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NOx controls for shipping in EU Seas

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Preface

This work is carried out by IVL Swedish Environmental Research Institute and CE Delft on assignment of Transport & Environment. IVL has been responsible for calculating NO_X emissions in the European Seas, and describing technical characteristics and expected costs of the investigated abatement options. CE Delft has conducted the geopolitical analysis and the cost benefit analysis.

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Summary

The aim of this study is to present a timeline for the likely introduction of an entry into force of a Nitrogen Emission Control Area (NECA) in the Baltic Sea, the North Sea and the English Channel. The purpose is also to produce a NO_X emission projection based on the introduction date and compare it to a scenario without a Northern European NECA. Alternative policy instruments that aim at reducing NO_X emissions from shipping are discussed in a comparative analysis including expected NO_X reductions and cost estimates.

An assessment of the outcome of the Baltic Sea and North Sea NECA negotiations has been made together with an estimation of the timeline of the most probable outcome.

Based on interviews with key stakeholders carried out end of 2015, we concluded that the parallel application of Baltic and North Seas was the most likely outcome of the NECA negotiations. The latest developments at HELCOM in spring 2016 have confirmed this assessment. According to the roadmap which Denmark submitted on behalf of the North Sea countries to HELCOM and which has been adopted by HELCOM in March 2016, the Baltic Sea and North Sea NECA applications will both be submitted to MEPC 70 and, if adopted at MEPC 71, will probably enter into force in late 2018. The effective date for both NECAs will be January 2021.

A review of the available technologies to reach the NECA NO_X emission limits indicates that three abatement technologies fulfil the requirements:

- Selective Catalytic Reduction (SCR), a mature after-treatment technology tested on over 500 ships and with efficient NO_X reduction at high exhaust gas temperatures;

- Exhaust Gas Recirculation (EGR), a technology less tested than SCR in marine applications, but confirmed by engine manufacturers to reach the Tier III level. EGR operations are most efficient at high engine loads, similar to SCR;

- Liquefied Natural Gas (LNG), an alternative fuel that has been proven for maritime use in several ships in coastal service the last decade. NO_X emission levels are low without additional abatement technologies. A prerequisite for a more widespread use of LNG as a marine fuel is more supply points of the fuel.

The EGR and the SCR are comparable in costs per kg NO_X not emitted. The costs for LNG are much depending on whether an existing engine is rebuilt for LNG or whether the LNG engine is installed on a new ship. The latter is considerably less costly than the previous.

A review of previous studies showed large variations in projected NO_X-emissions due to different assumptions of traffic density and fleet composition, and different methodological choices. For projections of emissions, choices are made concerning how traffic will change in the future and how energy efficient ships will be. These choices will further influence results. Projection studies for NO_X emissions also include the

ships' lifetime as an important parameter. The most detailed and recent inventories use AIS data to estimate ship traffic and identify individual ships for accurate information.

A projection of NO_X emissions to 2040 is done in this study based on input data from a study by Kalli et al. (WMU Journal of Maritime Affairs 2013(12): 129). Only commercial shipping is included in the study, which means that approximately 85% of NO_X emissions are covered. In our study, projections are performed for two scenarios: one where no NECA is enforced in the Baltic Sea and the North Sea region, and one where a NECA is in effect in 2021. The results indicate total NO_X emissions in 2040 of approximately 300 ktonnes with a NECA in effect from 2021, and 720 ktonnes without a NECA. This corresponds to approximately a 66% reduction in the NECA scenario, and 21% reduction in the scenario without a NECA, compared to emissions in 2010.

Three policy instruments are shortlisted as most promising to be used in addition or as an alternative to Baltic and North Sea NECAs:

1. Regulated slow steaming with a NO_X levy as alternative compliance option where the revenues are used to fund the uptake of NO_X abatement measures;
2. A stand-alone NO_X levy where revenues are not earmarked;
3. A NO_X levy whose revenues are used to fund the uptake of NO_X abatement measures.

These instruments are evaluated regarding their NO_X reduction potential and the associated costs for the sector if the levy rate was either set at €1/kg NO_X, €2/kg NO_X or €3/kg NO_X and if ships would have to reduce their baseline speed by 15%.

The evaluation shows that in terms of NO_X reduction and costs for the sector, two of the three instruments stand out as potential additional/alternative instruments for a Baltic and North Sea NECA. These are 1) a levy & fund and 2) regulated slow steaming combined with a levy & fund. With the levy & fund relatively high NO_X reduction can be achieved (about 70% annually if the NECAs are not established and about 60% in 2025 and about 30% in 2040 if the NECAs are established), which is roughly twice the reduction achieved with regulated slow steaming combined with a levy and fund, at least if the baseline speed is reduced by 15%. However, costs for the sector of a levy and fund are also roughly twice the costs of regulated slow steaming combined with a levy and fund.

1 Introduction

Emissions from shipping are known to contribute significantly to environmental risks and health risks, primarily in coastal regions. The emissions contain health affecting particles and gases, acidifying and eutrophying substances, as well as greenhouse gases. Nitrogen oxides (NO_X) contribute to particle and ozone formation and also potentially cause acidification and eutrophication upon deposition on land, lakes and seas. It is moved long distances in air and is, therefore, often considered a 'regional' pollutant.

Emissions from ships in EU waters are to some extent limited by regional and global regulations. In Annex VI of the MARPOL Convention (International Maritime Organization, 2013), sulphur content in marine fuels is regulated to 0.1% in the Baltic Sea, the North Sea and the English Channel with an effect on emissions of sulphur oxides and particles. The EU directive regulating the sulphur content of marine fuels is consistent with international commitments, but with further restrictions for passenger ships and ships in territorial waters. CO_2 emissions from new ships are regulated globally according to the EEDI regulation. Significant reductions of NO_X emissions from marine engines are however not accomplished by any regulation in effect today. Studies have indicated that the share of ship emissions in relation to land-based emissions will increase mainly due to regulations on land, while corresponding regulations for the ship industry are lacking (see e.g. European Environment Agency, 2013).

The NO_X regulation of MARPOL is constructed with three Tiers, and each Tier requires further reductions of emissions compared to the previous Tier. The tiered structure of these internationally agreed NO_X regulations for ships has so far only reached the second level, but Tier III levels will be applied for new built ships in the NO_X Emission Control Area (NECA) that currently exists for the North American NECA and the United States Caribbean Sea NECA. Tier II levels accomplish approximately 15% to 20% reductions compared to a Tier I engine. These reduction levels can often be accomplished by adjustments of combustion parameters of existing engine models. Fulfilling requirements of Tier III yields reductions of NO_X emissions of 80% compared to the Tier I levels. Reduction of NOx emissions to the significantly lower Tier III levels can be achieved by installation of abatement technology. Many options exist. Some of these aim at reducing combustion temperatures and there is also the option of installing a catalytic converter for aftertreatment of the exhaust gases. Yet another option is to run a ship on a fuel that causes less NO_X emissions when combusted. Liquefied natural gas (LNG) is one, and methanol is also a potential choice, although rarely tested as a marine fuel.

The main purpose of this report is to provide projections for NO_X emissions from ships in the Baltic Sea, the North Sea and the English Channel based on what we know today about geopolitical stands, and the feasibility and potential of widespread use of abatement technology. An assessment in terms of NO_X reduction instruments that could be implemented, in addition or as an alternative to the NECA requirements in MARPOL, is included in the study in order to indicate the feasibility to address NO_X emissions from the entire fleet. The report contains four sections; 1. on the expected establishment of NECAs in the Baltic Sea, the North Sea and the English Channel; 2. on the practicability and costs of mitigation options; 3. on forecasts of NO_X emissions; and 4. on additional/alternative potentially instruments to address NO_X emissions from the existing fleet in the seas defined above, including an assessment of the emission reduction potential and costs for the sector for three shortlisted instruments.

2 Analysis of NECA negotiations

The aim of this chapter is to make an assessment of the possible outcome of the Baltic Sea and North Sea NECA negotiations and to give an estimation of the timeline of the most probable outcome.

To this end, we will in the following, first describe the IMO regulation regarding the designation of Emission Control Areas (ECAs) and the duration of the designation process that can be expected from this regulation. Subsequently, the course of the negotiations regarding the Baltic Sea and North Sea NECAs is described in greater detail, including the development at HELCOM until end of November 2015. Based on interviews that have been conducted with representatives of agencies/authorities in different countries who are (in)directly involved in the NECA negotiations, the most likely outcome of the negotiations along with the shortest possible timeline for this scenario are presented. Finally, in section 2.4, the latest developments in the NECA negotiations, which took place in the period after the interviews had been conducted, are described.

2.1 Designation of ECAs: IMO regulations and timeline

A proposal for the designation of a specific area as an ECA has to be submitted by Party/Parties to the IMO. Where two or more Parties have a common interest in a particular area, they have to formulate a coordinated proposal. The proposal has to include specific information as laid down in MEPC 59-23-Add.1, Appendix III, like for example an assessment of the emissions from ships operating in the proposed area and their impact on human health and the environment.

For a specific area to be designated by the IMO as an ECA, MARPOL Annex VI has to be amended and the tacit agreement procedure applies (Marpoltraining, 2015):

- amendments to the MARPOL Convention have to be submitted to MEPC at least 6 months prior to their consideration;
- amendments shall be adopted by a two-thirds majority of only the Parties to the Convention present and voting;
- an amendment is considered as accepted at the end of a period which will be determined at the time of adoption, which is not less than 10 months after the date of adoption, unless prior to that date, not less than one third of the Parties or Parties the combined merchant fleets of which constitute not less than 50 per cent of the gross tonnage of the world's merchant fleet, have communicated to the Organization their objection to the amendments;

- an amendment to an Annex will enter into force 6 months after its acceptance.

From the IMO regulation it is thus clear that the period between the submission of a NECA proposal and the date of entry into force is at least 22 months, but since approval of the proposal and the adoption of the amendment will probably not be reached at one MEPC meeting, a period of 30 months can be expected on average[1]. For the existing NECAs this estimation is a good approximation (see Table 1 for an overview):

For the North American NECA, the period between the submission of the proposal and the entry into force amounted to 28 months:

- In April 2009, the US and Canada proposal was submitted to MEPC 59 (MEPC 59/6/5).
- In July 2009, the IMO approved the North American ECA application (NO_X and SO_X) at MEPC 59.
- In March 2010, the North American emission control area was adopted at MEPC 60 (resolution MEPC.190(60)).
- In August 2011, the North American ECA entered into force.

