completion. We have analysed different aspects of the impact of SECA, from technical issues to social and economic effects in the Baltic Sea region. One of the drivers behind the creation of EnviSuM was the need for up-to-date science-based information to guide future legislation on shipping emissions.

So, what lessons can be learned from the Baltic Sea SECA that will help inform forthcoming global regulation, the Sulphur Cap 2020? This limits sulphur in shipping exhaust gases at 0.5 per cent and will come into force globally in 2020.

We can extrapolate some of the findings in the Baltic Sea Emission Control Area to the 2020 global cap, albeit with some caveats.

We can safely say the feared negative economic consequences that were heatedly debated by the shipping sector before SECA regulations did not, for many reasons, materialize. In contrast, the anticipated environmental benefits did.

Shipping in the Baltic Sea, however, differs greatly from shipping in the High Seas and other parts of the world. In the Baltic Sea, sea journeys are short and shipping competes with road traffic. In addition, there is a limit on the size of vessels entering the Baltic Sea, due to the shallow depths of Danish straits.

The feared modal shift from sea to land due to cost increases as a result of SECA was not observed in the BSR and so we do not expect that to be an issue in other parts of the world either.

The costs of complying with SECA regulation generated much debate before the rules were implemented. Ship-owners do, undoubtedly, bear these costs, no matter what method for compliance is used and these are transferred to their customers. However, they will transfer the costs to their customers and ultimately to the consumers. Prior to the regulation coming into force, there was speculation that some industries, such as paper or metal industries in the northernmost part of the Baltic Sea, would suffer - and even relocate. Transport costs have increased, partly due to SECA, but no relocations can be attributed to it.

According to our and other studies, the costs of compliance are minor in the natural market variation of shipping.

Costs for global shipping can also be extrapolated from our numbers – albeit cautiously as the Baltic Sea is a special case due to the absence of larger vessels and its high share of RoRo-ships that have high fuel consumption.

Compliance has led to many challenges with respect to the usability of engines and technical devices. Air pollution control devices, such as scrubbers, cannot cut CO_2 emissions, do not fully reduce particulate emissions and will not be able to match long term MARPOL 6 deadlines, which require a drastic reduction of both SOx and NOx (scrubbers can cut only one exhaust at a time). This challenge may cause considerable technical and practical complications to regulated industries or individual countries, i.e. the costs may increase substantially and they may be asymmetric. This may not be a serious problem for seafaring at the high seas, but the Baltic Sea has its own unique country-specific features. Thus, there are three points of interests that should be analysed with care in the future:

1) A proactive study of the cost implications of mixed technologies for controlling multiple emission sources simultaneously;

2) Analysis on whether there are significant asymmetries in the regulatory costs and benefits between BSR countries that may impact national competitiveness and economic performance;

3) A study on how regulation should be organised and implemented at BSR so that its real effects are efficient and effective. Regulation that focuses directly on emissions and not on technologies leaves open the avenues to exploit innovation potentials of the market economies in full extent. Existing technologies and input resources can be understood as a portfolio of different options. Instead of prohibitions or detailed requirements for some technologies or inputs, the markets may find innovative discoveries that meet environmental targets the ways which regulators can't even expect beforehand. In other words, environmental policy and regulation should be strict enough, but the selected tools and methods to meet the environmental targets should be left to markets.

LNG is a cleaner fuel than traditional bunker fuel or marine diesel, but methane slip from LNG is a clear disadvantage for meeting forthcoming greenhouse gas emissions regulations. More research and more innovations are needed - compliance can be a business opportunity for industry actors.

Using high sulphur fuel without scrubbers installed, would give a ship-owner a competitive advantage over compliant fuels. Monitoring and sanctioning is important, therefore, to ensure a level playing field between operators.

In general, compliance in the Baltic Sea is good as ship-owners appear to have accepted the values of environmental regulation. Outside territorial waters, or far from known sniffers, however, the percentage of compliant vessels drops. Based on this and the difficulties of monitoring, we expect less compliance in high seas.

