THE SCIPPER PROJECT

Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations

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Executive summary

This report focusses on the effectiveness and costs of different approaches for monitoring and enforcement of pollutant emissions for sea ships. This concerns emissions such as NOx and SOx regulated under IMO MARPOL Annex VI but additionally also particulate matter emissions including Black Carbon can be monitored. Methane has recently also been included in some monitoring setups, although this is outside the scope of SCIPPER.

The work includes remote sensing in the exhaust plumes of ships and onboard monitoring with sensors mounted in the exhaust stack. The latter is combined with satellite data transmission and reporting to a centralized Environmental Shipping Monitoring Centre (ESMC). The remote sensing options include fixed station on shore, aerial vehicles (UAVs, aircrafts) and monitoring via the TROPOMI satellite. An overview of the monitoring options in terms of emission components, area of monitoring and limitations is given in Table 1-1 below.

Table 1-1. Monitoring of NOx, SOx, PM, BC emissions: effectiveness parameters for onboard monitoring (option 1) and remote monitoring options (options 2-6).

<table>
<tr><th>Monitoring</th><th>Pollutants</th><th>Area</th><th colspan="2">Other limitations</th></tr>
<tr><td>Onboard monitoring</td><td>NOx, NO NO_2, SO_2, PM, BC</td><td>Global coverage</td><td>Reliability of sensors and overall system</td><td rowspan="6">Legal implementation including simple, transparent, calculation methodology</td></tr>
<tr><td>Sniffer stations on shore</td><td>NO, NO_2, SO_2, PM, PN</td><td>Primarily ports</td><td>Wind direction</td></tr>
<tr><td>Small UAV</td><td>NO, NO_2, SO_2</td><td>Primarily ports and short-range areas (<5km from shore)*,</td><td>day light, air space restrictions may apply</td></tr>
<tr><td>Large UAV</td><td>NO, NO_2, SO_2</td><td>Primarily coastal and medium-range areas (<50 km from shore)*</td><td>day light, air space restrictions may apply</td></tr>
<tr><td>Manned aircraft</td><td>NO, NO_2, SO_2, PN</td><td>Primarily coastal and long-range areas (<100 km from shore) *,</td><td>day light</td></tr>
<tr><td>Satellite</td><td>NO_2, SO_2</td><td>Global coverage
Clear sky</td><td>Indicates total rather than specific emissions</td></tr>
</table>

* In the case of UAVs, the range refers to the operating distance between the pilot control station and the UAV limited by radio-line-of-sight (RLOS). For manned aircraft the distance refers to the safe operating distance from shore. Manned aircrafts can survey hundreds of km along coastal shipping lanes. In case of rotary aircrafts, the distance from shore can be larger if launched from a coast guard vessel deck.

Effectiveness

Remote sensing in the form of a fixed sniffer station on shore, unmanned and manned flights, or even on patrol vessels have been operational in Europe for a number of years. Onboard monitoring with satellite data transmission (option 1) and remote monitoring by satellite (option 6) are first investigated within the SCIPPER project.

The primary focus for enforcement has been FSC (Fuel Sulphur Content), but in the future this needs to be expanded to NOx, especially due to the growing fleet of Tier III vessels. The limitation of most remote sensing options is the limited physical sea area that can be covered, often limited to ports and coastal ranges (up to 100km from shore). Nevertheless, remote sensing has proven to be a good way to show ship owners that emissions monitoring is taking place (preventive effects) and provided valuable insight into real maritime emissions. It is also a cost-effective pre-selection instrument to spot vessels which violate the FSC requirements but also an option to optimize port state inspections by not wasting time sampling vessels which were found to be compliant at sea. When violations are spotted, an onboard vessel inspection is initiated to take fuel samples onboard for FSC analysis.

It is concluded that monitoring and enforcement for FSC is easier than for NOx, because no engine parameters are needed for FSC. NOx monitoring can provide good insight in the average NOx emission in g/kg fuel. However, the link with engine-based IMO legislation is difficult. An estimation of engine power and Specific Fuel Oil Consumption (SFOC) needs to be made in order to calculate engine work specific emission (g/kWh). This will always remain legally disputable, because of the uncertainty in engine power with several engines contributing to the overall plume. PN, PM and BC emissions can also best be expressed in g/kg fuel. No direct legal limits apply to this last group.

Monitoring costs

An overview of the indicative costs of monitoring is presented in Table 1-2 below. For the sniffer stations and aerial vehicles, the costs are calculated per vessel port visit. These costs include investment costs, manpower, maintenance, and service costs and all assume a sustainable campaign operation for an extended period of time. The cost range for remote sensing is primarily determined by the number of vessels in a shipping lane (traffic density) and for aerial vehicles also type of aircraft, its operational and sampling speed . No direct comparison should be made between the remote options because they are complementary to each other, they monitor in different areas, have distinctly different features, and are sometimes combined with other tasks like spill detections and fishery control.

Table 1-2. Indication of total costs in € for onboard monitoring (option 1) and typical cases of remote monitoring (options 2-6).

Monitoring	Ship owners	Authorities
Onboard monitoring	Per vessel (excl. ESMC*): 500 – 7,500 € per year	Total ESMC*: 500,000 € per year
Sniffer station on-shore (full year operation one system)		300,000 € per year, or 20 – 770 € per vessel-pass
Small UAV campaign		140 - 350 € per vessel-pass
Large UAV campaign		400-1000 € per vessel-pass
Manned aircraft campaign		200 - 870 € per vessel-pass
Satellite (globally)		1 – 5 million € per year, 100 € per vessel

* Environmental Shipping Monitoring Centre

The costs range for option 1, onboard monitoring is rather large; from 500 € to 7,500 € per year. For the low end of this range, it is assumed that the sensors are already installed on the ships engines, e.g. as part of emission control on a scrubber system, and that these same sensors are used for monitoring. This is for example also the case for road vehicles, where monitoring is required (OBD), but without data transmission to a central database.

The onboard monitoring cost are compared to the external costs of emissions and to the costs of SOx and NOx reduction. The monitoring costs for short sea ships ranges from about 0.1% to 2.3% of the external costs depending on the ship type, the sea area and emission requirements. In comparison to the SOx and NOx reduction costs, it ranges from 0.1% to 0.8%. For NOx monitoring only the range rises to 1% to 8%.

Recommendations

One of the main conclusions of SCIPPER is, that NOx enforcement is difficult because a legal framework is lacking. This in contrary to road vehicles in Europe for which legislation includes specific test procedures and limit values for In Service Conformity (ISC) and Real Driving Emissions (RDE). NOx monitoring and enforcement is especially important for Tier III vessels, since emission control systems like SCR can easily be switched off, or malfunction due to wear or lack of maintenance.

The main recommendation for sea shipping is, to implement specific legislation for NOx monitoring and enforcement and for Real Sailing Emissions, both for remote sensing as well as for onboard monitoring. This would include the following:

- A methodology for monitoring of Real Sailing Emissions (RSE) and Not-To-Exceed limits for NOx (and in a later phase PM and BC).
- A simple, at IMO level acceptable, onboard measurement procedure for onboard inspections, preferably based on exhaust concentrations measurements only.
- To further work out the technical concept for continuous onboard monitoring with satellite data transmission and reporting within a monitoring centre (ESMC).

It is recommended to implement continuous onboard monitoring for NOx, SOx and in the future also for NH_3 and PM, because the costs are relatively low and the relative contribution of these pollutants over land is rising.
Onboard monitoring can be implemented on a voluntary basis in form of an extension to IMO Tier legislation (e.g. Tier IIIb or Tier IV). It is recommended to further work out the technical details by an IMO Technical Working Group or Sub-committee.

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List of abbreviations

AIS	Automatic Identification System
AUTH	Aristotelio Panepistimio Thessalonikis
BH-12	Sniffer analyser built and operated by Aeromon
BSH	German Federal Maritime and Hydrographic Agency
CEMS	Continuous Emissions Monitoring Systems
CLD	Chemi-Luminescent Detector
CO	Carbon Monoxide
CPC	Condensation Particle Counter
CRDS	Cavity Ring-Down Spectroscopy
DOAS	Differential Optical Absorption Spectroscopy
EC	Elemental Carbon
ECS	Electro Chemical Sensor
eEE	exactEarth Europe Limited
EEPS	Engine Exhaust Particle Sizer
EMSA	European Maritime Safety Agency
ESMC	Environmental Shipping Monitoring Centre
EPC	Environmental Particle Counter
EU	European Union
FMPS	Fast Mobility Particle Sizer
FSC	Fuel Sulphur Content
FTIR	Fourier Transformation Infra Red (analyser)
GHG	Green House Gas
GPS	Global Positioning System
HMGU	Helmholtz-Zentrum München
IMO	International Marine Organisation
ICS	In-Service Conformity
IVL	IVL Svenska Miljoeinstitutet AB
IR	Infra Red
LASX-II	Airborne-particle spectrometer
MGO	Marine Gas Oil
NDIR	Non Dispersive Infra Red
NH_3	Ammonia
NM	Nautical Mile
NO	Nitrogen Monoxide
NOx	Nitrogen Oxides
OBD	On Board Diagnostics
OPS	Optical Particle Sizer
RDE	Real Driving Emissions
RSE	Real Sailing Emissions
s-AIS	Satellite AIS
PM	Particulate Matter
PN	Particle Number
RLOS	Radio Line of Sight
RPAS	Remotely Piloted Aircraft System
SCR	Selective Catalytic Reduction (of NOx)
SECA	Sulphur Emission Control Area
SEMS	Smart Emissions Measurement System
SFOC	Specific Fuel Oil Consumption
SO_2	Sulphur Dioxide
SOx	Sulphur Oxides
TAU	Tampere University
TNO	the Netherlands Organisation for applied scientific research
UAV	Unmanned Aerial Vehicle or drone
UAS	Unmanned Aerial System
UFP	Ultrafine Particles

ULSFO	Ultra Low Sulphur Fuel oil
UTC	Coordinated Universal time
VLSFO	Very Low Sulphur Fuel oil

1. Introduction

The overall SCIPPER project aims to deploy state-of-the-art and next-generation measurement techniques to monitor emissions of vessels under normal operation, investigate contributions to inland pollution and develop options for enforcement of regulations.

The emphasis of SCIPPER is on all polluting engine emissions including particularly NOx, SOx, PM, and BC.