For the United States Caribbean Sea NECA, the period between the submission of the proposal and the entry into force amounted to 30 months:

- In June 2010, the proposal was submitted to MEPC 61 (MEPC 61/7/3).
- In July 2011, MEPC 62 adopted the MARPOL Annex VI amendments (Resolution MEPC.202(62)).
- In January 2013, the MARPOL Annex VI amendments entered into force.

The effective date of Tier III requirements in future NECAs will differ from case to case, since the IMO regulation gives some flexibility in this respect: Tier III requirements will have to apply to ships constructed on or after the date of adoption by the MEPC of such an ECA, or a later date that may be specified in the amendment designating the NECA (IMO, 2014a).

[1] The average time between two MEPC meetings is 8 months.

Table 1. Overview dates special areas (IMO, 2015).

	Adopted	Date of entry into force	In effect from
Baltic Sea (SO_X)	26 Sept 1997	19 May 2005	19 May 2006
North Sea (SO_X)	22 Jul 2005	22 Nov 2006	22 Nov 2007
North American ECA (SO_X and PM)	26 Mar 2010	1 Aug 2011	1 Aug 2012
North American ECA (NO_X)	26 Mar 2010	1 Aug 2011	Ships built on or after 2016
United States Caribbean Sea ECA (SO_X and PM)	26 Jul 2011	1 Jan 2013	1 Jan 2014
United States Caribbean Sea ECA (NO_X)	26 Jul 2011	1 Jan 2013	Ships built after 2016

2.2 Course of Baltic Sea and North Sea NECA negotiations

In 2010, the Ministerial meeting of HELCOM decided to "work towards submitting, preferably by 2011, a joint proposal by the Baltic Sea countries to the IMO applying for a NO_X Emission Control Area (NECA) for the Baltic Sea." (EC, 2013) However, to this day, the proposal has not been submitted to the IMO.

In 2013, Russia spoke out in HELCOM against proceeding with the designation of the Baltic Sea as NECA at that stage and proposed to the IMO to delay the effective date of all NECAs for 5 years, i.e. from 2016 to 2021. Since Regulation 13.10 of MARPOL Annex VI called for a review of the status of technological developments to implement the 2016 Tier III NO_X emission limits, the Correspondence Group on Assessment of Technological Developments to Implement the Tier III NO_X Emission Standards under MARPOL Annex VI was established. In its final report of February 2013 (MEPC 65/4/7), the correspondence group recommended that no postponement of the 1 January 2016 Tier III effective date was necessary. However, the Russian Federation did not agree with this conclusion, arguing that more research and studies should be carried out to address the potential operational safety and environmental effects associated with NO_X emission reduction technologies.

At MEPC 65 it was agreed to consider the Russian Federation's proposal to amend the effective date for the NO_X Tier III limits to 2021 for adoption at MEPC 66, with 10 countries reserving their position on the proposed amendments. The following six EU countries thereby supported the Russian position: Cyprus, Estonia, Greece, Latvia, Malta, and Poland. Several countries opposed this delay, including the US, Japan, Denmark and Germany. Table 2 shows the main arguments for and against the delay of NO_X Tier III limits.

Table 2. Arguments for and against implementation NECA implementation in 2016 (Portnews, 2013; CNSS, 2014).

Arguments for implementation in 2016	Arguments against implementation in 2016
Necessary NO_X technology is available (Denmark)	No efficient technical measures to reduce NO_X are available (Russia)
Implementation of a Baltic Sea NECA could lead to increased volumes of transit cargoes for certain countries. (Denmark)	LNG has many years left to be developed and this is not useful for Russian industry (Russia)
	High costs for ships compliant to Tier III (Russia)
	Keeping 2016 will not lead to new NECA applications (Norway)
	Efficient solution without loss of competitiveness is needed (Poland)
	North Sea NECA only if Baltic Sea also designated as NECA as 30% of ships also sail in Baltic Sea (Dutch shipping industry)

The Marshall Islands and Norway proposed (MEPC 66/6/10) a compromise that would preserve the 2016 Tier III effective date in those NECAs that had, at that time, already been approved by the IMO, but would delay the effective date for application of further Tier III NO_X controls to 2021 in other ECAs that might later be designated as NECAs. In April 2014, at MEPC 66, the IMO agreed upon a different compromise, allowing current NECAs to come in effect in 2016, but giving new NECAs flexibility regarding the effective dates. The resultant amendments to MARPOL Annex VI Regulation 13 entered into force 1 September 2015.

Work on the proposal for a North Sea NECA which had started in 2010 had been on hold due to the IMO discussion on the effective date of NECAs and doubts from surrounding countries, but were taken up again after the compromise in the IMO had been reached. In spring 2015, the North Sea NECA countries agreed that their proposal was ready for submission.

From June 2014 on, it was worked towards an application for the North and the Baltic Sea NECA in parallel, resulting in a joint technical meeting held in June 2015 in which a roadmap for a parallel Baltic and North Sea application was discussed.

An overview of the timeline is presented in Table 3.

Table 3. Timeline of NECA negotiations.

Date	Baltic Sea NECA	North Sea NECA
May 2010	HELCOM Ministerial Declaration: Baltic Sea countries agree to work towards submitting a joint application to the IMO for the Baltic Sea to Baltic Sea to become a NECA.	North Sea countries have started considering possibility for North Sea area to become NECA.
March 2011	HELCOM (32/2011) agrees that Baltic Sea should be designated as NECA.	
March 2012	HELCOM (33/2012) agrees that NECA Baltic Sea application prepared in HELCOM fulfills IMO criteria.	
December 2012	HELCOM Heads of Delegation Meeting (39/2012) states that NECA application is finalized and agrees that final date of submission of application to IMO is to be taken prior to the October 2013 Ministerial Meeting	
May 2013	IMO: Russia proposes to delay effective date of all NECAs by 5 years (2021 instead of 2016)	
March 2014	IMO: Marshall Islands and Norway propose to delay effective date of not yet established NECAs by 5 years (2021 instead of 2016).	
March 2014		Negotiations on North Sea NECA on hold until IMO has made decision on effective date
April 2014	Compromise in IMO: existing NECAs come in effect in 2016 new NECAs get flexibility regarding effective dates.	
June 2014	A high-level letter is send to North Sea countries for support of an application in parallel between Baltic Sea North Sea.	

Date	Baltic Sea NECA	North Sea NECA
November 2014	Denmark submits draft road map (4-7) for parallel Baltic Sea & North Sea NECA application to 14th HELCOM Maritime Working Group; there is a broad consensus that a roadmap is valuable and needed; no specific dates are agreed on.	
Spring 2015		North Sea countries agree that they are ready to submit their application to MEPC.
May 2015		During MEPC 68 North Sea countries come to an agreement that they would like to develop a synchronized North Sea NECA application together with the Baltic Sea NECA application and HELCOM is officially approached in this regard.
June 2015	Joint technical meeting is held to discuss the roadmap for Baltic Sea and North Sea NECA.	
September 2015	Denmark submits, on behalf of all North Sea countries, second draft roadmap for the parallel designation of the Baltic Sea and the North Sea NECAs (4-1) to the HELCOM Maritime Group.	
November 2015	Draft roadmap is discussed at 15th HELCOM Maritime Working Group meeting where consensus is reached to forward roadmap to HELCOM Heads of Delegation (December 2015). It is agreed that a synchronized submission and process for the Baltic and North Sea NECA applications is strongly recommended. There is general agreement of the necessity to designate and effectuate Tier III requirements in the Baltic Sea in parallel with the North Sea. It is agreed to adjust the effective date in the roadmap to the 1st of January 2021.	

In September 2015, Denmark, on behalf of all the North Sea countries, submitted a revised proposal for a roadmap for the parallel designation of the Baltic Sea and the North Sea NECAs to the HELCOM Maritime Group (see Figure 1), which was discussed in November 2015.

In this roadmap it is assumed that it is realistic to submit the NECA applications in July 2016 and that it will take 27 months until the MARPOL Annex VI amendments enter into force (October 2018), assuming that proposals would be approved at MEPC 70 (October 2016) and MARPOL Annex VI amendments adopted at MEPC 71. The roadmap gives two possible Tier III effective dates: June 2020 and January 2021.

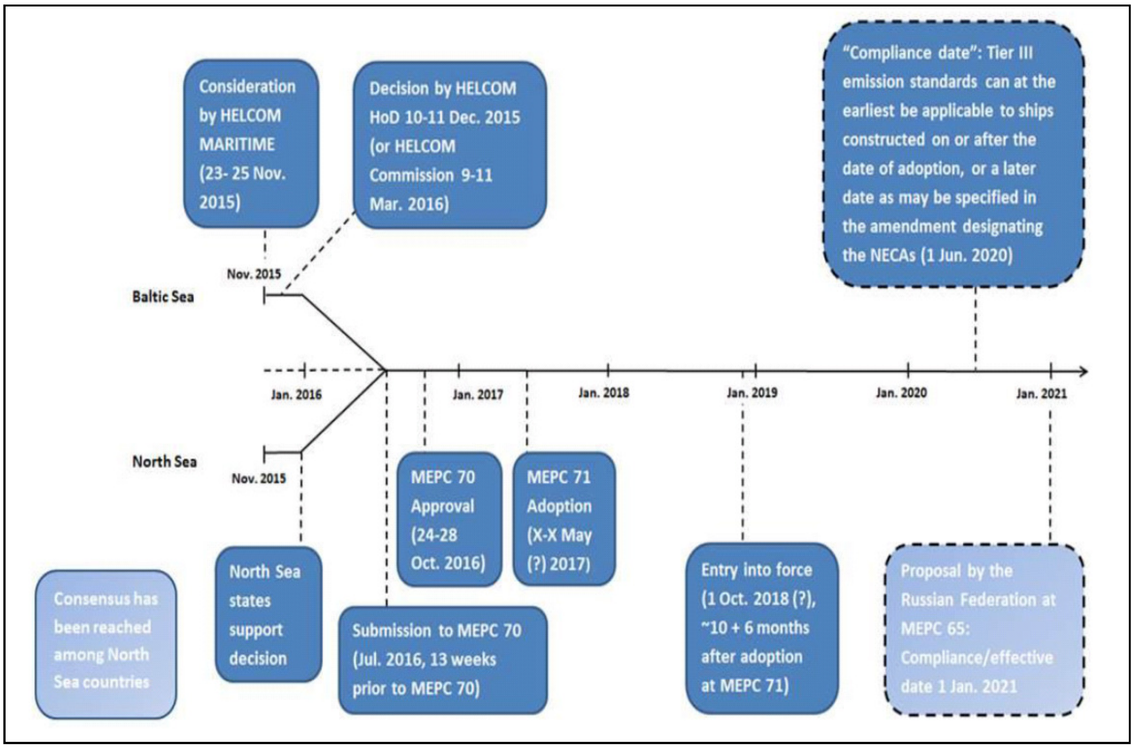

Figure 1. Proposed roadmap for parallel NECA designation in the Baltic and North Sea (BMEPC, 2015a).