Finally, what are the benefits of SECA regulation? In the Baltic Sea, the transition in 2015 was from 1 per cent to 0.1 per cent sulphur content in fuel. This is a reduction of 90 per cent. The global regulations in 2020 will see a transition from 4.5 per cent to 0.5 per cent - a reduction of 89 per cent. Are the effects of regulation linear for sulphur depositions? Our tests show in the BSR, sulphur emissions from shipping were a factor of 8.16 higher in 2014 compared to 2016. So not a factor of 10 - assuming purely 1 per cent to 0.1 per cent - but this is understandable because not everybody complies all the time.

When the 2020 regulation is in place, shipping companies and maritime authorities in other coastal regions are likely to face the same questions as their Baltic counterparts regarding how to comply with the rules, how to ensure efficient compliance monitoring and what sanctions there should be for non-compliance.

The shipping companies interviewed were rather pessimistic regarding compliance with global regulations. This is mainly due to significant differences in enforcement resources in coastal states outside Europe, marked differences in company attitudes towards environmental protection and respect for regulations in general, as well as technical difficulties in monitoring ships sailing in the High Seas.

Airborne sampling can be a good backup for port state controls. Another option is to have sniffer technology on-board all ships. With global rules on greenhouse gas emissions, more devices on ships is one option for monitoring the compliance of several environmental regulations.

Conclusions

As the global sulphur cap will affect deep sea shipping far away from coasts, most pollutants will be deposited in the ocean. However, densely populated areas in China and India will benefit greatly in health effects. We expect benefits for human health and land ecosystems, therefore, to be less than has been seen in the BSR as a result of SECA.

SECA has led to innovation in the BSR and improved the reputation of the shipping sector, which is now recognized as a frontrunner in clean shipping worldwide. The inducement for innovation will probably increase when markets are enlarged by the global cap and/or other regional regulation. Although the Baltic is a small market, having been at the forefront of SECA compliance may help companies sell tested compliance methods in the future.

Controlling sulphur emissions from shipping in the BSR was the biggest environmental effort in the sector so far, and included considerable costs. Accepting and internalizing this regulation has changed the attitude of the shipping industry towards environmental regulation and can be regarded as having led to a paradigm shift.

At the time it was first introduced, regional regulation for what is a ultimately global problem was considered unfair and risky for the shipping sector in the BSR. We have seen, however, not only that it can be done, but also that business can thrive.

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List of abbreviations

AAE Exceedance
AIS - Automatic Identification System
APM - Air Pollution Monitor
AQD - Air Quality Directive
ANATEX - Across North America Tracer Experiment
ARMAAG - Agency of Regional Air Quality Monitoring in the Gdańsk metropolitan area
BC - Black carbon
BDN - bunker delivery notes
BSR - Baltic Sea Region
CAPTEX – Cross-Appalachian Tracer Experiment
CBM - Carbon Bond Mechanism
CL - critical load (CL)
CLF – critical load function (CLF)
CLaci - critical load of acidity
CLeutN - critical load of nutrient N
CO_2 – Carbon dioxide
CTM_MGO - Chemical Transport Model Marine Gas Oil
DOC - diesel oxidation catalyst
EC - elementary carbon
EEDI - Energy Efficiency Design Index
EMEP - European Monitoring and Evaluation Programme
EN-standards
ESC Energy Supply Contract
EU - European Union
EUROSTAT
FDI foreign direct investment
FMI - Finnish Meteorological Institute
GT - gross tonnage
HFO - Heavy Fuel Oil
IMO - International Maritime Organization
IVL - Swedish Environmental Research Institute
ISO 17025:2005 - specifies the general requirements for the competence to carry out tests and/or calibrations, including sampling.
KT - kiloton
LRTAP - Long-range Transboundary Air Pollution
LSFO - low sulphur fuel oil
MARPOL - International Convention for the Prevention of Pollution from Ships
MEC - Maritime Energy Contract model
MGO – Marine Gas Oil
MSC-W- Meteorological Synthesizing Centre-West
NCAR - National Center for Atmospheric Research
Ndep – Nitrogen deposition