The aim of this report is to evaluate effectiveness and costs of different techniques and strategies for onboard monitoring and remote sensing. The latter includes a number of remote sensing options in which sniffers measure the plume of the exhaust gas. The sniffers can be located on land, or on aerial or nautical vehicles. The remote sensing also includes direct sensing via the TROPOMI satellite. The onboard monitoring options investigated are sensor-based options usually measuring within the exhaust stack, but also one option with 'remote' plume sensing onboard has been investigated. Additional objectives of the assessment are, to distinguish effectiveness according to enforcement area, to differentiate between costs for ship owners and authorities and to provide recommendations to policy makers.

Several SCIPPER reports provide key input to this deliverable. Specifically mentioned are SCIPPER D1.6, 2022: Conclusions of technical possibilities of onboard sensor monitoring, SCIPPER D5.1, 2022: Gaps in current emission enforcement regulations and impacts to real-world emissions and SCIPPER D2.4, 2022: Potential of satellite monitoring for shipping emissions enforcement.

The assessment and costs analysis of the remote and onboard monitoring options are provided, respectively, in section 2 and section 3. The results of these sections are further analysed and summarised in section 4, which also includes policy recommendations. The overall conclusions and recommendations are finally summarised in section 5. Additional information is provided in the appendices, such as details on reference vessels and costs in Appendix A, standard Emission Factors used for external costs calculations in Appendix B, and an overview of the regulatory and enforcement gaps in Appendix C.

2. Remote sensing options

2.1 SOx and NOx monitoring

At this stage there are several options for compliance monitoring using remote sensing. These range from various methods using gas monitors mounted on different platforms to satellite observations. The sniffer method is based upon measurement of gases directly in the vessels exhaust plume (in situ). Simultaneous measurement of the concentration of the gases or particles and carbon dioxide in the plume provides quantitative information on the emission rates. The ratio of the concentration of sulphur dioxide, nitrogen oxides or particles and carbon dioxide in the plume directly yields the emission of these components in g/kg fuel. The sulphur dioxide emission concentration in relation to the CO_2 concentration is a direct measure of the fuels sulphur content in g S/kg fuel or Fuel Sulphur Content (FSC) in % (m/m). The FSC is the measure to which IMO regulations apply, so the results of these in plume measurements may be compared directly. In Sulphur Emission Control Areas (SECA) such as around the North and Baltic seas, IMO regulations imposing a FSC limit of 0.10% are in force. NOx (and particulate) emission rates can be measured in a similar fashion, leading to emissions of g NOx/kg fuel. However, IMO limits for NOx are expressed in g/kWh, which is a more complex measure. To calculate the g/kWh value, the specific fuel consumption needs to be known during the measurement. This requires more information on the vessel specific properties, such as the rated engine speed and the Tier class (depending on keel laying date). Comparing these data to IMO regulations is even more complex, since the engine load during the measurement needs to be assessed as well. This is difficult and careful attempts are being made at this stage to compare measured emission rates with IMO regulations, e.g. by Knudsen et al. 2022 and Van Roy et al., 2022. In these cases the engine load is estimated from sailing speed, its maximum speed, etc. Some of the required information can be obtained from AIS data received from the vessel. Other information has to be retrieved from on ship technical databases.

Different implementations of the sniffer method are currently used. These differ especially on the positioning of the equipment. Shore-based sniffers can be positioned along important coastal waterways, or bridges where vessels pass monitoring stations at distances of hundreds of metres up to one kilometer. To be able to measure concentrations in these diluted plumes accurately, high end, expensive gas monitors are required. Similar quality monitors are needed for sniffer setups in fixed-wing aircraft, while rotary-based aircraft (either UAVs or helicopters) can fly very close to the vessels funnel and measure in the much less diluted plume. The concentrations measured on these positions do not require the high-end equipment needed on shore for instances. This equipment is, at the same time, normally smaller, lighter and has less power consumption – better fitting the payload requirements of especially smaller UAVs (Unmanned Aerial Vehicle or drone).

2.2 Overview options

A full overview of the different platforms for remote sensing is given in the table below. Fixed (land-based) stations for plume sensing are used on a continuous basis in and around several European ports. The other options such as the installation of sniffers on patrol vessels, UAVs (drone), and manned aircraft are used periodically for more detailed investigations and often covering a large(r) port or sea area. Table 2-1 provides, among others, information of the types of measuring techniques, the area coverage and operational time. It is important to note that these platforms are in different stages of development. For example, the use of stationary sniffers is a well-developed technology with a variety of suppliers on the market. However, for large UAVs, this is only recently available, and the satellite-driven approach is in its infancy.

Table 2-1 Different implementations of remote emissions monitoring with sniffer methods and satellite

Technique	Small UAV	Patrol-Vessel	Aircraft/Large UAV	Fixed Station	Fixed station	Optical - Satellite
Method	**Sniffers**				**Remote Optical**	
Most widespread detection techniques	SO_2 (ECS, DOAS) NO,NO_2 (ECS) CO_2 (NDIR) New concepts	SO_2 (UV-Fl.) NO, NO_2 (CLD) PN (CPC) CO_2 (NDIR, CRDS)			SO_2 (DOAS, IR Iradiance) NO_2, (DOAS)	NO_2, SO_2 (DOAS)
Experience EU	DK, FI, NL, EMSA	DE, FR, SE	EMSA, BE, FI, (SE), DK	DE, NL, SE, DK, FI	DE	FI, GR, NL
Availability of results	Immediately	Immediately	Immediately	Immediately	Immediately	Post-processing
Open Sea surveillance	No	Yes	Yes	No	No	Yes
Suitable area / sites	line of sight (smaller harbour, canal, etc..)	ports, busy lanes	coast and open sea up to 50km* (UAV) or 100km* (aircraft)	major shipping lane (harbour, canal, pole, bridge)	major shipping lane (harbour, canal, pole, bridge)	Away from other major sources (5.5×3.5 km^2, depends on pass)
Operation time	Daylight No rain or strong wind	24/7	Daylight No rain or strong wind	24/7 (automated) Right wind direction	24/7 (automated)	(automated) Daytime, mid-day clear skies
Resources cost/vessel	Low-Medium	Medium	Medium-High	Low	Medium	Medium
Maturity	Early maturity	Mature	Aircraft: Mature UAV: Early	Mature	Early maturity	Infancy

* In the case of UAVs, the range refers to the operating distance between the pilot control station and the UAV limited by radio-line-of-sight (RLOS). For manned aircraft the distance refers to the safe operating distance from shore. Manned aircrafts can survey hundreds of km along coastal shipping lanes. In case of rotary aircrafts, the distance from shore can be larger if launched from a coast guard vessel deck.

2.3 Costs

In Table 2-2 and Table 2-3, the costs are estimated of sampling with sniffers in the plume, and, respectively, onshore and installed on aerial vehicles. Note that the actual costs will vary for different locations and depending on the amount and type of equipment. For both onshore sniffer and aerial vehicles, the costs per vessel will be strongly dependent on the density of shipping in the measurement region.

For the onshore sniffer, the stations are usually fixed, thus the amount of vessels sampled will also depend on the wind direction. It is advisable, if possible, to put the measurement station downwind from the predominant wind direction. Alternatively, several shore-based sniffers can be installed in a network covering different wind directions or different port locations. In Figure 2-1 the cost per vessel-port-visit is presented as a function of the number of sampled vessels. The typical number of vessels for several ports (Rotterdam, Hamburg, Kiel and Plymouth) are indicated in this graph. Note that for this typical number of vessels sampled it was assumed that each vessels passes the measurement site twice (i.e. going into and out of the harbor), so the amount of plumes measured was divided by two. In Table 2-2, the cost per vessel-pass is given for a relatively quiet, average and busy port (with respectively 80, 200 and 800 vessels sampled per month); this shows the cost can vary up to a factor of almost 40 (in between €20 and €770 per vessel-pass). The staff deployment costs include the costs for supervision of the system, data evaluation and reporting. The maintenance and replacement of sensors is accounted for in the depreciation costs (20% per year). The initial investments costs include the costs of the overall sensor system including sensors, data collection and transmission and casing. The cost of programming software to analyze the concentration data per plume and link it to a certain ship is not included in the investment costs.

Table 2-2. Costs of sniffer on-shore measurements based on experience of SCIPPER partners. Note that the price per vessel strongly varies given the total amount of vessels sampled. Based on German & Dutch experience.

Port	Quiet	Average	Busy
Investment cost SOx, NO, CO_2		**75 000**	
Depreciation costs (20% per year)		15 000	
Staff deployment (per year)		100 000	
Total cost per year		**115 000**	
Number of measured vessels per year	150	2400	6000
Price per vessel-pass	**770**	**48**	**20**

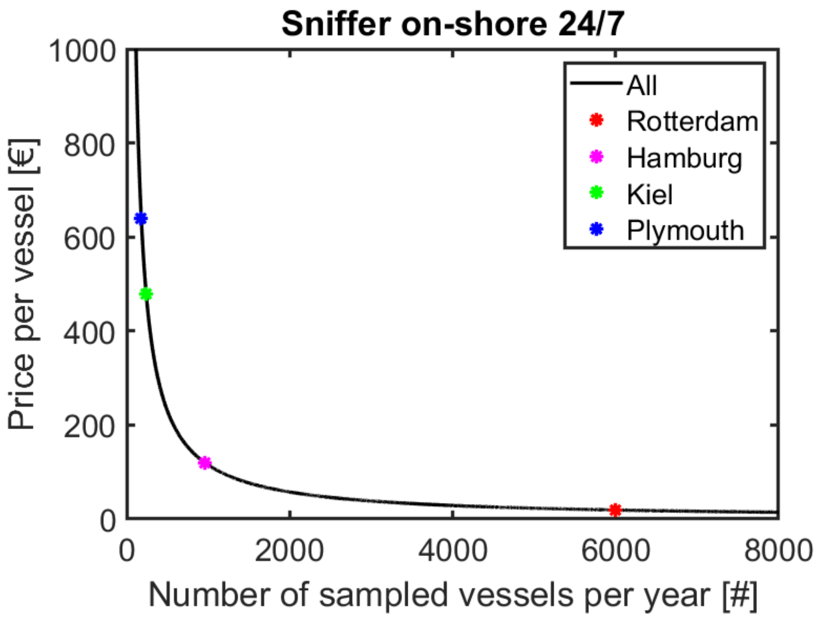

Figure 2-1. Measurement costs per vessel-port-visit for typical fixed sniffer station. The expected number of monitored vessels for several ports are indicated.

Table 2-3 shows the cost of sampling with sniffers installed on unmanned and manned aerial vehicles. The cost is estimated based on an EMSA tender (UAV program), and information from SCIPPER partners, including port state control of Belgium and the Netherlands. The costs are based on hourly rates of commercial companies providing emissions measurements as a service. The main costs are the flight operation costs and, in addition, there are costs for emissions measurement equipment and data processing. It does not include personnel or research specialists at port state control involved in preparations, or follow-up actions. It also does not include organisational work and (profit, risk) mark-up if entire campaigns are sourced out to specialised companies or research organisations.