At the 15th HELCOM Maritime Working Group meeting of November 2015, several agreements were made with regards to the NECAs (BMEPC, 2015c):

- there is a general agreement of the necessity to designate NECA and effectuate Tier III requirements in the Baltic Sea in parallel with North Sea NECA;
- the effective date in the proposed roadmap should be adjusted to 1 January 2021;
- a synchronized submission and process for the Baltic and North Sea NECA applications is strongly recommended;
- a meeting between the North Sea and Baltic Sea countries during spring 2016 to discuss the elements of Tier III technology, experiences within the North American ECAs and the NECA applications could be considered;
- decisions on how to proceed with the NECA issue and with the draft roadmap agreed by the Meeting should be taken by the upcoming HELCOM HoD/Helsinki Commission meetings.

However, Finland has not agreed to agree on the proposed dates of the NECA roadmap due to unfinished internal national discussions.

The political decision on this roadmap and the parallel submission of the NECA proposals for the North and Baltic Sea could be made at the 49th Meeting of the Heads of Delegation 10-11 December 2015 or at the 37th Meeting of the HELCOM Commission in March 2016.

2.3 Most likely NECA scenario and timeline – outcome of interviews

In order to make an assessment of the outcome of the NECA negotiations, six interviews with representatives of agencies/authorities in the Netherlands, Germany, Belgium, Denmark, Finland, and Sweden, who are directly or indirectly involved in the negotiations have been conducted (see Table 4). In these interviews the most optimistic date for political agreement and implementation of a NECA was discussed along with the most important national arguments for a NECA.

Table 4. List of interviews

Country	Authority/Agency
Netherlands	Ministry of Infrastructure and Environment
Finland	Finnish Transport Safety Agency
Sweden	Swedish Transport Agency
Denmark	Ministry of Environment and Food
Germany	Ministry of Transport and Digital Infrastructure
Belgium	Federal Public Service for Mobility and Transport

Most of the interviewed authorities have stated that currently only the scenario with a combined NECA for the Baltic and North Sea is discussed.

Important arguments that play a role in the national NECA discussions depend on the geographical location of the countries and their ports and on the economic importance of the shipping sector for the country.

For the North Sea for example, the main argument for a NECA is air quality, since the population density in the coastal areas of the North Sea is relatively high, whereas for the Baltic Sea, a NECA is primarily important to prevent further eutrophication.

And for countries located at the border of (only) one of the NECAs, the level playing field argument plays a more important role, especially if only the North Sea was designated as a NECA.

The modal shift argument does not seem to play a role in any country interviewed, which is in line with the impact assessments that show relatively small impacts of the NECAs on modal shift.

Also the costs associated with the NECAs do not, at least at present, play a role in the national discussions in the countries interviewed. This is probably due to the fact that only new ships are affected and due to the current low oil price.

The cost argument might play a more important role in Russia, where ship owners would have to import most of the required technologies and where the exchange rate is currently not favourable.

There are a few factors leading to uncertainty on the submission of the new parallel NECA applications, especially that, although a technical agreement has been achieved, a political agreement might not.

The fact that the impact assessments would need to be updated is not perceived as a factor that could delay the process.

As the shortest possible timeline for a political agreement, December 2015 or March 2016 were named by the majority of the interviewees, with March 2016 being more realistic. Also, several interviewees have indicated that the application of this combined NECA could be discussed at MEPC 70 in 2016, adopted at MEPC 71 in 2017, and that the effective date in scenario 1 could be January 2021 – all in line with the roadmap that Denmark has submitted to HELCOM on behalf of the North Sea countries.

2.4 Latest developments

Table 5. Latest developments in the NECA negotiations.

<table>
<tr><th>Date</th><th>Baltic Sea NECA</th><th>North Sea NECA</th></tr>
<tr><td>December 2015</td><td colspan="2">At the time of the Heads of Delegation meeting (HOD 49/2015) national consultations in Finland are still ongoing.</td></tr>
<tr><td>March 2016</td><td colspan="2">HELCOM (37/2016) adopts the “Roadmap for the simultaneous designation of Baltic Sea and the North Sea NECAs” (4-3 Rev. 1) and thus decides to submit the HELCOM proposal to designate the Baltic Sea as a NECA with the corresponding submission by the North Sea countries to IMO MEPC 70 in 2016.</td></tr>
</table>

In March 2016, after Finland had finished its national consultations, HELCOM adopted the “Roadmap for the simultaneous designation of Baltic Sea and the North Sea NECAs” (see Figure 2) at its 37th meeting. According to this roadmap, Baltic Sea and North Sea NECA applications will both be submitted to MEPC 70 and, if adopted at MEPC 71, will probably enter into force in late 2018. The effective date for both NECAs will be January 2021.

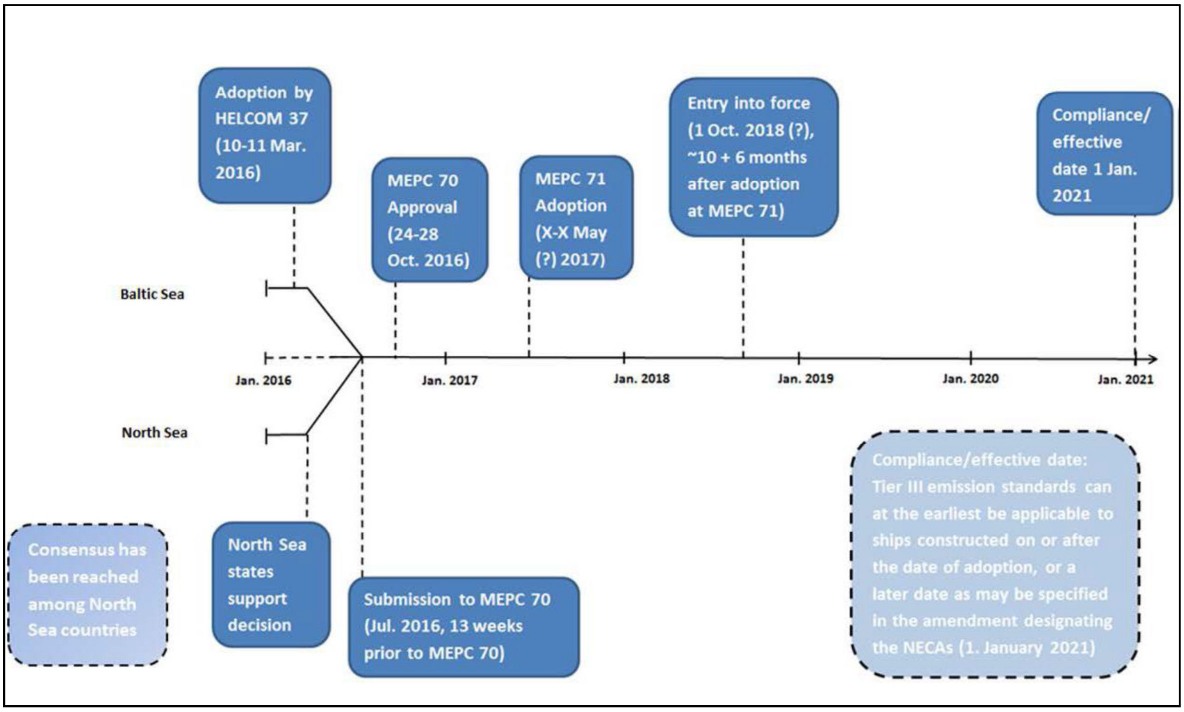

Figure 2. Roadmap for the simultaneous designation of Baltic Sea and the North Sea NECAs as adopted by HELCOM.

3 Feasibility and potential of abatement technology

Nitrogen oxides (NO_X) is the sum of NO and NO_2 and usually measured as mass of NO_2. In the emissions from a marine combustion engine the NO_X is typically around 90% NO, but through oxidation reactions in the atmosphere NO_2 will eventually dominate. The main formation mechanism for NO in a combustion engine is through the Zeldovich mechanism taking place at elevated temperatures where NO is formed from nitrogen and oxygen in the atmosphere.

The emissions of NO_X from engines in international shipping were unregulated until year 2000, after which new engines had to comply with the so called Tier I levels. The allowed NO_X emissions in the regulations are expressed as mass of NO_X per kWh engine work and are a function of the engine speed, allowing for higher emissions from slow speed engines than from high speed engines. For Tier I the allowed emissions are in the range 9.8 –17 g/kWh. For engines from 2011 the Tier II regulations apply with allowed emissions in the range 7.7 – 14.4 g/kWh. The Tier III regulations which will begin to apply from 2016 are much stricter, 1.96 – 3.4 g/kWh, and will only be applied in dedicated NO_X emission control areas. At the moment the only such areas are the North American NECA and the United States Caribbean Sea NECA.

3.1 Abatement technologies

Emission reductions to Tier II levels can be accomplished by internal engine modifications that adjust combustion parameters. However, to reach the Tier III limits major changes will be needed.