NGOs – Non-governmental organizations
NMVOC - Non-methane volatile organic compounds
NO_x - Nitrogen oxide
OC - Organic Carbon
PAH - polycyclic aromatic hydrocarbons
PAH7 - Seven species of polyaromatic hydrocarbons
PM - Particulate matter 2,5 , 10
QA/QC - Quality Assurance/Quality Control
QS - Quality System
RR - Ring Road
RoRo - Roll on/Roll off
SCM - Standard Cost Model
Sdep – Sulphur deposition
SER sulphur emission restriction
SECA - Sulphur Emission Control Area
SILAM - System for Integrated modeLling of Atmospheric coMposition
SLA SECA Logistics Cost/Benefit Analysis
SNAP - Selected Nomenclature for sources of Air Pollution
SO_x – Sulphur Oxide
STEAM - Ship Traffic Emission Assessment Model
TEOM - Tapered Element Oscillating MicroBalance
TSP – total suspended particles
UNECE - United Nations Economic Commission for Europe
VOC - volatile organic hydrocarbon
WRF - Weather Research and Forecasting
WSD - Western Speedway Diameter

Notes to the report

Page 8 MARPOL Tier III limits refer to the limits (tier) set by the "1997 Protocol", which is popularly known as MARPOL (from MARine POLlution). Regulation 14 of MARPOL revised Annex VI concerns NO_X emissions from marine diesel engines and related limits. The introduction schedule of each limit is allocated as a Tier and depends on a vessel's construction date. The NO_X limit represents a set of weighted, specific emission factors applicable to engines, differentiated by rated rotational speeds, and is presented in Figure 1. Marine engine testing and survey for NO_X certification demonstrates a complex issue that is included in IMO's NOX Technical Code /MEPC 177/58 2008/. Initially, NO_X limit – Tier 1 introduced in 2000 - was achieved mainly by means of combustion and fuel injection process adjustments. However, primary NO_X emission control exhibits undesired effects of fuel consumption increase and PM emission intensification. Additional internal engine measures further supported NO_X control and allowed fulfilling Tier 2, presently in force since 2011.

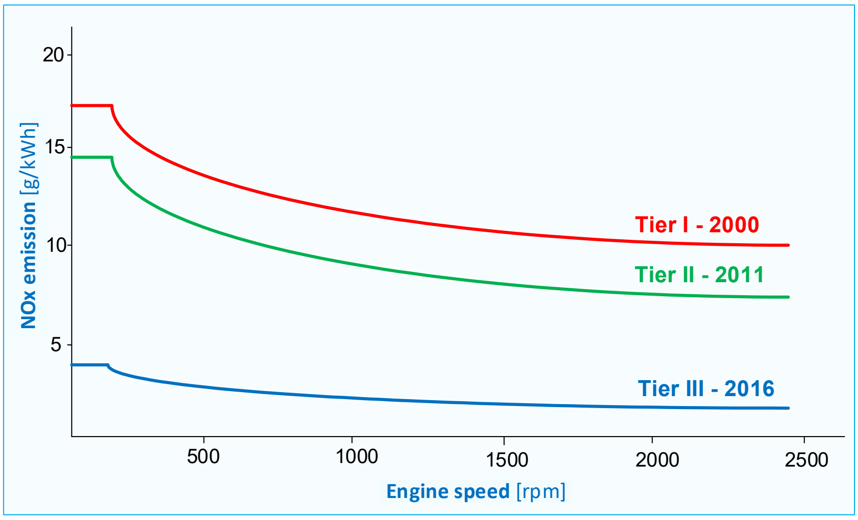
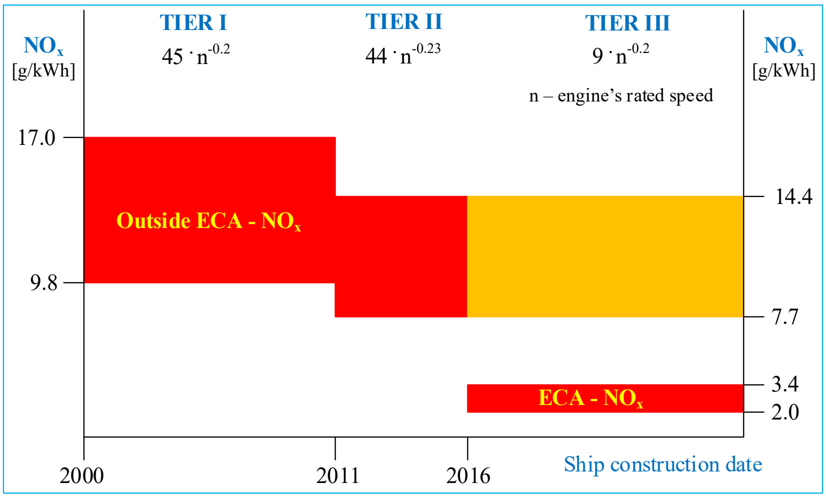


Figure I: MARPOL Annex VI – NO_x limits

Nevertheless, it appears that only exhaust gas treatment system can resolve the NO_X reduction issue to satisfy Tier III limits. Tier III NOX limits would apply to all ships constructed after 1 January 2016 and operating inside ECA-NO_X.