The costs per vessel-port-visit is very much dependent on the number of vessels that can be measured per hour. This, in turn, is dependent on the number of vessels in the shipping lane; there is also a practical maximum number per hour due to the manoeuvring time from one vessel to the other. For UAVs (large and small) this maximum is about five due to the slower speed of this type of aircraft, while manned aircrafts (heli or fixed wing) can comfortably sample up to about 12 vessels per hour. The dependency of the costs per vessel is presented in Figure 2-2. In Table 2-3, typical numbers are given for quiet and busy shipping lanes. Busy would be for example the English Channel or Danish waters on the entry to the Baltic Sea. Quiet would be for example the fjord leading into Kiel and the area outside Plymouth. Small UAVs are least expensive with a costs per vessel-pass in the range of 140 to 350€. All other options are usually more expensive and fall in an overall range of 200 to 1000€ per vessel-pass.

Table 2-3. Costs of remote sensing with aerial vehicles. Prices for small drones and large drones are based on EMSA tender.

		Small UAV		Large UAV		Helicopter		Aircraft	
Costs per hour	EUR	700	700	2000	2000	2600	2600	2400	2400
Shipping lane		Quiet	Busy	Quiet	Busy	Quiet	Busy	Quiet	Busy
Typical number of vessels per flight hour	nb	2	5	2	5	3	12	3	12
Price per vessel-pass €	EUR	350	140	1000	400	867	217	800	200

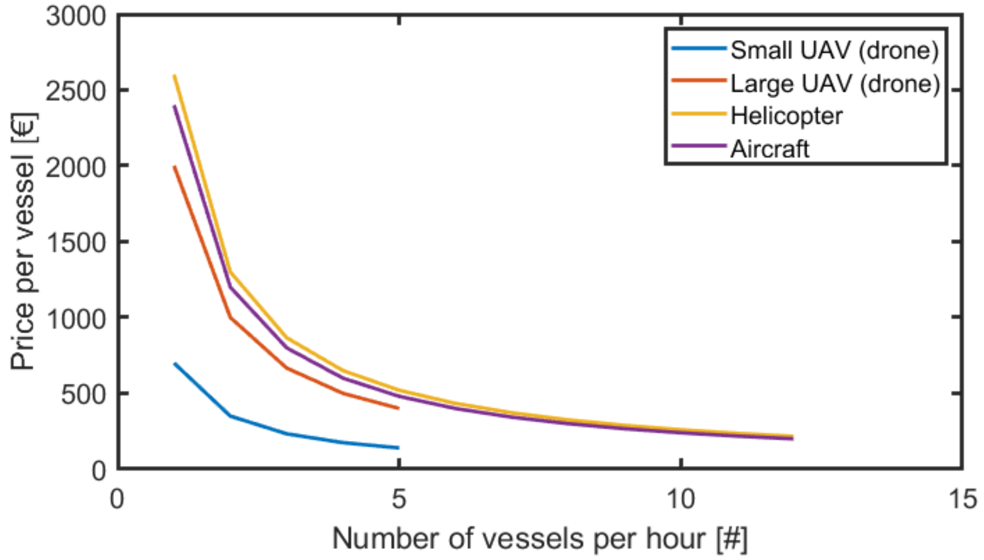

Figure 2-2. Measurement costs per vessel-port-visit for different types of aerial vehicles.

The estimated cost for using satellites is uncertain as this is a methodology that is currently under development. As is explained in detail in SCIPPER D2.4, there is growing literature on the feasibility of using satellites to identify and quantify emission plumes of individual ships, particularly for NOx monitoring while SOx monitoring is more uncertain. Currently, ships can be identified as small as 150 metres, and other improvements in satellite retrieval show increased sensitivity for retrieving particular shipping emissions. Important constraints for this technology are the requirement for clear skies and no, or only limited, background pollution from land-based sources. Although measurement uncertainty is high, the repeated measurement of the same ships over a longer time period will allow for specifying deviations in emission of individual ships or even individual measurements. The costs of this solution will be composed of investment for developing algorithms for generating ship emission profiles and implementation and deployment of these algorithms by a service provider that generates near-real-time emission profiles. The Dutch Human Environment and Transport Inspectorate (ILT) has invested 500,000 € in a first research project to generate a minimum viable product; a second similar investment may be required to further expand the methodology. Next to investments, there are also annual costs, which are mostly computational facilities and maintenance of a measurement results interface; these costs are unknown - possibly between 1 and 5 million € /year. Satellite data are provided as an open-source data set and therefore require no costs. Given the size of the target population (35,000 ships), low levels of detection coverage, and the constraints mentioned above, such an approach would generate thousands of daily updates of emission profiles for the total population. This would place the costs for satellite-based monitoring in the similar price range per ship as stationary sniffer solutions, with a global coverage, albeit at a lower level of accuracy.

There are also different advantages and disadvantages given the different techniques. The small UAVs, although relatively cheap, are limited in the range they can cover. Thus, small drones are mainly suitable for measurements near ports or coastal shipping lanes. Both helicopter and aircraft have a larger range, and can go up to 100 km offshore tracking shipping lanes for several hundreds of kilometres. For all aircraft, no measurements can be carried out in unfavourable meteorological conditions, e.g. more than 25 knots mean winds, and larger UAVs in particular are relatively expensive. In practise these have a limited operating range up to 50km from the launching site due to the need to maintain RLOS. Because the sniffer operation is taking place at low altitudes (40-60m above sea level), the curvature of the Earth prevents further radio distance without compromising navigational control and safety. Large UAVs, as well as manned helicopters, can however be launched from shore as well as from a coast guard vessel. The aircraft and large UAVs can also combine flights of FSC measurements with other activities (e.g. general aerial marine pollution surveillance, oil spill detection, SAR operations, fishery control, FRONTEX operations etc.). A further benefit to aerial surveillance is the mobility of sampling. Consequently, the vessel will not know where they will be sampled and even vessels at berth can be measured. The onshore sniffer measurements are relatively inexpensive and vessels can be sampled 24/7 (given favourable wind conditions).

There is one other trade-off to take note of, which is the one between measurement accuracy and costs. An in-stack sensor is likely to have higher accuracy than any of the remote sensing options, but this comes at higher costs. Within the remote sensor group the achieved measurement quality of mobile sensors is comparable to that of the stationary sensors, because the latter group measures in a less concentrated plume with more sensitive sensors. Finally, a satellite will be able to monitor globally at relatively low costs per ship, but uncertainty is very likely to be larger than any of the other solutions.

3. Onboard monitoring options

3.1 SCIPPER sensor systems

Continuous Emissions Monitoring Systems (CEMS) are already available from commercial suppliers like ABB, Danfoss, Sick, Siemens and others. These systems make generally use of certain types of infrared or ultraviolet analysers, but also electro chemical sensers (ESC) are used in some cases. An overview of the commercial systems is for example given in De Jong, 2018. The SCIPPER sensor systems are characterized by their low costs. These sensor systems are based on automotive sensors or low costs air quality sensors.

In the table below, an overview of the sensor systems for onboard monitoring is given. In addition to this, PML and eEE provide s-AIS satellite data transmission and web-based user access services. Referring to Figure 3-1 below, CML also developed within SCIPPER an ‘Environmental Emission Monitoring Centre’ (ESMC), for end-user data presentation and averaging.

IVL has carried out extensive high-end reference measurements to validate the results of the sensor systems (Moldanova, 2022), and the results of sensor-based onboard monitoring, as well as the satellite data transmission concept, are reported in respectively SCIPPER D1.6, 2022 and SCIPPER D1.5, 2021. SCIPPER D1.6 further includes data presentation options for NOx in g/kWh and in g/kg fuel in the form of maps as a function of engine power or vessels speeds, and as daily averages. SCIPPER D1.5 also includes a standard data format for s-AIS data transmission.

Table 3-1. Overview SCIPPER onboard sensor systems

Partner	Main activity	Parameters for monitoring
AEROMON	BH-12 sensor system	CO_2, NO, NO_2, SO_2, NH_3, CO, PM_1, $PM_{2.5}$, and PM_{10}
AUTH HMGU	Development Black Carbon sensor, Literature study	Black Carbon, BC
CML	Development of the Sensor Box (monitoring in plume)	NO, NO_2, SO_2 and PM
TAU	Preparation dilution system + sensors	Diffusion charging PN sensors (DePS and PPS-M)
TNO	Preparation SEMS monitoring system, Literature study, Reporting formats and interface with WP5	NOx, NH_3 Automotive sensors

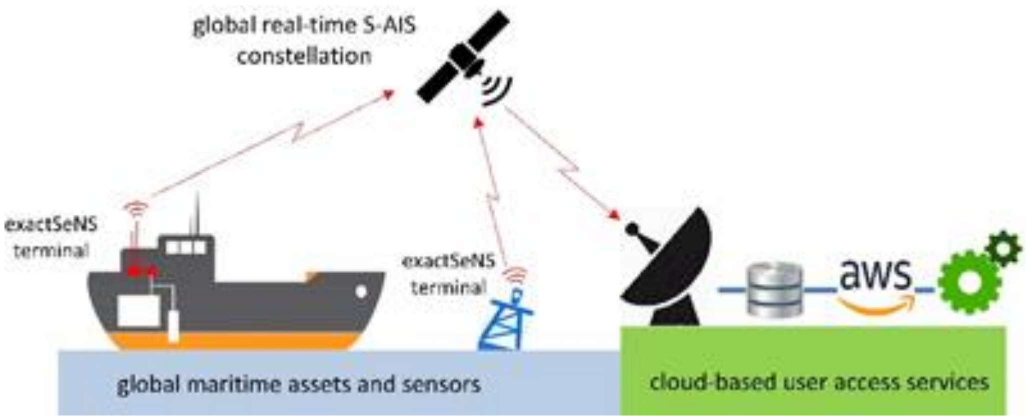

Figure 3-1. A schematic showing the end-to-end emissions reporting service - from ship-to-shore and then to the cloud-based user access services

3.2 Reference vessels

Vessels sailing in Emission Control Areas (ECA) are seen as the first market to be developed for continuous onboard monitoring. Therefore, typical vessels for North European ECAs have been chosen as reference vessels for doing the cost effectiveness analysis. These vessels are presented in the table below. More information is given in a table in Appendix A.