The alternatives to reduce the emissions of NO_X from marine engines can be divided into four categories:

- Aftertreatment where the main option is selective catalytic reduction (SCR).
- Combustion modification through e.g. exhaust gas recirculation (EGR) or methods where water is introduced in the engine.
- Fuel switch from marine fuel oils to, e.g., liquefied natural gas (LNG) or methanol.
- Reduced fuel consumption through e.g. slow steaming (this option is not fulfilling MARPOL Annex VI requirements on NO_X emissions).

Within the IMO a "Correspondence Group on Assessment of Technical Developments to Implement the Tier III NO_X Emissions Standards under MARPOL Annex VI" was set up in order to study technical means to reach Tier III and the availability of these techniques. The final report from 2013, which can be found in MEPC 65/4/7 and MEPC 65/INF.10, contains a thorough assessment of the options and is the main reference for the following text. The information is also updated through literature searches and discussions with engine manufacturers and shipowners.

The test protocol for verifying compliance with the Tier III NO_X requirements for installations on marine engines, requires testing at four different load points of the engine. Measurement results are weighed and combined to one emission factor for the ship.

3.1.1 Aftertreatment

Reducing NO_X in the exhaust from combustion engines with aftertreatment implies the use of catalytic converters. For petrol engines the three-way catalyst (TWC) has been very successful in reducing NO_X to N_2 and at the same time oxidising carbon monoxide (CO) and remaining hydrocarbons (HC). However, the TWC only works for stoichiometric gas-mixtures and can therefore not be used for the lean exhaust from diesel engines. Catalytic converters used for diesel engines today are basically either NO_X storage catalysts (also called NO_X-traps) or Selective Catalytic Reduction. In storage catalysts NO_X is trapped in the catalyst through formation of nitrates which are released and reduced during rich spikes. The latter are obtained by running the engine rich and implies a certain fuel penalty. The catalyst also contains noble metals (Pt) to catalyse the oxidation and reduction reactions. However, these catalysts are not suitable for marine engines. The main reason is that they are poisoned by sulphur oxides in the exhaust. Even if marine gasoil (MGO) would be used, the SO_2-content in the exhaust would be much too high. Further, the sizes that would be required would make the systems very expensive.

In selective catalytic reduction, nitrogen oxides are reduced to nitrogen gas over a catalyst in the exhaust system by an added reducing agent. For marine application the active catalyst material is usually vanadium oxide which is combined with titanium oxide in a washcoat over a honeycomb ceramic or metallic structure. Other catalyst materials such as zeolites can also be used, but these are usually sensitive to sulphur poisoning. The reducing agent is in principle ammonia. However, normally urea is used for practical reasons; urea decomposes through hydrolysis when introduced to the catalyst, forming ammonia. Ammonia and nitrogen oxides react rapidly (selectively) through a number of reactions forming N_2. The SCR system sometimes also includes an ammonia slip catalyst where remaining ammonia is oxidised in order to minimise the release of ammonia to the atmosphere.

SCR performance on ships applying for fairway fee reductions from the environmentally differentiated Swedish fairway due system are indicated in Figure 3. As can be seen the majority of engines have emissions below the Tier III limit. However, it should be noted that the measurement protocol is different from the one of IMO. The data in Figure 3 are taken only at one load point while the testing for Tier III requires testing at four load points. This is not an unimportant difference since the test cycle contains a low-load point where the exhaust temperature can be expected to be low; these are the conditions where it is most difficult to obtain high SCR activity. However, the IMO-report as well as contacts with engine manufacturers are all clear on that SCR can reach Tier III limits today.

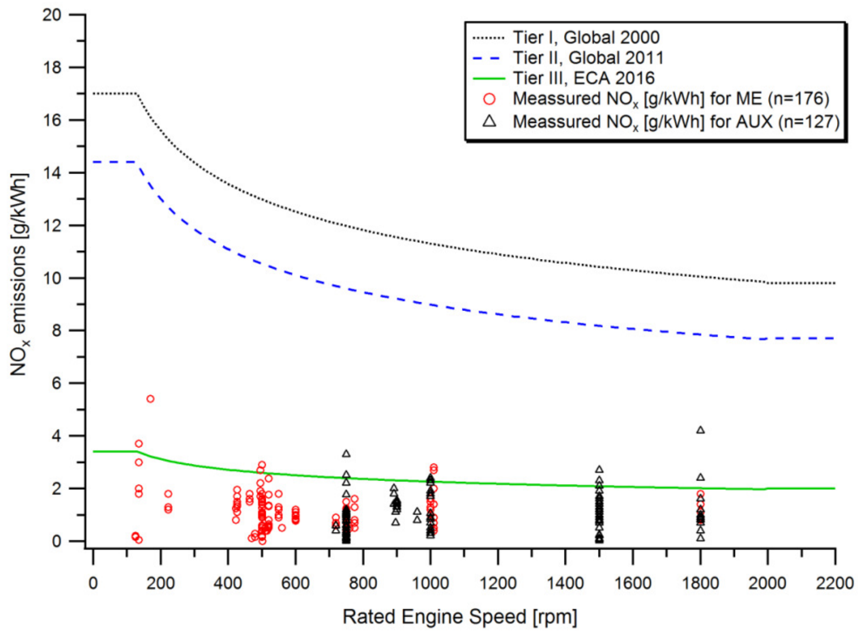

Figure 3. IMO NO_X emission regulation and measured NO_X emissions in accordance to Swedish environmental differentiated fairway dues. From Brynolf et al. (2014).

For the catalytic reactions to occur in the SCR system, a certain exhaust temperature is needed. This temperature is higher if the content of sulphur oxides in the exhaust gas is high (i.e. when high sulphur fuels are used). This is a challenge during engine start-up and when operating at low engine loads, and means that the SCR system cannot be in operation during these conditions. More effective heat management on ships can be expected to result in even lower exhaust temperatures which may further limit the operational window for the SCR. Further, SCR catalysts have been observed to become deactivated after a period of operation. This leads to expensive repairs where the catalyst (the “stone”) is replaced. The cause of the deactivation can be low quality urea, containing substances like aldehydes, low quality fuel containing substances that deactivate the catalyst, or operation at too high temperatures. All these factors should be manageable with better standards for urea and fuel and system control; however, it should be expected that the stones may need to be replaced at certain intervals.

An advantage of SCR over other technologies is that it is a well proven technique that has been used for many years both in marine and other applications. The IMO report from 2013 lists over 500 ships equipped with SCR. Further, it is very effective in reducing NO_X, and emission levels far beyond Tier III can be reached. It can be used in all types of marine engines although it needs to be positioned upstream of the turbine for two-stroke engines for the exhaust temperature to be high enough. SCR will influence other exhaust components only to a minor degree. Remaining hydrocarbons and carbon monoxide can be expected to be oxidised over the catalyst, as well as a smaller fraction of the soot in the exhaust. Looking at the life cycle of the system, the CO_2 emissions will increase through the energy used in plants to produce the urea. However, with an SCR system it is possible to tune the marine engine to higher fuel efficiency, yielding more NO_X from the engine that can be dealt with by the SCR. It is unclear if this potential is utilized today.

It is advantageous for an SCR if low-sulphur fuel is used. If SCR is to be used in combination with a wet scrubber system for SO_2, the SCR needs to be positioned upstream of the scrubber for the exhaust temperature to be high enough. This means that the exhaust reaching the SCR would contain high levels of SO_2. It has been demonstrated that SCR can be operated in such conditions provided that the temperature is high enough. Ships that have SCR to fulfil the NECA Tier III regulation can be expected to turn off the SCR system when operating outside NECAs. The reason is that the operation of the SCR implies a cost mainly through the consumption of urea. SCR can be combined with dry scrubbers, which can operate at high temperatures, in a way where the SCR unit is positioned downstream of the dry scrubber unit.

3.1.2 Combustion modifications

Modifications of combustion parameters have been used to a large extent on engines in order to reach Tier II emission levels. In principle, these modifications aim at increasing the heat capacity of the cylinder gases and lower combustion temperatures. In order to comply with Tier III emission levels without using aftertreatment, one option is to use exhaust gas recirculation (EGR) on the engine. So far this option has less widespread use than SCR in the maritime industry.

In EGR, a fraction of the exhaust gas is cooled and recirculated into the engine. This lowers the formation of NO through changes in oxygen concentration and heat capacity. According to engine manufacturers, EGR can be used to reach Tier III levels for all marine engine types. The exhaust that is recirculated must be purified from particles and sulphur oxides in order to protect the engine from soot deposits and corrosion. This can be achieved by filters if low-sulphur fuel is used or with scrubbers which can absorb both SO_2 and particulate matter. A scrubber with this purpose would normally use sodium hydroxide and freshwater, and the water will be recirculated in the system. A small fraction of the scrubber liquid is discharged to the sea as bleed off. This water is contaminated from the exhaust gas and the effects on the marine environment from these discharges remain to be quantified. In comparison to SCR, EGR has not been as extensively shown to reach Tier III levels.

The NO_X reduction efficiency of EGR depends on the amount of recirculated gas. Larger fractions of exhaust gas in the cylinder yield greater reductions but increased smoke formation and fuel consumption. The function of the EGR is influenced by the engine load; the recirculated portion of gases at reduced loads is less CO_2 dense than at operations at full speed when both the turbo charger efficiency and the fuel injection are high, resulting in higher efficiencies of the EGR at high engine loads.

An advantage with EGR is that it is a well proven technique in applications on land. It can reach low NO_X concentrations in the exhaust; however, it is doubtful if it can go much further than Tier III. A disadvantage in marine applications is the high concentrations of SO_2 and PM leading to the use of a complex scrubber system. The cost implied in using the latter will likely mean that EGR systems will not be in operation while sailing outside NECA areas. EGR can be used in combination with scrubbers to reach low emissions of both SO_2 and NO_X while using heavy fuel oil. However, this would require significant purification of the recirculated gas.

Adding water to the combustion is another method to decrease the combustion temperature and thus the formation rate for NO. Water can be added in three different ways: either by direct injection into the engine, through saturation with water vapour of the scavenging air or through a fuel-water emulsion. These methods have been used for several years and can reduce the emissions of NO_X significantly, however not down to Tier III levels. The methods may be used in combination with e.g. EGR to reach Tier III.