The NO_X Tiers enforcement schedule is presented in Figure 2. Marine Environment Protection Committee (MEPC) of the IMO adopted amendments to the MARPOL Annex VI regulation to uphold the original 2016 deadline for the implementation of Tier III NO_X emission standards for ships within IMO emission control areas (ECAs). The amendments were adopted at the 66th MEPC session held from 31 March to 4 April 2014 and provide for the Tier III standards to be applied to a ship which operates in the North American ECA or the US Caribbean Sea ECA—currently the only IMO ECAs applicable to NO_X, SO_X and PM emissions, while the other two ECAs currently in effect, the Baltic ECA and the North Sea ECA, are applicable only to SO_X emissions. The 2016 was the original deadline for the Tier III standards. However, MEPC voted to postpone the Tier III implementation by 5 years, until 2021. The postponement of the Tier III standards, proposed by Russia, was passed by a marginal majority. The amendments adopted also include certain changes to the NOx Technical Code, an extension of the application of the Energy Efficiency Design Index (EEDI) to more ship categories, as well as draft amendments to MARPOL Annex VI regarding engines solely fuelled by gaseous fuels, to clarify that such engines should also be covered by the Annex VI NO_x regulations.

Figure II: MARPOL Annex VI – NO_x limits schedule



Page 37 The air pollution model for the St Petersburg region is referred to here as CTM_MGO. A description of this model was published in Genikhovich et al. (2016). In some features it is similar to the SILAM model, developed at the Finnish Meteorological Institute, because of long-lasting close cooperation between developers (Sofiev et al, 2015). CTM_MGO is a Eulerian grid model working offline with a meteorological driver. Calculations for the St. Petersburg area were carried out using the numerical weather prediction model WRF, and NCAR global reanalysis is used to generate initial and boundary conditions for WRF.

Characteristic features of the CTM_MGO model are as follows:
- terrain-following sigma coordinates;
- splitting in physical processes;
- semi-Lagrangian approximation of advective terms using M. Galperin numerical scheme;
- scale-dependent horizontal diffusion with Smagorinsky-type account for the grid size;
- simultaneous account for vertical diffusion and convective terms;
- dry deposits: the EMEP scheme for gases and FMI scheme (M. Sofiev, R. Kuznetsov) for aerosols;

• homogeneous chemistry using CBM-IV and Sandu and Sander (2006) solver.

The model was successfully validated upon the data of the CAPTEX and ANATEX field experiments.

Input data

The computational domains are conditionally shown on Fig. 3.RU.3. The outer cell corresponds to the grid mesh used in calculations with the EMEP model. It is assumed that the data generated with this model at the influx boundaries of this cell will be used to determine the boundary and initial conditions for the “inner” computational domain. The solution for the inner rectangle (“internal domain”) will be obtained using CTM_MGO.