Table 3-2. Reference vessels defined for Northern European ECA zones. All ships are equipped with MS engines and use MGO fuel

Typical ECA vessels	Number of engines	Number of funnels	Total power kW	Fuel use ton/year
General cargo	3	1	3 350	2 400
Container 1000 TEU	4	1	12 900	5 600
Cruise	4	1	30 400	20 000
Service offshore PSV	4	1	7 300	4 900
Dredging	6	1	12 500	12 500
Ferry-RoPax	9	2	28 000	11 500

3.3 Costs sensor-based options

In this section, the costs of five different sensor options are evaluated. The options are all tested on one or two ships. They consist of different sensor types in combination with satellite sAIS data transmission and reporting via the Environmental Shipping Monitoring Centre (ESMC).

The options are:

- Option A: Only s-AIS data transmission and reporting
- Option B: Automotive sensors per each engine: NOx, NH_3 and O_2
- Option C: Air quality sensors per each funnel
- Option D: Option C plus PM or BC sensor
- Option E: Plume and background sensor boxes

An overview of these options is given in the table below.

Table 3-3. Overview of (SCIPPER) sensor-based options for onboard monitoring

Option	A	B	C	D	E
Sensor type	Use of existing sensors for emission control or onboard diagnostics (OBD)	NOx - NH_3 automotive sensors	NOx, SOx air quality sensors	NOx, SOx, PM/BC sensors	Plume sensor box
Installation	Only s-AIS transmission + reporting	Installed on each engine	Installed per funnel. Engine sampled one by one	Installed per funnel. Engine sampled one by one	Installed per funnel plus background box
Individual engine monitoring	Yes	Yes	Yes	Yes	No

Option A is the lowest cost option. In this option, it is assumed that the sensors or measuring devices are already onboard as part of an emission control system (for NOx, SOx, PM), as is currently the case with road transport and mobile machinery.

For option B automotive sensors are installed in the exhaust pipe of each engine. The sensors measure NOx and NH_3. For option C and D, air quality sensors for NOx and SOx are used in combination with a central sampling and air dilutions system per funnel. Option D is very similar, but with the addition of a PM or BC sensor. The sampling system will sample the exhausts of the engines one by one, so is not fully continuous, but for example, once every five minutes. The air dilution system dilutes the exhaust gas by a factor 100 or more; this to avoid fouling and exposure of the sensor to too high concentrations. The dilution system may include a filtered sample stream for the gaseous component sensors, and a non-filtered sample stream for the PM/BC sensors.

Option E consists of fixed plume sensor boxes installed on the vessel. Each vessel will then have one sensor box specially for background emissions monitoring and one plume sensor box for each funnel on the vessel. The plume sensor box measures the mixture of all engines feeding into the plumes.

The following cost types are reviewed:

- Investment costs: includes hardware and installation costs
- Annual costs, divided into two groups:
  - sensor maintenance and replacement costs - annual replacement of sensors is assumed, including annual calibration of the new sensors
  - annual fees for data-transmission, data storage, and reporting via the ESMC.

The annual fees for data-transmission and reporting are assumed to be the same for all options A through E.

The ESMC is a SCIPPER development described in Deliverable D5.2. The annual operating costs of the ESMC is only roughly calculated, based on the number of FTEs needed, overhead, database and cloud service costs. It is assumed that at least three persons are needed to operate an ESMC:

- 1 FTE for management, communication and future developments
- 1 FTE for communication with participating ship owners
- 1 FTE for technical developments and maintenance of the ICT systems

Based on this, it is estimated that the minimum annual costs including overhead and cloud services would total 500,000 €. Based on a participation of 250 vessels, the annual costs per vessel is 2,000 €. This number is used for all options. It can be imagined that the number of participating vessels would grow to some 2,000 vessels of more after 10 years. In that case, additional FTEs are likely needed for communication with ship owners and ICT maintenance and updates. Never-the-less this may lead to lower annual costs per vessel.

The sAIS satellite data transmission is also a SCIPPER development, and is described in Deliverable D1.5. The costs are assumed to be the same for all monitoring options, and include:

- an investment costs of 3000 € for the data transmission system (exactSeNS VHF transmitter), including wiring, connectors, and installation
- an annual fee for data transmission (i.e. airtime) of 125 €.

In the four tables below, the costs are specified for on-board monitoring options A through E. The tables show that the annual costs for the sensor systems are significant. This is because the exhaust gases of marine engines consists of particles, sulphated ash and (heavy) hydrocarbons and water, all of which can cause deposits on sensors. As such, and despite the presence of air shield systems or periodic sampling systems, annual replacement of sensor is expected to be necessary and therefore included in the cost calculations.

Table 3-4. Investment and annual service and maintenance costs for monitoring option A

Option A: Only data transmission and reporting	Per	Investment €	Annual costs €
s-AIS exactSeNS data transmission system including wiring, connectors, installation and airtime.	Vessel	3,000	125
Environmental Shipping Monitoring Centre - ESMC	Vessel		2,000

Table 3-5. Investment and annual service and maintenance costs for monitoring option B

Option B: Automotive sensors, data transmission and reporting	Per	Investment €	Annual costs €
General installation costs & central controller (e.g. SEMS)	Vessel	5,000	
Installation costs sensors NOx, NH_3, O_2	Engine	1,000	400
Air shield system	Engine	1,000	100
s-AIS exactSeNS data transmission system including wiring, connectors, installation, and airtime.	Vessel	3,000	125
Environmental Shipping Monitoring Centre - ESMC	Vessel		2,000

Table 3-6. Investment and annual service and maintenance costs for monitoring options C + D

Option C + D: Air quality sensors, data transmission and reporting	Option	Per	Investment €	Annual costs €
General installation costs & central controller (e.g. BH12)	C+D	Vessel	5,000	
Installation costs sensors NOx, SOx, CO2	C+D	Funnel	5,000	1,000
PM or BC sensor	D	Funnel	2,000	400
Air dilution system	C+D	Funnel	3,000	200
s-AIS ExactSeNS data system including wiring, connectors, installation, and airtime	C+D	Vessel	3,000	125
Environmental Shipping Monitoring Centre - ESMC	C+D	Vessel		2,000

Table 3-7. Investment and annual service costs and maintenance for monitoring option E

Option E: Plume boxes, data transmission and reporting	Per	Investment €	Annual costs €
General installation costs sensor boxes	Vessel	2,500	
Background measuring box NOx, SOx, PM	Vessel	1,900	1,050
Plume measuring box NOx, SOx, PM	Funnel	1,900	1,050
s-AIS ExactSeNS data system including wiring, connectors, installation, and airtime	Vessel	3,000	125
Environmental Shipping Monitoring Centre - ESMC	Vessel		2,000

The total annual costs are calculated based on the investment costs and the annual costs from the four tables above. The annual CAPEX costs are estimated to be equal to 15% of the investment costs. This is constructed as follows:

- Lifetime and payback time is 10 years equal to 10% depreciation per year
- Interest costs 8%: 4% average during the lifetime
- Insurance costs: 1%.

The annual costs for most monitoring options, A through E, is only dependent on the number of funnels. The total annual costs are given in the table below.

Table 3-8. Total annual costs in € for onboard monitoring options, dependent on number of funnels (sensors for monitoring on all engines)

Option	A	B	C	D	E
Sensor type	Use of existing sensors for emission control or OBD	NOx - NH_3 automotive sensors	NOx, SOx air quality sensors	NOx, SOx, BC sensors	Plume sensor box NOx, SOx, PM
1 funnel	2,575	Dependent number of engines	5,725	6,425	5,620
2 funnels	2,575	Dependent number of engines	8,125	9,525	6,955

In the table below, a full overview is given for the total annual monitoring costs for the ECA reference vessels.

Table 3-9. Total annual costs € for onboard monitoring options per vessel type (OBM on all engines)

Option	A	B	C	D	E
Sensor type	Use of existing sensors for emission control or OBD	NOx - NH_3 automotive sensors	NOx, SOx air quality sensors	NOx, SOx, BC sensors	Plume sensor box
General cargo	2,575	5,725	5,725	6,425	5,620
Container 1000 TEU		6,525			
Cruise		6,525			
Service offshore		6,525			
Dredging		8,125			
Ferry-RoPax	2,575	8,925	8,125	9,525	6,955

From the tables, it can be concluded that the annual costs onboard monitoring of options B through E are not very different. The costs range from a little below 6,000 € annually for a smaller vessel and gaseous emission monitoring to about 9,500 € annually for a larger vessel with two funnels and gaseous plus PM emissions monitoring. Only option A is much more cost effective, with an annual cost level of about 2,600 €. In this case, it is assumed that sensors or emission analysers are already a part of the emission control system, and the monitoring system can use these sensors. This is basically the normal situation with road & non-road vehicles, where emissions control sensors are also used for OBD/OBM.

In the following sections the monitoring costs will be compared with the external costs of emissions and with the costs of NOx and SOx emissions reduction.

3.4 Relative monitoring costs

3.4.1 External costs of emissions

All the previous monitoring costs calculated are direct, associated to a product, device, or activity. However, shipping, like other transportation sectors, is characterized by high quantities of pollutants emitted. These incorporate a cost but are not compensated for as direct ones can be. This type of cost, referred to as 'external', is related to the impact that pollutant emissions impose on society and the environment, and can be expressed in monetized values. For the purposes of the present report, we calculate the shipping induced annual external costs of NOx, SO_2 and PM emissions, for the main European sea regions, and for the ship types previously defined.

Sea areas are characterized by different emission control regulations. Specifically, from January 2020, IMO applied a fuel sulphur content cap of 0,5% globally to reduce SO_X emissions. In areas established as SECAs, a stricter limit of 0.1% FSC exists. Moreover, NO_X regulation applies for all ship engines above 130 KW, with stricter emission limits within NECAs for Tier III ships. To study the externalities on European seas, taking into account the different regulations, we distinguished the following four cases:

- The Mediterranean Sea as it stands now, to reflect a non-SECA region, where the FSC is at 0.5%.
- The Mediterranean Sea as it will be in the near future (2025), to reflect a SECA region where the FSC is limited to 0.1%.
- The Baltic Sea, representing both a SECA and a NECA.
- The North Sea, representing both a SECA and a NECA.

The methodology for estimating the shipping induced external costs for the above sea areas relies on a combination of monetized values of the emission quantities damage cost (euro/kg), and the annual emissions footprint of the ship types (kg/year).

The damage cost rates for the three sea regions were retrieved from the EU Handbook on the external cost of Transport (EC, 2019). Externalities differentiate according to the area where the shipping activity takes place. Such costs also vary with the pollutant type, because of the different level of consequence severity the emissions are associated with.