3.1.3 Fuel switch

A third method to reach Tier III levels is to use liquefied natural gas (LNG). LNG engines can either use only gas in a spark ignition engine, or use a combination of LNG and fuel oil (dual fuel engine) in a compression ignition engine. Both methods have been shown to reach Tier III levels. The use of LNG engines is increasing since it is a method to reach the SECA limits. Both new engines and rebuilt existing diesel engines are being used.

An often low availability of LNG and the extra space requirements for the cooled tanks are disadvantages with the LNG technique. However, the emissions of PM and SO_2 are very low and in principle only arise from the few percent of fuel oil used in dual fuel engines. There is thus no need to combine with other methods to decrease the emissions of these substances. Another often discussed downside with the use of LNG engines is the slip of methane, which is a very potent greenhouse gas, a problem that may well have to be addressed.

LNG has been used as a fuel in gas carriers for decades and has a good safety record. Safety issues coupled to a more extensive use of LNG on ships have been discussed and there is a draft to an international code of safety for ships using gases or other low-flashpoint Fuels (IGF Code) issued by the IMO. Other safety measures are rules developed by classification societies for using gas as ship fuel. Furthermore, there are recommended practices on the development and operation of LNG bunkering facilities.

Also use of other fuels such as dimethyl ether and alcohols will lower emissions of NO, PM and SO_2. Methanol is currently being tested on board the Stena Germanica ferry between Gothenburg and Kiel, and seems to be able to reach levels close to Tier III. It can also be combined with e.g. SCR. Since there is still only one ship with an installation of a methanol engine (as far as the authors are aware), it is not reasonable to draw conclusions on what emission levels will be reached.

The wide spread use of alternative fuels is to a high degree dependant on the status of fuel infrastructure. LNG is a gas at room temperatures and transport of liquefied gas depends on cryogenic tanks. The supply of LNG as marine fuels can be expected to increase following the Directive 2014/94/EU (European Union, 2014). The directive clearly states that by 2025 there should be a core network of LNG supply points established for ships in maritime ports. The directive also emphasises that the network in the long term might well be expanded to ports outside the core network. Other fuels are not treated in detail in the Directive although it mentions that the actions taken to establish the LNG network should not hinder the development of potentially upcoming energy-efficient marine fuels.

3.1.4 Reduced fuel consumption

Reducing fuel consumption in relation to the performed transport work will in most cases be accompanied by reductions in NO_X emissions. The use of slow steaming will reduce the emissions of NO_X approximately in proportion to the reduction in fuel consumption. For an individual ship there may be some variations since the emission of NO_X per amount of fuel consumed will vary somewhat with the engine load and the engine configuration on the ship. At low loads, and thus low engine temperatures, less NO_X may be produced but then the abatement system (if used) may be less efficient. However, slow steaming may also mean that a ship uses fewer engines for propulsion and that the engines used are at high load.

In recent years there has been a focus on lower speeds at sea in order to reduce fuel consumption. However, the average speed of the world fleet depends foremost on freight rates and on the bunker price (Faber et al., 2012; Smith, 2012). There is thus a risk that ships will speed up again and that emissions will increase when freight rates rise in times of prosperity. A vessel's fuel consumption is strongly dependent on vessel speed. Simplified, the fuel consumption per unit of time can be described by a third-degree function of the vessel's speed, so that a speed reduction by 10% reduces the consumption by 27% (Faber et al., 2012) per unit of time. The relationship between ship speed and fuel consumption per unit of time is thus close to cubic, and a small decrease in speed entails a relatively large impact on the fuel consumption. However, if the same transport work is to be maintained, more ships are needed, unless there is significant free capacity of the existing ships. Further, ships are built to operate at a certain design speed, and the fuel saving potential related to slow steaming depends in practice largely on the ship's design speed and present service speed. In addition, if the ship is already going slow, further speed reduction might damage the engines or even increase the fuel consumption (Johnson and Styhre, 2015). Thus, this effect is mainly dependent on the world economy and the demand for shipping services (Lindstad, et al. 2011).

There are however no prospects of including slow steaming or other fuel reducing measures as compliance measures to reach Tier III requirement. One reason is simply that the regulations apply to the amount of NO_X emitted by kWh engine work. The main objective with slow steaming is to reduce the amount of engine work needed. Thus, the emissions of NO_X may be lowered in absolute terms but not in relation to engine work. Other policy instruments aiming at NO_X emission reductions or reduced fuel consumption might however include such measures.

3.2 Technology costs

Each of the described technologies is accompanied with financial costs or benefits for the ship owners/operators. The costs indicate the potential success of a technology on the market, although also other factors may have a significant effect on the demand of a technology. The following paragraphs accounts for costs of the Tier III technologies described previously. Costs for three water-based technologies that reach Tier II levels are presented below. Also costs for using methanol as fuel are accounted for, although these are accompanied with very high uncertainties. All costs are presented with a minimum and maximum value. The range can depend on price differences between different installations on similar engines and ships, but most often has to do with different characteristics of different engines. There are for example in many cases economies of scale causing installations on larger engines to be less costly per unit of energy output than installations on smaller engines. There are also price differences between new installations and retrofits.

The cost calculations comprise investment costs, including installation costs when available, and operation and maintenance costs. Neither costs relating to infrastructure nor subsidies or support schemes are taken into account. Fuel costs and savings are accounted for separately. For each technology, associated add-on costs (or savings) are presented in $€_{2010}$ per kg removed NO_X, and per costs component. The calculations on SCR, EGR and the water-based technologies are based on the assumption that marine distillate fuels are used.

To enable comparisons of investment costs with other cost components, they are annualized with the following Equation 1 (Bosch et al. 2009):

$$I_{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \qquad \text{Eq. 1}$$

Where:

I_{an}	= Annual investment costs ($€_{2010}$)
I	= Total investment costs ($€_{2010}$)
q	= Investment interest rate (shares)
lt	= Investment lifetime (years)

The calculations are based on current interest rates (q) and all costs are recalculated to 2010 rates. Learning curves are not included.

The annual costs are calculated from two different perspectives:

1. Socio-economic perspective, with 4% interest rate and investment lifetime equal to equipment lifetime. Average lifetime for all considered technologies is the same as a vessel lifetime and assumed to be 25-29 years (Kalli et al. 2013).
2. Shipping company perspective, with assumed 7% investment rate and 5 year investment lifetime (this assumption has been made based on discussions with Swedish shipping company representatives).

Annualized costs per kW power are recalculated into costs per MWh using the assumption of 1584 – 6648 hours spent by a vessel at sea per year. The range is from IMO (2014), where the number of days at sea was established from AIS data for different ship categories and size categories. This implies that any equipment installed or alternative fuel used, is used full time during operations, i.e. not only time of operations in NECA area.

Operation and maintenance (O&M) costs may include different components and are described more in detail for each considered technology in Appendix B. All O&M costs in this analysis are recalculated to €$_{2010}$/MWh.

To calculate costs per ktonnes removed NO_X, emission factors for Tier 0 – Tier III in g/kWh (see Table 12) are used together with total technology costs in €/MWh.

Fuel costs reflect differences in fuel prices and are mostly relevant for NO_X abatement by means of alternative fuels: LNG and methanol. Depending on price relationships between the four considered fuels (heavy fuel oil (HFO), low-sulphur MGO, LNG and methanol) a fuel shift may result in either cost savings or extra fuel costs. We use the European fuel price intervals for the first half of November 2015, as presented in Table 6.

Table 6. Fuel price intervals.

Fuel	Price, €$_{2010}$/MWh Min	Price, €$_{2010}$/MWh Max	Sources	Comments
HFO (IFO 380)	32	37	Bunkerindex	2015-11-17, based on prices in Rotterdam, Antwerp and Piraeus
MGO	68	81		
LNG	43	43	LNG daily, EEGA	2015-11-01, European price
Methanol	45	45	Methanex	European Posted Contract Price for November 2015 with 13% discount; 5.5. MWh/tonne assumed based on Marine methanol assessments

For the newest technologies (i.e. EGR or alternative fuels), cost estimates are very uncertain.

Table 7 (a and b) presents an overview of the costs associated with the different technologies. All costs in this table are allocated to NO_X abatement, although fuel switch options result in reductions of SO_X and PM as well. Within the presented cost intervals there might be significant variations between engine types and new builds vs. retrofits. However, detailed analyses of these differences are not included in this study.

Slow steaming is not part of Table 7, since it cannot be considered a measure that accomplishes the Tier III limits. Instead sailing with slow speed can be viewed as a cost efficient measure to reduce fuel use and NO_X emissions that can be considered in other policy instrument than the NECA-regulations. According to IMO (2014), during 2007-2012 the average reduction in speed at sea relative to design speed was 12% and the average reduction in daily fuel consumption was 27%. However, reducing speeds in times of high demand of the transport service would cause a need for more ships. Costs for introducing and operating new ships to fulfil this purpose have not been considered in this study.

A more detailed description of the cost calculations and the sources used are given in Appendix B.

Table 7.

a)Costs for NO_X emission reduction technologies for MGO driven vessels. Effects of fuel costs included in total costs.

NO_X reduction alternative	Investments, €2010/kW						O&M costs, €2010/MWh				Fuel costs, €2010/MWh		Total costs, €2010/t reduced NO_X			
	Total		Per year				Fuel penalty/ premium		Other							
			Socio economic perspective		Company perspective								Socio economic perspective		Company perspective	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
SCR	19	103	1.1	10	4.6	38			1.36	3.78			112	819	151	2 025
EGR	36	60	2.1	3.8	8.8	15	0.20	0.24	1.34	2.10			137	492	210	1 194
WIF	16	16	0.9	1.0	3.9	3.9	1.63	1.95					590	998	738	1 697
HAM	97	141	5.7	9.0	24	34			0.15	0.15			336	2 249	1 236	8 408
DWI	21	81	1.2	5.2	5.1	20			1.98	1.98			722	2 021	917	5 558
LNG*	219	1260	13	146	53	556					-39	-25	-2 690	2 655	-2 242	17 406
Methanol*	290	339	17	22	71	83					-36	-23	-11 219	-3 526	-8 529	11 281

*Negative costs indicate gains. Both LNG and methanol are expected to be less costly than MGO which is why the costs in €/MWh is negative; the costs for MGO are used as baseline. The value indicating the lower limit of resultant total costs are also negative from both a socio economic-, and a company perspective. For methanol also the upper limit of total costs is a negative value.

b) Costs for NO emission reduction technologies for MGO driven vessels. Effects of fuel costs <u>not</u> included in total costs.