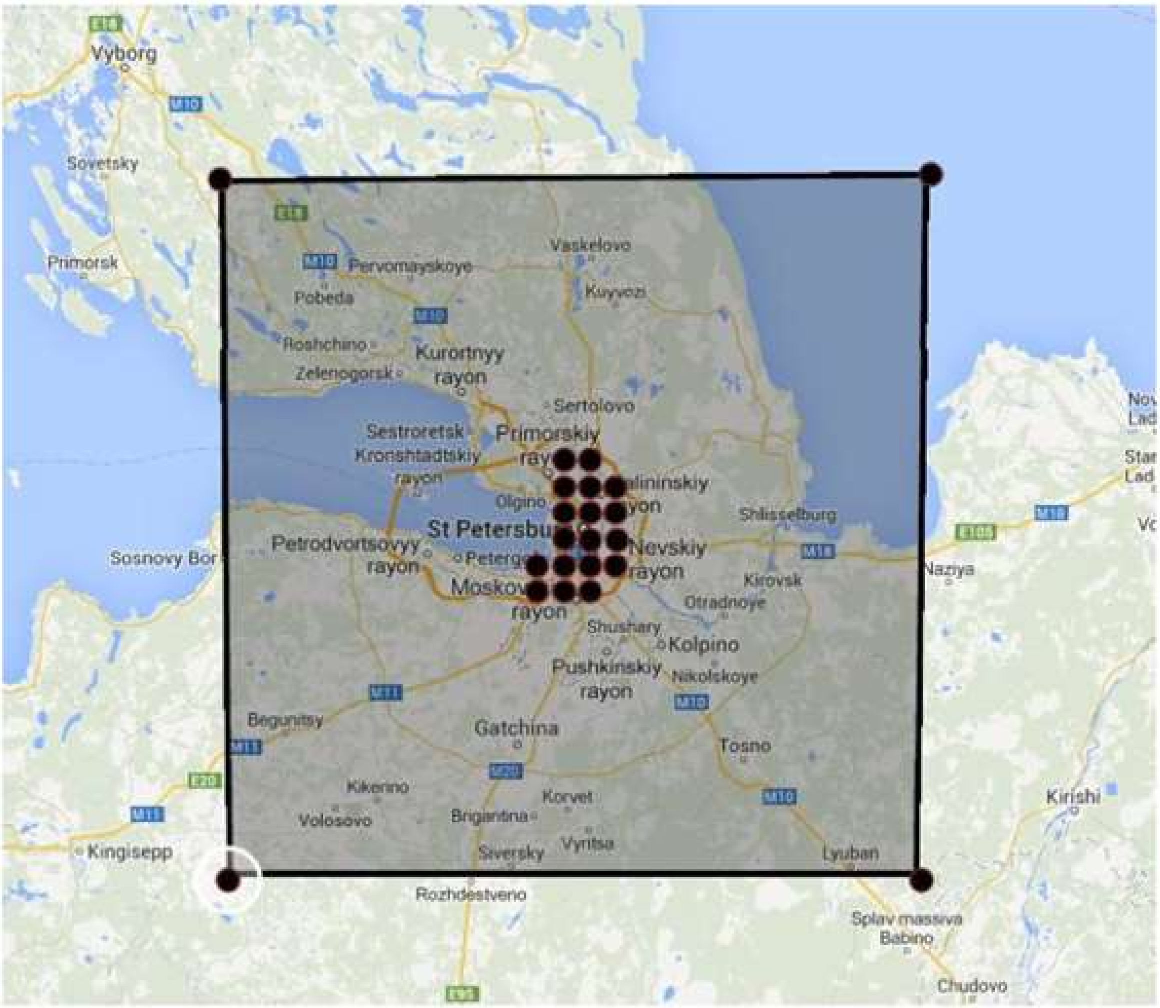


Figure III: Domains of computations for the St. Petersburg area

Initial and boundary conditions for CTM_MGO were derived from results of computations with the EMEP model.

Pollutant dispersion was modelled with particular emphasis on SO2 and the impact of emissions from ships calling to both ports. The calculations were made for 2014 and 2016 and concerned the following pollutants: NO_2, SO_2, PM_{10} and $PM_{2.5}$. The scope of analysis included:

● collecting archive data on emissions, from the Tri-City and surrounding areas, divided into point emissions (energy and industrial, ships at berths), surface emissions (household heating, ships – manoeuvring and approaching) and linear emissions (traffic), together with the creation of a time variability model;

● preparing meteorological data;

● formatting input data on ship emissions provided by the Meteorological Institute from Helsinki and the Maritime University of Szczecin;

● determining computational domain and boundary conditions, taking into account the guidelines of the Norwegian Meteorological Institute;

● model calculations using the CALMET/CALPUFF system;

● analysing modelling results, taking into account the impact of ship traffic, including the preparation of digital maps of concentrations of gaseous and particulate pollutants;

● model validation based on air quality monitoring station data.