Table 3-10. External costs of pollutant emissions, €/ton emission. Source handbook (EC, 2019).

Sea region	NMVOC	NO_X	$PM_{2,5}$	SO_2
Baltic Sea	1,000	7,900	18,300	6,900
Black Sea	200	7,800	30,000	11,100
Mediterranean Sea	500	3,000	24,600	9,200
North Sea	2,300	10,700	34,400	10,500
Remaining North-East Atlantic	400	3,800	7,200	3,500

The annual emissions footprint was estimated using the fuel-based emission factors from SCIPPER D4.1, generalized for MGO/LSFO fuel and MS engine type. For the Mediterranean (before 2025), the EFs reflect a non-SECA condition, where LSFO fuel (0,5% FSC) was used, while for the SECA characterized North, Baltic, and Mediterranean Sea (as future SECA after 2025), MGO fuel (0.1% FSC) was considered. For non-NECA areas (e.g. Mediterranean), or vessels build before 2016 (Baltic Sea) and 2021 (North Sea), we assumed a ship fleet synthesis of NOx Tier II compliant engines, while for new vessels in NECA zones (Baltic Sea and North Sea), the Tier III standard was applied. These EFs were also adjusted to represent an average vessel operation by applying a sequence of load factors as a typical activity profile. A total emissions footprint was then estimated by applying the adjusted fuel-based EFs to an annual fuel consumption of the ship types. For more details, refer to Appendix B.

Based on the annual emissions and the external cost rate per pollutant, the total annual damage cost is calculated and provided in Table 3-11.

Table 3-11. Total and per pollutant external costs in € in the three different sea regions for a variety of ship types

Sea Area	Ship types	NO_X	SO_2	PM	Total
Global 0.5% FSC (Mediterranean)	General cargo	325.440	213.734	161.770	700.944
	Container 1000 TEU	759.360	498.714	377.462	1.635.536
	Cruise	2.712.000	1.781.120	1.348.080	5.841.200
	Service offshore	664.440	436.374	330.280	1.431.094
	Dredging	1.695.000	1.113.200	842.550	3.650.750
	Ferry-RoPax	1.559.400	1.024.144	775.146	3.358.690
Future SECA 2025 (Mediterranean)	General cargo	340.560	39.744	66.715	447.019
	Container 1000 TEU	794.640	92.736	155.669	1.043.045
	Cruise	2.838.000	331.200	555.960	3.725.160
	Service offshore	695.310	81.144	136.210	912.664
	Dredging	1.773.750	207.000	347.475	2.328.225
	Ferry-RoPax	1.631.850	190.440	319.677	2.141.967
SECA & NECA (Baltic Sea)	General cargo	254.064	29.808	49.630	333.502
	Container 1000 TEU	592.816	69.552	115.802	778.170
	Cruise	2.117.200	248.400	413.580	2.779.180
	Service offshore	518.714	60.858	101.327	680.899
	Dredging	1.323.250	155.250	258.488	1.736.988
	Ferry-RoPax	1.217.390	142.830	237.809	1.598.029
SECA & NECA (North Sea)	General cargo	344.112	45.360	93.293	482.765
	Container 1000 TEU	802.928	105.840	217.683	1.126.451
	Cruise	2.867.600	378.000	777.440	4.023.040
	Service offshore	702.562	92.610	190.473	985.645
	Dredging	1.792.250	236.250	485.900	2.514.400
	Ferry-RoPax	1.648.870	217.350	447.028	2.313.248

In Figure 3-2, a graphic illustration of external costs (Euro/year) for each of the different sea areas (cases), and per pollutant, is presented, for a container ship 1,000 TEU as a reference vessel type.

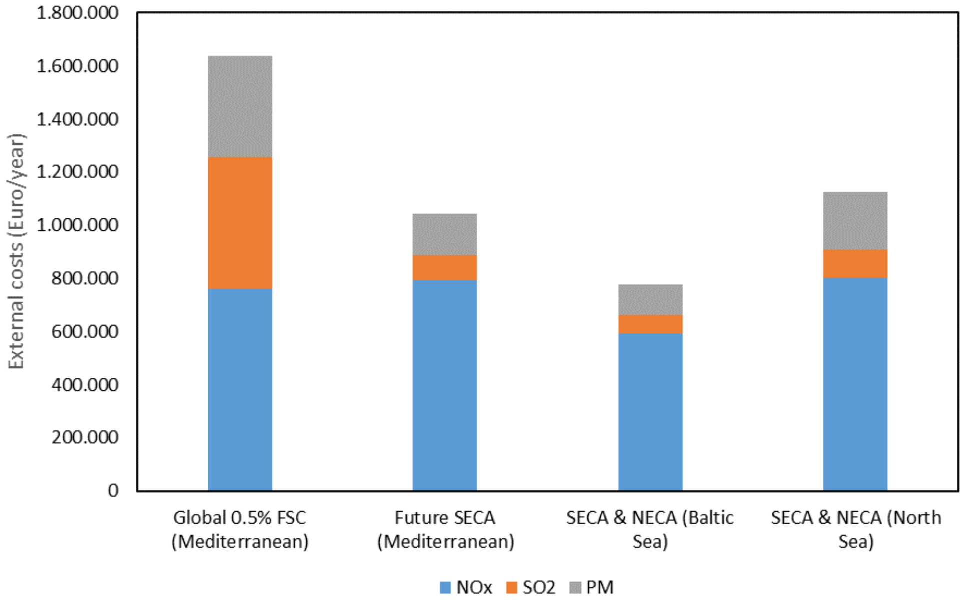

Figure 3-2. External costs per pollutant and per sea region for 1000 TEU container ship as a reference vessel type.

For comparison purposes, we selected a containership of 20,000 TEU to evaluate the inter-continental navigation part. A similar calculation was made using the external cost of sailing in the Atlantic. Results show that inter-continental navigation is associated with an external cost at the level of 7 million euros/year, over four times higher than the 1,000 TEU container vessel sailing in the Mediterranean sea (0.5% FSC).

3.4.2 External costs versus monitoring costs

In section 3.6 it was concluded that the annual monitoring costs of onboard sensor systems are not strictly correlated to the size of the vessels. The annual costs range from about 2,500 € to 9,500 €, depending on the monitoring option A through E and number of engines onboard of the vessel and/or the number of funnels (Table 3-7).

The external costs are, however, very much dependent on the size of the vessel, and especially on the annual fuel consumption, the engine Tier level, and the fuel type.

In the Tables 3-12 and 3-13 below the annual monitoring costs are calculated as percentage of the annual external costs (from table 3-10). This is only done for the monitoring options B (automotive NOx sensors) and D (air quality sensors NOx, SOx, and PM/BC). In Table 3-11, the relative monitoring costs are calculated for the Mediterranean Sea. For option D, this is done for two cases: current FSC requirements (FSC<0.5%), and planned SECA zone for 2025 onwards. In Table 3-12, the monitoring costs are given for the both the Baltic Sea and the North Sea for ships that comply both with SECA and NECA, so basically ships with Tier III engines.

From the tables, we can conclude that the influence on the reference vessel type is larger than the influence of the sea area. We can also conclude that the monitoring costs range from about 0.1% to 2.3% of the external costs of emissions depending on the ship type and the sea area and emission requirements. This percentage is inversely proportional with the annual bunker fuel quantity, meaning the relative costs of onboard monitoring would be lower for deep sea ships. For the large container vessel example mentioned in section 3.7.1 (external costs 7 million € per year), the monitoring costs are around 0.1%.

Table 3-12. Mediterranean Sea: onboard monitoring costs with sensors as percentage of external costs of pollutant emissions for short sea reference vessels. Based on Medium Speed Tier II engines running on MGO fuel.

	NOx monitoring with automotive sensors as percentage of NOx (Tier II) external costs	NOx + SOx + PM monitoring with air quality sensors as percentage of total external costs	
Monitoring option (Table 3-2)	B	D	D
Scenario		Global 0.5% FSC	SECA 2025
General cargo	1.8%	0.9%	1.4%
Container 1000 TEU	0.9%	0.4%	0.6%
Cruise	0.2%	0.1%	0.2%
Service offshore	1.0%	0.4%	0.7%
Dredging	0.5%	0.2%	0.3%
Ferry-RoPax	0.6%	0.3%	0.4%

Table 3-13. Baltic Sea and North Sea: onboard monitoring costs with sensors as percentage of external costs of pollutant emissions for short sea reference vessels. Scenario SECA+NECA. Based on Medium Speed Tier III engines running on MGO fuel.

	NOx monitoring with automotive sensors as share of NOx (Tier III) external costs		NOx + SOx + PM monitoring with air quality sensors as share of total external costs	
Monitoring option (Table 3-2)	B		D	
Area	Baltic Sea	North Sea	Baltic Sea	North Sea
General cargo	2.3%	1.7%	1.8%	1.3%
Container 1000 TEU	1.1%	0.8%	0.8%	0.5%
Cruise	0.3%	0.2%	0.2%	0.2%
Service offshore	1.3%	0.9%	0.9%	0.6%
Dredging	0.6%	0.5%	0.4%	0.2%
Ferry-RoPax	0.7%	0.5%	0.6%	0.4%

3.4.3 External costs with non-compliance

In the current assessment, the external costs are lower with more stringent emission requirements applied. Therefore the external costs are the lowest within SECA + NECA areas. However, this is also where the relative impact of non-compliance on the external costs is highest. If a NOx reduction catalyst fails or is deliberately switched off, the NOx emissions will rise by a factor of 3 to 4. Also, if a SOx scrubber fails, or fuel with 0.5% FSC is used inside a SECA instead of 0.1%, the SOx emissions will increase by a factor five to ca. a factor thirty[1]. This means external costs will rise dramatically in case of non-compliance.

In IIASA, 2018 and ECAMED, 2019, the benefits and costs were investigated of the introduction of SECAs and NECAs for Europe including the Mediterranean Sea. IIASA concluded that the health benefits for 2030 and 2050 for both SECA and NECA would be a factor of 6 and 12 times higher, respectively, than the costs of complying with SECA and NECA requirements. For the Mediterranean Sea specifically, these numbers were slightly lower (4.4 and 7.5). ECAMED concluded that the value of health benefits for the Mediterranean Sea is at least three times higher than the costs. Of course, the cost-efficiency of monitoring is also dependent on the emissions compliance rate. If the compliance rate is very high, there is no strict reason to mandate continuous monitoring, unless the data from such (compliant) monitoring is also used for other purposes, e.g. to further reduce fuel sampling costs in port.