NO_X reduction alternative	Investments, €$_{2010}$/kW						O&M costs, €$_{2010}$/MWh				Fuel costs, €$_{2010}$/MWh		Total I+O&M costs, €$_{2010}$/t reduced NO_X			
	Total		Per year				Fuel penalty/ premium		Other				Socio economic perspective		Company perspective	
			Socio economic perspective		Company perspective											
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
SCR	19	103	1.1	10	4.6	38	0	0	1.36	3.78	0	0	112	819	151	2 025
EGR	36	60	2.1	3.8	8.8	15	0.20	0.24	1.34	2.10	0	0	137	492	210	1 194
WIF	16	16	0.9	1.0	3.9	3.9	1.63	1.95	0	0	0	0	590	998	738	1 697
HAM	97	141	5.7	9.0	24	34	0	0	0.15	0.15	0	0	336	2 249	1 236	8 408
DWI	21	81	1.2	5.2	5.1	20	0	0	1.98	1.98	0	0	722	2 021	917	5 558
LNG	219	1 260	13	146	53	556	0	0	0	0	-39	-25	143	5 249	591	20 000
Methanol**	290	339	17	22	71	83	0	0	0	0	-36	-23	856	5 269	3 546	20 076

**Negative costs indicate gains. Both LNG and methanol are expected to be less costly than MGO which is why the costs in €/MWh is negative; the costs for MGO are used as baseline.

3.3 Concluding remarks on the potential of abatement technologies

Not many techniques have yet been proven to reduce NO_X emissions from marine engines to Tier III levels. Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR) and using Liquefied Natural Gas (LNG) as fuel are the only three abatement measures identified to fulfil the requirements of the regulation. Of these, SCR has the longest history of marine applications. LNG is becoming increasingly used as a marine fuel and its further use will be supported in the future according to the EU directive on establishing a network of LNG supply points for ships. EGR is said by engine manufacturers to live up to the regulations, but few data from practice are available. The EGR and the SCR are comparable in costs per kg NO_X emitted. The costs for LNG are largely depending on whether an existing engine is rebuilt for LNG or whether the LNG engine is installed on a new ship. The latter is considerably less costly than the previous. Fluctuations in LNG price also affect the potential of return on investment for the ship owner.

4 NO_X emissions from ships in EU seas, 2010-2040

Future trends for emissions of NO_X from shipping can be expected to be highly linked to an expected growth of ship traffic. Factors that influence future emission levels also include more efficient ships, i.e. ships that use less fuel for the same transport work, and the turnaround time of the fleet. Only new ships are required to comply with existing NO_X regulations, and with a significant number of old ships in the fleet, emissions remain at high levels.

4.1 Previous studies

A review of available projections of NO_X emissions from ships in the Baltic Sea (BS) and the North Sea including the English Channel (NS) has been conducted. Table 8 presents an overview of input data, methods used and results of previous emission inventories and projections. A major difference between studies is their input source for ship traffic data. Some studies have used data from ships' Automatic Identification System (AIS) to map the traffic, while others use approaches based on port call statistics and freight volumes. All vessels over 300 gross tonnes are equipped with an AIS transmitting the ship's ID, position, direction, speed and destination via digital radio channels. Information can be received by AIS receivers on land, aboard other vessels or by satellites. Emission inventories based on AIS data are activity-based and may be more detailed than inventories based on data on port calls, which do not contain information about the vessel's speed and often lack crucial information on the individual vessels.

Table 8 contains a summary of the studies that present the total emissions of NO_X in the Baltic Sea and the North Sea. These studies indicate rather stable NO_X emissions over the period 2000-2013. The lowest estimate for both sea areas during the period was 738 ktonnes in 2005 and the highest was 1035 ktonnes representing emissions in year 2000[2] . Both studies rely on statistics on port calls and freight for their estimation of ship traffic. AIS data is used as input to two inventories arriving at emission levels of 878 and 1014 ktonnes NO_X for 2009 and 2011, respectively. Both studies use the same model for emission calculations (the STEAM model). The results from the two AIS studies are well in line with the EMEP inventory results for 2013, which indicate emissions of 915 ktonnes NO_X from ships in the area.

Emission projections for NO_X in scenarios where no NECA is assumed to be implemented are made in five of the studies presented in Table 8. The two highest estimates represent emissions in 2015 and 2020, 1470 and 1699 ktonnes of NO_X, respectively, and are significantly above the emission levels arrived at in the other studies. Considering all studies together, there is a slight

[2] One estimate from Bosch et al is higher (1041 ktonnes), this estimate does however not consider any NO_X regulations at all

decrease in NO_X emissions from 2010 to 2040 - an effect of the enforcement of Tier II regulations.

The same five studies include scenarios with formation of NECAs for NS and BS with Tier III regulations in effect by 2016. These scenarios all show a decrease in NO_X emissions. Compared to the projections without the formation of NECAs, the emission estimates in these scenarios are between 26% to 47% lower in 2030.

Table 8. Overview of studies quantifying NO_X emissions from ships in the Baltic Sea, the North Sea and the English Channel. Tier III are expected to be effective by 2016, in the studies including NECA calculations.

Study	Year of inventory	Method for estimating ship traffic	NO_X emissions Baltic Sea (ktonnes)	NO_X emissions North Sea (ktonnes)	Projection: Year	Projection: NO_X emissions Baltic Sea (ktonnes)	Projection: NO_X emissions North Sea (ktonnes)
Whall et al. (2002)	2000	Port calls	1074		No projection for the Baltic Sea and the North Sea specifically		
Cofala et al. (2007)	2000	Port calls	315	720	No projection for the Baltic Sea and the North Sea specifically		
Bosch et al. (2009)	2000	Port calls	283	664	2015 (2020) scenarios without NECA	439 (498)	1031 (1171)
					2015 (2020) scenarios with NECA	364 (325)	856 (765)
Jonson, J. E., et al. (2015).	2011	Ship movements, AIS	337	677	2030, scenario without NECA	293	642
					2030 scenario with NECA	217	457
Kalli, J., et al. (2013).	2009	Ship movements, AIS	878		2020 (2040), scenario without NECA	827 (686)	
					2020 (2040) scenario with NECA	783 (183)	
Hammingh, P. Holland M. et al, (2012)	2009	Ship movements, AIS	n/a	472	2030 scenario without NECA	n/a	446
					2030 scenario with NECA	n/a	317
Campling P. et al (2013)	2005	Port calls	220	518	2030 scenario without NECA	202	503
					2030 scenario with NECA	108	269
Jalkanen and Johansson (2013)	2012	Ship movements, AIS	370	n/a	No projection included in study		
HELCOM, 2012	2008	Ship movements, AIS	333	n/a	Projections are made but without presenting mass of NO_X in particular		
Norwegian Met. Inst. , 2015 (EMEP)	(2005/ 2010) 2013*	Combination	(318/267)271	(755/635)644	No projections included in study		
Amann et al., 2010	2000	Not known	276	649	2020/2030 Scenario with a NECA	387/461	915/1092

*Calculated with updated methodology

In addition to the studies listed in Table 8, other studies on NO_X emissions from European shipping include Tremove, which estimates that the total emissions of NO_X from shipping in Europe during the ten year period 2010-2020 is just over 37 million tonnes (Van Zeebroeck, The Ceuster et al. 2006), but makes no division into the different sea areas. Further, HELCOM presents annual data on emissions from shipping in the Baltic Sea based on AIS data (Jalkanen and Johansson 2013), and has funded a study with the intention to make a proposal to bring the

Baltic Sea into a NECA for Marine Environmental Protection Committee in 2012 (HELCOM 2012). A study covering the North Sea exclusively is presented in Hammingh et al., (2012)

Additional information on emissions can be gathered from satellites. For example, Vinken et al., 2014 used satellite information on NO_2 concentrations over busy ship lanes and compared the results to EMEP data. The satellite observations thus cover only parts of the oceans. However, the study indicates that EMEP overestimated emissions in the North Sea region by 35 % and significantly underestimated emissions in the Baltic Sea for 2005 (Vinken et al. 2014). Results from the satellite studies also indicate that NO_X emissions in the studied shipping lanes increased from 2005 to 2008, decreased in 2009 following the economic downturn, and then remained relatively constant until 2012. The low levels are reasoned to be an effect of not only the economic recession, but the choice to sail at lower speeds due to overcapacity in the shipping sector, i.e. slow steaming (Boersma et al. 2015).

Only two of the studies cover both the Baltic Sea and the North Sea (including the English Channel) and use the more detailed AIS methodology for estimating ship traffic; Kalli et al. (2013) and Jonson et al. (2015). The study by Kalli et al. (2013) includes expected development of different segments of shipping. Jonson et al. (2015) does not distinguish between ship types, and produces projections that refer to and use input values on the development of shipping from Kalli et al. (2013). Despite the similarities in methodology, the estimated NO_X emissions differ between the two studies; Kalli et al. (2013) estimated 878 ktonnes for 2009 and Jonson et al. 1014 ktonnes for 2011. There might be an actual difference in ship activity between the years causing an increase in emissions over time. The scenarios in Kalli et al. (2013) include only commercial shipping activities and thereby cover approximately 85 % of the fuel consumption, while such a limitation is not mentioned in Jonson et al. (2015). Due to the detail level of the study by Kalli et al. (2013), this study was chosen to provide the basis for the projections developed in this study. It should however be kept in mind that the fuel consumption in 2009 was relatively low due to the recession in the world economy, and that values are only representative for commercial shipping.