Page 41 Meteorological parameters for modelling air pollution in the Tri-City area were provided by the WRF numerical weather forecasting system. For the purpose of the study, a computational domain covering the Tri-City agglomeration area together with a strip of 5-10 km from its borders was determined. As a result, the grid is 39 km along the X axis and 30 km along the Y axis. The resolution of the meteorological field information grid is 0.5 km.

The terrain information is based on SRTM-3 data, which allow a model of the terrain surface with the resolution grid: Δx=20m and Δy=30m. Concentration distribution calculations were made on the basis of discrete receptors and meteorological data for 2014 and 2016. The distribution of receptors was based on a grid with a resolution of 0.25 km. As a result, 6,785 receptors were obtained. To assess the impact on human health impact, the receptor height above ground level was set at 1.5m.

Page 53 Figure 2.23. The daily average values of PM10 and PM2.5 mass concentration for site analyzer and the reference method. The orthogonal regression analysis of the site analyzer against the reference method is also presented in the small graph. The results from Eberline, (PM10), TEOM 1400ab (PM2.5), optical analyzer (PM10 and PM2.5) by Grimm and reference method at station AM8 in Gdansk (above). Results from Derenda APM (PM10), Derenda APM (PM2.5) and reference method (PM10 and PM2.5) at station no 4 and no 24 in St.Petersburg (middle). Results from TEOM 1400ab (PM10), optical analyzer (PM10), IVL-sampler (PM10) and reference method (PM10) at station Gårda in Gothenburg.

Description of Table 2.3. A summary from the correction factors based on the comparison results for the particulate matter and gaseous compounds is presented in Table 3.3.1. The correction factors in case of PM10 and PM2.5 includes only the correction for the slope i.e. the regression equation is forced through the origin. The Expanded uncertainty in case of PM10 and PM2.5 is calculated based on the analysis of the comparison results while in case of the gaseous compounds the expanded uncertainty is estimated by the network. It should be kept in mind that the Data Quality Objective as stated by the Air Quality Directive (AQD) includes the expanded uncertainty for PM10 and PM2.5 as 25 per cent and for the gaseous compounds of SO2, NO-NO2 and O3 is 15 per cent.

Page 75 Administrative tasks for maritime authorities in the BSR are mainly related to compliance checks of ships in national ports. The majority of the compliance checks are executed in the frame of port state controls of national maritime authorities which comprise checks of all six MARPOL issues. All port state controls with European Union are inserted in the THETIS-EU databank at the European Maritime Safety Agency (EMSA) located in Lisbon. The report of the European Commission on implementation and compliance with the sulphur standards for marine fuels reveals a total number of MARPOL VI inspections in the Baltic Sea and shows the following table as reported by HELCOM (2018):

Table I: Number of MARPOL VI inspections in BSR

Year	Number of inspections	Number of Non-compliance
2015	1903	73 (3.8%)
2016	1975	71 (3.6%)
2017	1972	45 (2.3%)
Average	1950	

Table highlights the high compliance rate, which was improved over the last three years and reached about 97% in BSR. The MARPOL VI related issue is only in one part and the expert interviews revealed an average time consumption for a MARPOL VI inspection of 4 hours that composes of 1-hour preparation time, 2 hours on-board inspection time and 1-hour post-check time including the entry of the results of the inspection into the THETIS-EU database of EMSA. Thus, the annual time for MarPol VI inspections in BSR sums up to a total number of 1950 hours. Like in the case of the calculation of the administrative burden of shipowners, we assume an average monthly staff cost of 5000€ in Denmark, Finland, Germany and Sweden as well as average monthly staff costs of 3500€ in Estonia, Latvia, Lithuania and Poland. The calculations yielded an hourly rate for the inspections of about 26.88 €, i.e. the total annual administrative burden for the inspection of SECA regulations for the EU Maritime Authorities in the BSR yield 209 625€.

In addition to the annual administrative burden, the costs for fuel sample testing have to be calculated. Unfortunately, the existing data does not explain the number of taken and analysed fuel samples but according to the EU regulations 40% of the MARPol VI inspections have to be linked to fuel sample tests, i.e. 789 fuel samples can be assumed to be tested annually in the BSR (EU, 2015). One fuel testing costs about 60€ yielding additional costs of 46 800€ have to be added to the administrative burden of the Maritime Authorities.