[1] Average FSC of HFO is around 2.7% . So if a scrubber fails SOx emissions are a factor 27 above the sulphur limit of 0.1%

According to THESIS-EU, and based on fuel sample data, the 2022 EU compliance rate with the sulphur limits improved from 96% (outside SECA area) in 2015 to 98-99% (within SECA area) in 2022. These high compliance rates have also been achieved because of extensive compliance monitoring via onshore remote sensing, aerial campaigns and fuel sampling. The compliance of NOx is more difficult to enforce than FSC. Furthermore, NOx catalysts can easier be switched off. Also, technical failures and catalyst aging can lead to diminished NOx reduction and/or increased NH_3 emissions. So, particularly for Tier III vessels, onboard emissions monitoring is important.
It can therefore be concluded that there is a risk of a large rise in external costs, despite possible low non-compliance rates. This makes continuous onboard monitoring advisable, also to keep everyone aware that these systems need regular attention and despite the significant costs. It should be noted that other options for NOx enforcement are very difficult in the absence of a simple onboard measurement procedure. Also the onboard monitoring costs are 50-70% lower if a ship is already equipped with sensors or other analysers for emissions monitoring. In that case, only the s-AIS data transmission and ESMC costs are additional.

3.4.4 Monitoring costs relative to abatement costs

In this section, the onboard monitoring costs are compared with the costs of NOx and SOx emissions reduction. The SCR operating costs are primarily based on EMERGE D1.1, 2020. The FSC reduction costs are based on the difference between the fuel costs (as of August 2022) for a FSC of 0.5% (global requirement) and 0.1% (SECA requirement). In this case the bunker price difference between VLSFO and ULSFO is taken. This difference for August 2022 was about 320$[2] per metric tonne. The difference is 50 €/tonne larger if MGO instead of ULSFO would have been used. In the table below the annual costs for the short sea reference vessels are calculated, based on the total installed power and the annual fuel use.

Table 3-14. Total annual costs in € for SCR NOx reduction (Tier III) and FSC reduction (0.5% to 0.1%) for ECA reference vessels.

€	Total power kW	Fuel use ton/year	SCR deNOx* €	FSC 0.1% versus 0.5% ** €
General cargo	3,350	2,400	71,000	768,000
Container 1000 TEU	12,900	5,600	210,000	1,792,000
Cruise	30,400	20,000	614,000	6,400,000
Service offshore PSV	7,300	4,900	149,000	1,568,000
Dredging	12,500	12,500	328,000	4,000,000
Ferry-RoPax	28,000	11,500	444,000	3,680,000

* SCR costs based on EMERGE D1.1, 2020: investment costs 72€/kW engine power, with annual CAPEX costs 12% of investment costs and urea + maintenance costs: 3.52 €/MWh (converts to 17.58 €/ton fuel with average SFC of 0.2ton/MWh).
** FSC reduction costs based on Rotterdam bunker price difference ULSFO and VLSFO: 320$=€ (August 2022 average).

In the Table 3-15 below, the onboard monitoring costs with sensors (including satellite data transmission and reporting via the ESMC) are expressed as percentage of the NOx and FSC reduction costs. This is done for option B, automotive sensors only for NOx and NH_3 compared to SCR operational costs and, for option D, air quality sensors for NOx, SOx and PM or BC, compared to the sum of FSC and NOx reduction costs.

Table 3-15. Onboard monitoring costs with sensors as percentage of pollutant emission reduction costs for short sea reference vessels. Based on input from Tables 3-9 (monitoring costs) and 3-14 (NOx and SOx reduction costs).

	Option B (automotive sensors) NOx, NH_3 as share of SCR deNOx costs	Option D (air quality sensors) NOx + SOx + PM as share of FSC reduction + SCR deNOx costs
General cargo	8.1%	0.8%
Container 1000 TEU	3.1%	0.3%
Cruise	1.1%	0.1%

[2] There is substantial uncertainty about this 320$ difference taking into account the current worldwide crises. In contrast for August 2021 this difference was limited to 50-60 $/ton, but this was during the Corona crisis. Exchange ratio of 1€ for 1$ is used.

Service offshore PSV	4.4%	0.4%
Dredging	2.5%	0.1%
Ferry-RoPax	2.0%	0.2%

From the table, it can be concluded that the costs are significant for the first option B, NOx monitoring. The relative costs range from 1% to 8%. Especially for a vessel with a rather low annual fuel consumption, it can increase up to 8%. For option D, monitoring NOx, SOx and PM emissions, the relative monitoring costs stay below 1% of the cost of NOx and SOx emissions reduction (based on the price difference assumption for ULSFO and VLSFO of 320 €/ton).

4. Effectiveness of remote sensing and onboard monitoring

4.1 Area and time coverage of emissions monitoring

There are large differences between the onboard and the different kinds of remote sensing options in terms of area and time coverage. Onboard monitoring can basically operate globally and 24/7, but for all other options, there are restrictions. Satellite emissions monitoring can operated globally and 24/7, but the atmosphere needs to be cloud-free. For the other remote sensing options (i.e. fixed sniffer stations, UAVs, and manned aircrafts), the area of monitoring is restricted to port and coastal areas, and there are also weather and daylight restrictions (and for the UAVs in some cases also air space restrictions).

In Table 4-1, an overview is given with respect to effectiveness parameters for the different remote and onboard monitoring options. The remote monitoring options with sniffer stations or small UAVs are usually restricted to a small area such as ports and part of coastal (ECA) areas, but they are operational and can provide excellent coverage of ships that may exceed the FSC limits and possibly also NOx limits. Similarly, the manned aircraft can provide excellent large(r) area coverage along dense shipping lanes with sufficient traffic to justify the operational costs.

Remote sensing, especially fixed sniffer stations, has proven to be a good way to impose a preventive pressure on ship owners to comply with emissions regulations. It is also a cost-effective, screening instrument to spot vessels which violate the FSC requirements. When spotted, an onboard vessel inspection is initiated to take actual fuel samples for FSC analysis. Also due to this effective system, the share of vessels violating the FSC requirements in Europe has dropped from 2% / 5.5% (depending on the area) in 2015 to 0.25% / 3% in 2022[3].

Only satellite monitoring and onboard monitoring have global coverage. Satellite monitoring is promising and costs-effective, but it is still at a low TRL level with respect to its development. It also indicates a total mass of NOx (NO_2) emission rather than a specific NOx emission (NOx/CO_2 ratio and from that a g/kWh emission projection). Furthermore, it must be pointed out that satellites can only measure NO_2, but not NO. Ships, on the other hand, mainly emit NO, which is oxidised to detectable NO_2 during ageing of the plume. Satellite NOx monitoring can compare similar vessels in terms of size or energy consumption and then indicate higher (Tier I or II) or lower NOx levels (Tier III). Possibly satellite monitoring can also indicate lower NOx emissions when SCR systems are 'on' within NECA areas, in comparison to the higher emissions with SCR 'off' outside the areas. This make satellites a potential future option for surveying in particular the NECA borders. Onboard monitoring is the only system which can always monitor, provides the most direct link with emission legislation, has global coverage, and is independent of time of day and weather.I

Sensor-based onboard monitoring, however, still has some developments considerations and draw backs:

- Sufficient lifetime of the sensors, even with annual replacement, has not yet been demonstrated and will require further development.
- Installation and operations of sensors, or other measuring instruments, come with significant costs and maintenance.
- Tampering is possible, so there is a need for independent validation. Additionally, a system with remote sensing is required to periodically check the correct operation of the onboard monitoring system (satellite monitoring may fulfil such a role in the long term).
- Comprehensive monitoring with on-board sensors requires agreement on standards for installation and operation at IMO level.

Onboard monitoring and satellite monitoring are excellent ways to monitor pollutant emissions on a global level. In addition to this, remote sensing in plumes remains important to independently check the onboard monitoring systems, and to monitor emission of vessels without onboard monitoring.

[3] Statistics on the EMSA webpage THETIS-EU - Compliance (europa.eu))

Table 4-1. Monitoring of NOx, SOx, PM, BC emissions: effectiveness parameters for onboard monitoring (row 2) and remote monitoring options (row 3-7).

Monitoring	Components	Area	Other limitations	
Onboard monitoring	NOx, NO, NO_2, SO_2, PM, BC	Global coverage	Reliability of sensors and overall system	Legal implementation including simple, transparent, calculation methodology
Sniffer stations	NO, NO_2, SO_2, PM, PN	Primarily ports	Wind direction	
Small UAV	NO, NO_2, SO_2	Primarily ports and short-range areas (<5km from shore)*	day light, air space restrictions may apply	
Large UAV	NO, NO_2, SO_2, PN	Primarily coastal and medium-range areas (<50 km from shore)*	day light, air space restrictions may apply	
Manned aircraft	NO, NO_2, SO_2, PN	Primarily coastal and long-range areas (<100 km from shore)*	day light	
Satellite	NO_2, SO_2	Global coverage Clear sky	Indicates total rather than specific emissions	

* In the case of UAVs, the range refers to the operating distance between the pilot control station and the UAV limited by radio-line-of-sight (RLOS). For manned aircraft the distance refers to the safe operating distance from shore. Manned aircrafts can survey hundreds of km along coastal shipping lanes. In case of rotary aircrafts, the distance from shore can be larger if launched from a coast guard vessel deck.

4.2 Costs for ship owners and authorities

As described, continuous onboard monitoring with central (public) reporting and remote emissions sensing programme come with costs. However, even though some would argue that these costs are significant, they are very low in comparison to the external costs of emissions and in comparison to the comparative added costs to compliant ship owners over those who cheat. The monitoring costs, which are below, or in many cases far below 2% of the external costs, can be seen as an insurance premium to prevent potential damage in terms of high external costs of emissions and destructive competitive pressures.

The onboard monitoring costs are most naturally to be covered by the ship owners. Although costs could also be split between ship owners and authorities by putting the ESMC under a public authority. Refer to Table 4-2.This could be on a European or global level, e.g. as an extension to the EU-MRV or IMO Data Collection Systems. Remote sensing, as well as onboard monitoring, will also lead to a higher efficiency of other types of enforcement, such as taking fuel or NOx measurement samples onboard in the future. The typical costs of taking a fuel sample onboard and its subsequent analysis for FSC is €400 per sample; the costs of an onboard NOx emission measurement will be much higher. In PROMINENT D3.5, 2017, the costs for an onboard emissions measurement ranged between 6,000 and 12,000 € per vessel, dependent on the number of engines onboard. With remote sensing, the sampling and measurements onboard can be focussed on suspicious vessels, which increases effectiveness.