4.2 Calculation model

A model for calculating NO_X emissions for the time period 2005 to 2040, containing the crucial input parameters for estimating total NO_X emissions from different ship categories, has been set up. NO_X emissions are calculated from data on fuel consumption of different ship categories. In this study, the fuel consumption statistics are from Kalli et al. (2013). A basic input parameter to the calculations is also the emission factors describing the amount of NO_X emitted per unit of fuel combusted or per work delivered by the engine, expressed as e.g. g NO_X/kg fuel or NO_X/kWh. The units are interchangeable if you know the specific fuel oil consumption of the engine, i.e. the fuel consumption in g/kWh. The structure of the regulations on NO_X emissions from marine engines is also an important parameter since it has a direct effect on NO_X emission factors for ships of different ages. The three tiers of the MARPOL NO_X regulations are presented in Figure 3.

The calculation model used for the projections separates between ten different ship types, listed in Table 10. The main reasons for the differentiation are that the ship types have different average lifetimes, different expected changes of transport efficiency and transport increase. Further, each ship type has a different typical composition of engines, and different engines produce different amounts of NO_X during the energy conversion.

In the following paragraphs it is described how lifetime estimates, changes in transport efficiency and traffic, and emission factors may influence results. Variations in these parameters between ship categories and over time are also specified.

4.2.1 Lifetime

The importance of lifetime is related to the replacement rate of ships in a fleet and the fact that the NO_X regulations in MARPOL only affect new built ships. A long lifetime causes a slower exchange of old ships for new, which also slows down the effects of the regulations.

In this study the data on average lifetimes of ships are taken from Kalli et al. (2013) and are assumed to stay at the same values over the period of this study. The average lifetime of ships ranges from 25 years for container ships to 28 years for Liquefied Gas (LG) tankers. See Table 9 for the average lifetimes of different ship types. No other estimates of average lifetimes that suit the purpose of this study have been found. However, average values of ship age are reported yearly in the review of maritime transport (UNCTAD, 2015) and also by Hammingh et al. (2012). Although the average age cannot be used for direct comparisons with the average lifetime, it is clear that there is a significant difference in age structure between different ship types and that the average age of the global fleet is approximately 20 years, which is only 5-9 years shorter than the lifetimes reported by Kalli et al. (2013), see Table 9. A sensitivity analysis including variations of lifetime estimates is made supplementary to the calculations in this report, and is presented in Appendix 1.

Table 9. Comparison between average lifetime of ships in Kalli et al. (2013) and average age of ships in UNCTAD (2015).

Study	Kalli et al. (2013)	Hammingh et al. (2012)	UNCTAD
Ship type	Average lifetime for ships (years)	Average age for ships (years)	Average age for ships 2013 (number of ships /DWT)
Reefer	26		
General cargo	26		24.99/19.10
Product tanker	26		
Containership	26	12	10.81/8.25
Chemical tanker	26		
Oil tanker	26		16.74/8.14
LNG tanker	29		
Bulk carrier	26		9.94/8.36
Ro/Ro ship	27		
Ro/Pax ship	27		
Vehicle carrier	27		
LPG tanker	26		
Cruise ship	27		
Other		19	22.57/16.07
All ships			20.34/9.60

4.2.2 Increased transport efficiency

Transport efficiency can be assumed to increase in shipping due to both financial and regulatory reasons. Increased transport efficiency will yield lower fuel consumption for comparable amounts of transport work. In the model used, the projected NO_X emissions are proportional to fuel consumption. Kalli et al (2013) propose that the transport efficiency will increase between 1.3% and 2.25% per year for the different ship types, see Table 10. These values are used in this study. A more moderate estimate of efficiency increases of 0.96% per year for all ship types is used by Hammingh et al. (2012). Assumptions on increased efficiencies are accompanied with high uncertainties and in Appendix A a sensitivity analysis including this variable is presented.

4.2.3 Traffic increase

Growths in traffic and transport will result in higher fuel consumption and higher emissions of NO_X, unless emissions are mitigated. The traffic increase for shipping is expected at 1.5% for all ship types except container ships, where the increase is 3.5% on a yearly basis by both Kalli et al.,

(2013) and Hammingh et al., (2012). These values are also used in this study. Different rates of traffic increase are tested in Appendix A.

4.2.4 Input values for the calculation model

Table 10 presents a summary of the input values on fuel consumption, average lifetime, annual efficiency increase and annual traffic increase for this study. The values are based on Kalli et al., 2013, although ship categories are regrouped in order to reduce the number of categories, and recalculated to match the base year of this study.

Table 10. Input values on fuel consumption, average lifetime, efficiency increase and traffic increase, for the NO_X calculation model.

Ship categories	Fuel consumption 2010 (ktonnes)	Average lifetime (years)	Annual efficiency increase	Annual traffic increase
Bulk carrier	807	26	1.9%	1.5%
Chemical tanker	1778	26	1.9%	1.5%
Container ship	3272	25	2.25%	3.5%
General Cargo	1624	26	1.3%	1.5%
LG tanker	257	28	1.9%	1.5%
Oil tanker	891	26	1.9%	1.5%
RoRo cargo	1089	27	2.25%	1.5%
Ferry	2632	27	2.25%	1.5%
Cruise	370	27	2.25%	1.5%
Vehicle carrier	407	27	2.25%	1.5%

4.2.5 Emission factors

The emission factors for NO_X depend to a large extent on the engine type. Marine diesel engines in general have high emissions of NO_X due to the combustion characteristics. In general, slow speed diesel engines (often around 100 revolutions per minute) present the highest emission factors, while medium speed engines and high speed engines cause less NO_X emissions per performed work.

We have assumed that all ships in the North European seas used heavy fuel oils in 2010. From 2015, it is assumed that all ships use marine gasoil (MGO) following the SECA regulations that came into effect that year. Marine gasoils have higher energy content than heavy fuel oils, and it is expected that the amount of fuel used will be reduced accordingly. Compared to heavy fuel oil, combustion of marine gasoil causes around 6 % less NO_X formation.

For the projections an increasing use of LNG fuel in the studied region is assumed during the studied time period. Each year 0.5% of all fuel used in new ships (in tonne oil equivalents) is expected to be LNG. This is a low estimate, loosely based on the number of LNG driven ships on order, and an assumption that a majority of these are destined for service in either the North American or the European ECAs.

Ships' machinery layout comprises main engines, auxiliary engines and boilers. For the purpose of this study, we use a simplified approach and assume that all ships use diesel engines for main engines and auxiliary engines. No turbines are thus included in the calculations, although a few ships still are driven by power from gas or steam turbines. On all ships there is also at least one oil fired boiler installed. Boilers are used for heating water on board the ships. These are often complementary to 'economisers' that fulfil the same purpose by using excess heat from the exhaust gases, but that can only be used when the main engine is used on high loads.

For the model, an estimate has been done on the distribution of fuel use between the engines and the boilers on board the ships for the different ship types. Statistics on main engine speed in different ship types are from the ship database IHS SeaWeb. (IHS, 2015). Information on how much fuel is used by main engines, auxiliary engines and boilers for different categories of ship types and ship sizes can be found in the 3rd GHG report of the MEPC (IMO, 2014b). This information is used to assess the distribution of fuel use in different engine types and boilers for the different ship types, Table 11. All auxiliary engines are assumed to be medium speed diesel engines.

Table 11. Distribution of fuel consumption in different engine types for the studied ship categories.

Ship categories	Slow speed diesel engines	Medium Speed engines	High speed diesel engines	Boilers
Bulk carrier	81%	2%	14%	3%
Chemical tanker	52%	15%	23%	10%
Container ship	74%	3%	20%	3%
General Cargo	28%	44%	26%	2%
LG tanker	48%	30%	17%	5%
Oil tanker	68%	2%	24%	7%
RoRo cargo	17%	43%	36%	4%
Ferry	1%	57%	40%	2%
Cruise	2%	67%	24%	6%
Vehicle carrier	75%	4%	17%	3%

The emission factors of the engine types prior to, and following, the three tiers of the NO_X regulations are presented in Table 12. Boiler emissions are set to 2.9 g NO_X /kg fuel combusted (USEPA, 1999), which is significantly lower than Tier III emission levels of the diesel engines. Emission factors for LNG engines, Table 12, are estimates corresponding to Tier III emission levels in medium speed engines. Emission factors in a range from 1.1-3 g/kWh are reported by López-Aparicio and Tønnesen, 2015.

Table 12. Emission factors for marine engines with different speeds under the three tiers of the NO_X regulations and prior to regulations (Tier 0). Emission factors for Tier 0 are from Cooper and Gustafsson, 2004. MD –Marine distillate oil, LNG-Liquefied Natural Gas.

Engine type	Fuel	Assumed engine speed (rpm)	NO_X (g/kWh) TIER 0	NO_X (g/kWh) TIER I	NO_X (g/kWh) TIER II	NO_X (g/kWh) TIER III
Slow speed diesel engines	MD	100	17	17	14.4	3.4
Medium Speed engines	MD	500	13.2	13	10.5	2.6
High speed diesel engines	MD	1000	12	11	9.0	2.3
Dual Fuel LNG engine	LNG	500	2.6	2.6	2.6	2.6

4.3 NO_X emission projections

Following the development over time reveals only small changes in the total amount of fuel consumed by shipping in Northern Europe, for the projected period. Increases in traffic are more or less evened out by increased efficiencies. In a scenario with no NECAs in the seas of Northern Europe, a continuous decrease in emissions until around year 2035 is projected. After that the regulation is fully effective, and the NO_X emissions follow the trend in fuel use. The emissions of NO_X in five year intervals from 2010 to 2040 are presented for different ships types in Table 13. In both the scenarios with and without NECA, future emissions are lower than in 2010. The Tier II regulations alone are projected to accomplish reductions of approximately 20% by 2040. Only container shipping will increase their emission during this time period. With the NECA in force, total reductions are 66% by 2040 and include significant emission reductions from all ship categories.

The date for a NECA in effect is set to 1 Jan 2021 in this study, which is judged the most likely year for Tier III to gain effect in the Baltic Sea, the North Sea and the English Channel. Comparisons with previous studies, which have a Tier III implementation date of 2016 are therefore not straightforward. However, the resulting NO_X emissions in this study seem to be slightly above the results from Kalli et al., (2013) for 2040 and Campling et al., (2013) for 2030, and below the emission levels projected by Jonson et al. (2015) for 2030.