The combination of onboard monitoring and remote sensing is also important. Remote sensing should be used to monitor as many as possible ships, with or without onboard monitoring systems. For the ships with onboard monitoring system, the remote sensing can also be used to independently verify correct working of the onboard monitoring system. In this respect, it is important that the remote sensing covers different circumstances within the operation profile of each ship. This means that also checks with drones or even manned aircrafts are necessary. In the longer-term future, NOx monitoring via the TROPOMI satellite may also become an option for this.

Table 4-2. Indication of total costs for onboard monitoring (row 2) and typical cases of remote monitoring (row 3-7).

Monitoring	Ship owners	Authorities
Onboard monitoring	Per vessel (excl. ESMC*): 500 – 7500 per year	Total ESMC*: 500,000 per year
Sniffer station onshore (full year operation one system)		300,000 per year, or 20 – 770 € per vessel-pass
Small drone campaign		140 - 350 € per vessel-pass
Large drones campaign (3 months)		400-1000 € per vessel-pass
Manned aircraft campaign		200 - 870 € per vessel-pass
Satellite (globally)		1 – 5 million € per year 100 € per vessel (both indicative)

* Environmental Shipping Monitoring Centre: estimate based on 250 participating vessels, 2000 € per vessel

4.3 Recommendations to policy makers

It has become clear that the costs of onboard or remote monitoring options are low in relation to the external costs of emissions (section 1.7.2), and also in relation to the abatement costs of emissions (section 1.7.3). This makes monitoring and enforcement of emissions compliance a logical step to take. However, to make a regional or global monitoring and enforcement truly effective, several technical and legal steps need to be taken.

Firstly, requirements for onboard monitoring and Real Sailing Emissions (RSE) or In Service Conformity (ISC) need to be implemented in the MARPOL legislation. This could be a next step within the MARPOL Tier legislation, e.g. Tier IV or Tier III-b, which can be taken on a voluntary basis (per country or for certain ship owners).
Such RSE procedure and requirements would involve the following elements:

- Averaging period and/or Not-to-Exceed (NTE) emissions. Load profile preferably to be based on real use, rather than on ISO E2 or E3 test cycle. NTE means that certain emission levels may not be exceeded under specified normal circumstances. In that way compliance with certain limit values can always be checked with the ship in normal service.
- 'Margin' with respect to limit value, with possible cut-off as function of vessels speed or engine load. This margin would be on top of the normal limit value for the official test cycle.
- Measurement or monitoring method including required parameters and dimensions. It is recommended to implement RSE based on g/kg fuel values and limits instead of based on g/kWh.
- a precise calculation methodology, including reference values for fuel properties.

All these elements would need to be evaluated and developed in a 'Technical Working Group'. Ship driveline specialists, engine specialist and air quality specialists should work together in this TWG. This TWG could work out several options to be evaluated by policy specialists at EU or IMO level, and stakeholders from industry.

In the table below, a comparison is made between implemented 'continuous monitoring and Real Driving Emissions' requirements for road vehicles and the SCIPPER proposal for continuous monitoring and RSE for ships. For road vehicles, a specific test trip is done on the road. This trip must include different road types (urban, rural and motorway) representative for normal use. The proposal for ships goes a step further than the current requirements for cars and trucks because the monitoring is continuously with a ship in normal service. On the other hand, the proposal for ships can be implemented on a voluntary basis, or for specific areas where ships emissions need to be reduced for air quality reasons.

Table 4-3. Comparison of implemented legislation on real world emissions for road vehicles and SCIPPER proposal for ships

<table>
<tr><th></th><th>Road vehicles (implemented)</th><th>Sea ships (proposal SCIPPER)</th></tr>
<tr><td>Name</td><td>Real Driving Emissions
In Service Conformity</td><td>Real Sailing Emissions, or
In Service Conformity</td></tr>
<tr><td>Legal position</td><td>Part of type approval of vehicle</td><td>Requirement for overall ship in normal service</td></tr>
<tr><td>Test procedure</td><td>Approximately 3 hours' drive with equal time split between Urban, Rural and Motorway driving</td><td rowspan="2">Continuous monitoring with transmission of monitoring data to central database
Weighted average all engines used*</td></tr>
<tr><td>Continuous monitoring during lifetime</td><td>OBD, with light-off of control lamp on dashboard vehicle and storage in memory ECU</td></tr>
<tr><td>Parameters & dimensions</td><td>Cars: g/km
HD-vehicles: g/kWh</td><td>g/kg fuel
(g/kWh)</td></tr>
<tr><td>Limit value for real-world emissions</td><td>150% of limit value
(applied to Moving Average Windows)</td><td>150% of limit value applied as NTE
(low vessel speed or low power could be excluded from NTE area)</td></tr>
</table>

* Weighted average to be calculated via power ratios, or fuel ratios or air flow ratios between engines

Introduction of continuous monitoring with a form of limit setting, as a next step within IMO Tier emissions legislation, takes considerable time. However, a possible timeline could be as follows:

- 2023-2024: Technical working group to work out details on monitoring parameters, averaging and options for limit setting
- 2025-2026: Start monitoring, voluntary basis
- 2027-2028: Collect & report results, evaluate options for limit setting. Proposal for formal step Tier IV or Tier IIIb
- 2030: Implementation, voluntary basis (e.g. for reduced port duties), possible obligatory for areas where air quality issues require further action.

5. Conclusions and recommendations

5.1 Remote sensing

Remote sensing in the form of a fixed sniffer station, unmanned and manned flight, or patrol vessels have been operational in Europe for several years. The primary focus for enforcement has been FSC, but in the future this needs to be expanded to NOx, especially due to the growing fleet of Tier III vessels. The limitation of most remote sensing options is the limited physical sea area that can be covered, although with the existing techniques described here, a dominant part of ship traffic can actually be covered via some form of remote sensing since most of it happens within 100 km range of shore.. The main limitation for flights is the restriction to daylight, although this may change with future developments.
Nevertheless,
The following conclusion regarding remote sensing are made:

- The cost of maintaining monitoring programs is fully reasonable compared to the external environment and health costs they are aimed at preventing.
- Historic statistics show that intense remote sensing (in Northern Europe) has had a preventive effect.
- The differences in monitoring techniques and cost profiles is diverse enough to fit a multitude of different monitoring / traffic scenarios and budgets.

It is also concluded that FSC monitoring, and enforcement is easier than NOx monitoring, because no engine parameters are needed for FSC. NOx monitoring can provide good insight in the average NOx emission in g/kg fuel. However, the link with engine-based IMO legislation is difficult because of the need to also estimate engine power and Specific Fuel Consumption (SFC) to calculate an engine load-specific emission (g/kWh). This will always remain legally disputable, because of the uncertainty in engine power of what will often be several engines contributing to the overall plume. PN, PM and BC emissions can also best be expressed in g/kg fuel, and additionally no direct legal limits currently exist.

The costs per vessel-pass for remote sensing can be summarized as follows:

- Sniffer stations: 20 - 770 €
- UAVs: 140 - 350 € for small UAVs, and 400-1000 € for large UAVs
- Manned aircrafts: 200 - 870 €
- Satellite, indicative: 100 € per vessel (continuous)

Satellite monitoring is still in its early stage of development and is currently only suitable for NO_2. The main advantage is its global coverage at very low cost per vessel.

5.2 Onboard monitoring

For NOx monitoring and enforcement, the need for full coverage of the sea area (e.g. NECA area), or the complete trip of the vessel, increases. This is because NOx abatement systems can easily be switched on and off or can suffer from some issues which reduce their reduction potential. Also, NOx emission levels cannot be verified in port 'post-voyage'. Continuous onboard emissions monitoring systems with continuous satellite data transmission to a central database and Environmental Shipping Monitoring Centre (ESMC) are an ideal and effective option to fulfil such a role. In the SCIPPER project a number of sensor-based onboard monitoring system options have been investigated, in terms of practical application and costs.
The overall annual costs per vessel (based on six short sea reference vessels) of the different options can be summarized as follows:

- A: Only monitoring and reporting (use of existing sensors or instruments): 2,575 €
- B: NOx-NH_3 monitoring with automotive sensor on each engine: 5,700 – 9,000 €
- C: NOx, SOx monitoring with dilution system and air quality sensors: 5,700 – 8,100 €
- D: NOx, SOx, PM/BC monitoring with dilution system and air quality sensors: 6,500 – 9,500 €
- E: NOx, SOx, PM/BC monitoring with plume sensor boxes and air quality sensors: 5,600 – 7,000 €

These costs include all investment, maintenance, and service costs, and include a 2,000 € per vessel service costs for the ESMC. The costs are substantial, but are still very low compared to the annual external costs of emissions. Onboard mmonitoring costs range from about 0.1% to 2.3% of the external costs depending on the ship type, the

sea area and emission requirements. In comparison to the SOx and NOx reduction costs, it ranges from 0.1% to 0.8%. For NOx monitoring only, the ranges rise to 1% to 8%.
It is concluded that onboard monitoring is an attractive way of creating fairness by shifting the cost of monitoring to those who actually pollute. If using the solutions demonstrated in SCIPPER, the costs are also reasonable compared to the external costs (and the general costs of operating a ship). The costs for onboard monitoring can be split between ship owners and authorities - the authorities can for example bear the costs of the ESMC. In that way the authorities can also control more effectively which date they need for their monitoring and enforcement role.
Remote sensing remains very important, both for ships which do and do not participate in an onboard monitoring system (if not introduced as mandatory at IMO level). In the latter case, remote sensing should function as a periodic check of correct operation of the onboard monitoring system.

5.3 Policy recommendations

In general it is recommended to pursue both the remote and onboard monitoring options presented in this report, particularly for NOx and SOx, because the monitoring costs are low in relation to the external costs to environment and human health. Also remote and onboard monitoring lead to costs reductions for ship inspections. Also taking into account that comprehensive inspection of NOx compliance onboard is very costly.

This leads to a second recommendation, namely to implement specific legislation for NOx monitoring and enforcement and for Real Sailing Emissions, both for remote sensing as well as for onboard monitoring. This would include the following:

- A methodology for monitoring of Real Sailing Emissions (RSE) and Not-To-Exceed limits for NOx (and in a later phase PM and BC).
- A simple, at IMO level, acceptable, onboard measurement procedure for validation measurements based on exhaust concentrations measurements only and using generic SFC values to process g/kWh emissions.
- To further work out the technical concept for continuous onboard monitoring with satellite data transmission and reporting within an EMSC.

The first two measures are necessary to make monitoring and enforcement feasible.

Onboard monitoring could be implemented on a voluntary basis in form of an extension to IMO Tier legislation (e.g. Tier IIIb or Tier IV). It is recommended to further work out the technical details by an IMO Technical Working Group or Sub-committee. This work should include averaging method of real sailing emissions, precise calculations methods, options for future limit settings. It is proposed that the Real Sailing Emissions address the performance of the whole ship rather than individual engines within the ship. By operating the engines in an optimal way (e.g. engine load and number of engines running), the RSE can be reduced.
For the introduction, a phasing in scheme is recommended, which includes the start of monitoring on a voluntary basis and without limit setting. Ports could offer discounts for port fees for ships which monitor pollutant emissions. After evaluation of several years of results, limit values for RSE can be added. Continuous monitoring is especially useful for ships with Tier III engines, since for these ships, NOx emissions can vary mostly depending on optimal operation of the engines and SCR catalyst. A complete phasing in scheme could take some 7 to 10 years.

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Appendix A: Reference vessels & onboard monitoring costs details

A.1 Reference vessels

An overview of the reference vessels used for the onboard monitoring costs calculation is presented in the table below. The vessel types and operational profiles are meant to fit coastal shipping in shipping emission control areas in Europe. The first four vessels of the list are based on CE Delft, 2015, an LNG market assessment and case study report. The last two vessels are based on specifications which can be found on the internet, in combination with an assumed average engine load of 65% and 50% for respectively the dredging and ferry-RoPax vessel.

Table 7-1. Reference vessels defined for Northern European ECA zones. All ships are equipped with MS engines and use MGO fuel

Typical ECA vessels	# main engines	main engine type	Total main Power kW	# aux engines	nb engines total	nb of funnels	Total aux power kW	Total power kW	Fuel use ton/year
General cargo	1	MS	2400	2	3	1	950	3350	2400
Container 1000 TEU	1	MS	10800	3	4	1	2100	12900	5600
Cruise	4	MS	30400		4	1	-	30400	20000
Service offshore PSV	2	MS	5200	2	4	1	2100	7300	4900
Dredging	2	MS	11200	4	6	1	1300	12500	12500
Ferry-RoPax	4	MS	24000	5	9	2	4000	28000	11500

A.2 On board monitoring costs

An overview of the onboard monitoring options, as provided in section 1.7, is presented in the table below.

Table 7-2. Overview of (SCIPPER) sensor-based options for onboard monitoring

Option	A	B	C	D	E
Sensor type	Use of existing sensors for emission control or OBD	NOx - NH_3 automotive sensors	NOx, SOx air quality sensors	NOx, SOx, PM/BC sensors	Plume sensor box
Installation	Only s-AIS transmission + reporting	Installed on each engine	Installed per funnel. Engine sampled one by one	Installed per funnel. Engine sampled one by one	Installed per funnel plus background box

The details of the different types of costs per monitoring option is provided in the tables in section 1.7.
In the five tables below, these costs details are worked out per monitoring option for the reference vessels. In these tables the costs are split across total investment costs, annual service cots and total annual costs. The annual investment costs are calculated as 15% of the investment costs (CAPEX). The monitoring costs of Option B, automotive sensors are primarily dependent on the total number of engines onboard. Options C, D and E are dependent on the number of funnels.

Table 7-3. Cost details for option A: Costs of only s-AIS transmission + independent reporting (use of of existing sensors for emission control or OBD).

<table>
<tr><th>ECA reference vessel</th><th># engines total</th><th>Total investment costs</th><th>Annual service</th><th>Total annual costs</th></tr>
<tr><td>General cargo</td><td>3</td><td rowspan="6">3,000</td><td rowspan="6">2,125</td><td rowspan="6">2,575</td></tr>
<tr><td>Container 1000 TEU</td><td>4</td></tr>
<tr><td>Cruise</td><td>4</td></tr>
<tr><td>Service offshore</td><td>4</td></tr>
<tr><td>Dredging</td><td>6</td></tr>
<tr><td>Ferry-RoPax</td><td>7</td></tr>
</table>

Table 7-4. Cost details for option B: NOx and NH_3 monitoring with automotive sensor installed on all engines per vessel

<table>
<tr><th>ECA reference vessel</th><th># engines total</th><th>Total investment costs</th><th>Annual service</th><th>Total annual costs</th></tr>
<tr><td>General cargo</td><td>3</td><td>14,000</td><td>3,625</td><td>5,725</td></tr>
<tr><td>Container 1000 TEU</td><td>4</td><td rowspan="3">16,000</td><td rowspan="3">4,125</td><td rowspan="3">6,525</td></tr>
<tr><td>Cruise</td><td>4</td></tr>
<tr><td>Service offshore</td><td>4</td></tr>
<tr><td>Dredging</td><td>6</td><td>20,000</td><td>5,125</td><td>8,125</td></tr>
<tr><td>Ferry-RoPax</td><td>7</td><td>22,000</td><td>5,625</td><td>8,925</td></tr>
</table>

Table 7-5. Cost details for option C: NOx, SOx monitoring with air quality sensors: one set per funnel

<table>
<tr><th>ECA reference vessel</th><th># funnels</th><th>Total investment costs</th><th>Annual service</th><th>Total annual costs</th></tr>
<tr><td>General cargo</td><td>1</td><td rowspan="5">16,000</td><td rowspan="5">3,325</td><td rowspan="5">5,725</td></tr>
<tr><td>Container 1000 TEU</td><td>1</td></tr>
<tr><td>Cruise</td><td>1</td></tr>
<tr><td>Service offshore</td><td>1</td></tr>
<tr><td>Dredging</td><td>1</td></tr>
<tr><td>Ferry-RoPax</td><td>2</td><td>24,000</td><td>4,525</td><td>8,125</td></tr>
</table>

Table 7-6. Cost details for option D: NOx, SOx and PM monitoring with air quality sensors: one set per funnel

<table>
<tr><th>ECA reference vessel</th><th># funnels</th><th>Total investment costs</th><th>Annual service</th><th>Total annual costs</th></tr>
<tr><td>General cargo</td><td>1</td><td rowspan="5">18,000</td><td rowspan="5">3,725</td><td rowspan="5">6,425</td></tr>
<tr><td>Container 1000 TEU</td><td>1</td></tr>
<tr><td>Cruise</td><td>1</td></tr>
<tr><td>Service offshore</td><td>1</td></tr>
<tr><td>Dredging</td><td>1</td></tr>
<tr><td>Ferry-RoPax</td><td>2</td><td>28,000</td><td>5,325</td><td>9,525</td></tr>
</table>

Table 7-7. Cost details for option E: NOx, SOx and PM monitoring with plume sensor box: one per funnel plus one for background air.

<table>
<tr><th>ECA reference vessel</th><th># funnels</th><th>Total investment costs</th><th>Annual service</th><th>Total annual costs</th></tr>
<tr><td>General cargo</td><td>1</td><td rowspan="5">9,300</td><td rowspan="5">4,225</td><td rowspan="5">5,620</td></tr>
<tr><td>Container 1000 TEU</td><td>1</td></tr>
<tr><td>Cruise</td><td>1</td></tr>
<tr><td>Service offshore</td><td>1</td></tr>
<tr><td>Dredging</td><td>1</td></tr>
<tr><td>Ferry-RoPax</td><td>2</td><td>11,200</td><td>5,275</td><td>6,955</td></tr>
</table>

Appendix B Emission Factors

Emission Factors according to SCIPPER D4.1, 2021 are expressed in g/kWh. For the external costs analysis the emission factors were transferred to g/kg fuel values using a simple load profile presented in third column in the table below. A reasonably 'even' load profile across the engine load curve was used with an average load of 55%.

Table 8-1. Adjusted weighting factors in comparison with ISO E2/E3 cycle weighting factors

Engine load	E2/E3 weighting factor	Adjusted weighting factor
100%	0.2	0.1
75%	0.5	0.3
50%	0.15	0.3
25%	0.15	0.3
Overall average load	0.69	0.55

The fuel properties used for the g/kg fuel calculation are:

Table 8-2. Fuel properties considered

Fuel	FSC (%)	FCC (%)	LHV (MJ/kgfuel)
LSFO (< 0.5% FSC)	0.5	86.8	41.5
MGO (< 0.1% FSC)	0.0931	86.5	43.4

The Emission Factors used for the external costs calculation in g/kg fuel are presented in the table below.

Table 8-3. NOx Tier II & Tier III, SO_2 and $PM_{2.5}$ Emission Factors in g/kgfuel (and SFOC in g/kWh)

Engine type	Fuel	SFOC (g/kWh)	NOx Tier II	NOx Tier III	SO_2	$PM_{2.5}$
SSD	LSFO	216	61.2	17.5	9.68	2.73
SSD	MGO	206	64	18.3	1.8	1.13
MSD	LSFO	214	45.2	12.9	9.68	2.74
MSD	MGO	205	47.3	13.4	1.8	1.13
HSD	LSFO	248	28.1	7.82	9.68	2.52
HSD	MGO	237	29.4	8.18	1.8	1.01

Appendix C Regulatory and Enforcement gaps

Identified gaps as per SCIPPER D5.1, 2019

Gaps related to SOx and PM emissions:

- Regulations on other fuel characteristics than S-content are lacking.
- Regulated limits on PM are lacking.
- Regulated limits of emission of the non-volatile particulate fraction BC are lacking.
- Regulations on negative side effects of EGCS are lacking.
- PM emission measurement standards of emissions to air are insufficient.
- Regulatory prescribed approaches to the use of remote sensing technology is lacking.
- Cost efficient technologies for certifying compliance at sea are lacking.
- SO_2/CO_2 ratio from EGCS logs need are possibly not reliant over time.

Regulatory gaps regarding NOx:

- NECA geographical scopes are possibly not enough to accomplish the technology demand from the industry that would be needed to have efficient NO_X-regulations.
- Simple legislative test procedure allows for a substantial difference between test cycle emissions and real sailing emissions, especially using modern engine technology.
- Control procedures to discover SCR deactivation are missing.
- Regulation on ammonia slip over time after SCRs are lacking.
- SCR functioning in port areas and other close to shore locations are not well covered by the regulation.
- Knowledge of NO_X sensor performance over time.
- Side effects on the marine environment from the use of EGR scrubbers are not regulated.
- EGR function in port areas and other close to shore locations are not well covered by the regulation.
- No regulation limits the methane slip from LNG engines.

Enforcement gaps:

- Emissions of NO_X from the operational phase are not monitored.
- Time intervals for parameter checks are not specified.
- The applicability of NTE limit for international shipping is small
- Regulatory prescribed approaches to the use of remote sensing technology for NO_X emissions is lacking.
- Sufficient monitoring procedures at the use of NO_X abatement equipment for Tier III is lacking.