Table 13. Overview of projected NO_X emissions (ktonnes) 2010 to 2040.

	Projected total emissions in the Baltic Sea, the North Sea and the English Channel if no NECA is established							Projected total emissions in the Baltic Sea, the North Sea and the English Channel if a NECA becomes effective in 2021						
Ship categories	2010	2015	2020	2025	2030	2035	2040	2010	2015	2020	2025	2030	2035	2040
Bulk carrier	66	60	56	53	50	48	46	66	60	56	45	36	27	20
Chemical tanker	113	102	96	91	86	81	79	113	102	96	72	59	46	35
Container ship	258	250	253	256	259	262	275	258	250	253	214	181	143	112
General Cargo	110	101	98	95	92	90	90	110	101	98	81	66	51	38
LG tanker	18	16	15	14	14	13	12	18	16	15	12	10	8	6
Oil tanker	64	58	54	51	49	46	45	64	58	54	42	34	26	20
RoRo cargo	68	59	55	50	47	43	41	68	59	55	43	34	25	18
Ferry	157	137	126	116	107	98	93	157	137	126	100	78	58	42
Cruise	21	18	17	16	14	13	13	21	18	17	13	10	8	6
Vehicle carrier	32	29	27	25	23	22	20	32	29	27	21	17	13	9
All	**906**	**830**	**798**	**768**	**741**	**716**	**715**	**906**	**830**	**798**	**644**	**524**	**404**	**306**

Emissions in 2005 were according to Campling et al. (2013) 738 ktonnes NO_X for the NS and the BS together. This study is however not using detailed information on ships' positions. According to the methodology used in this model, the emissions would be around 930 ktonnes in 2005.

Figure 4 presents a diagram of total emissions and fuel use in the Baltic Sea, the North Sea and the English Channel for the period between 2010 and 2040 in a scenario without a NECA. The decrease in fuel consumption in 2015 is the calculated effect of the SECA regulation. A shift from heavy fuel oil to marine distillates with higher energy content results in lower fuel consumption calculated as fuel mass for the same amount of performed work.

With a NECA in effect in 2021, the emission reductions compared to a scenario without Tier III regulations are significant. There is a rapid decrease in NO_X emissions starting just after 2021 which in large part is due to a high expected replacement of old ships with new ones.

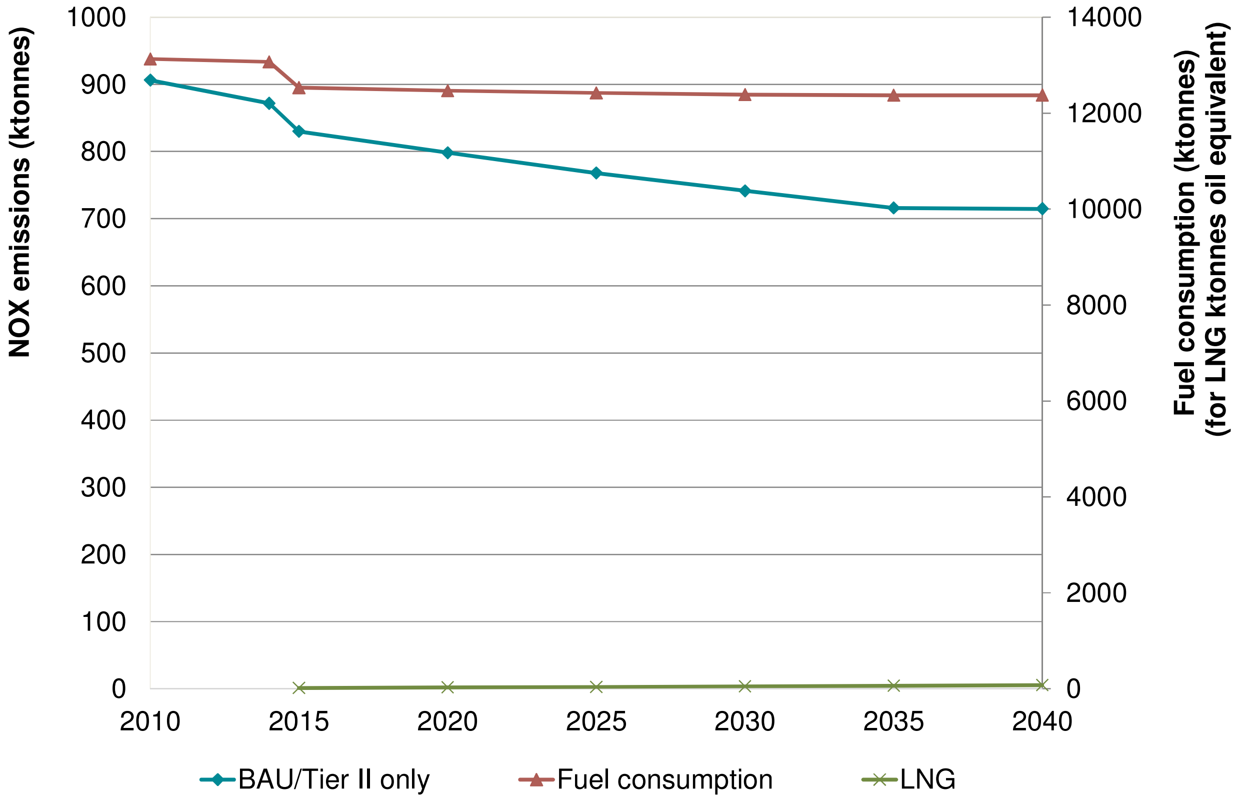

Figure 4. Projections of NO_X emissions and fuel consumption in a scenario without NECA regulations (Tier III) in force.

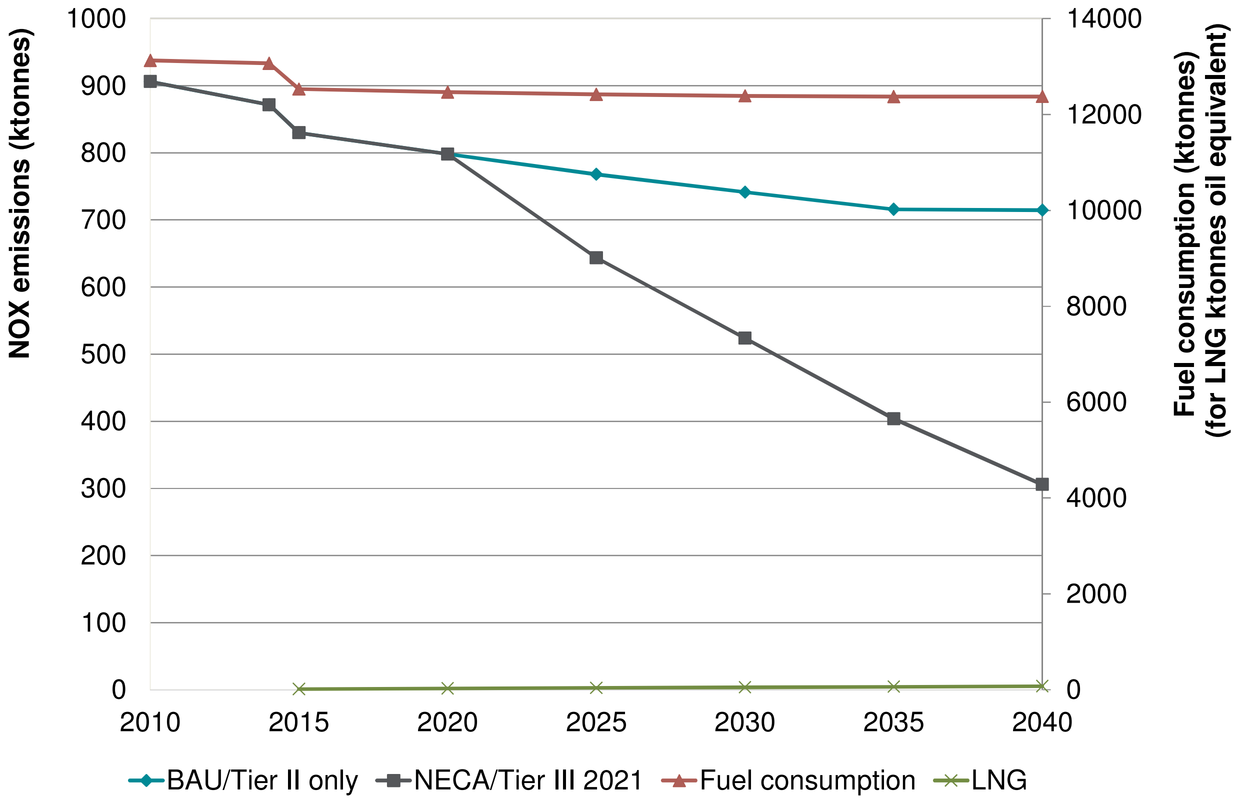

Figure 5. Projections of NO_X emissions and fuel consumption in a scenario with NECA regulations (Tier III) in force 2021.

There are concerns that the format of the regulation will cause ship operators to designate old ships to the NECA areas. New ships without abatement technology installed are not allowed to enter the area, and for ship operators with only a few calls to Northern Europe each year, there is little incentive to invest in abatement technologies. Relevant quantitative estimates of such concerns are difficult to make and are not included in the calculation model.

4.4 Concluding remarks on NO_X calculations

Many studies have quantified emissions of NO_X from ships in Northern European waters. The results vary among them due to traffic density differences between different years, different methodological choices, and different assumptions on fleet compositions. For projections of emissions, choices are made concerning how traffic will change in the future and how energy efficient ships will be. These choices will further influence results. Projection studies for NO_X emissions also include ships' lifetime as an important parameter. The most detailed and recent inventories use AIS data to estimate ship traffic and identify individual ships for accurate information.

We have done a projection of NO_X emissions to 2040. As input data we have chosen results from a study by Kalli et al., 2013, which includes only commercial shipping in their study meaning that approximately 85% of NO_X emissions are covered. In our study projections are performed for two scenarios; one where no NECA is enforced in the region, and one where a NECA is in effect 2021. The results indicate total NO_X emissions in 2040 of approximately 300 ktonnes with a NECA in effect from 2021, and 720 ktonnes without a NECA. This corresponds to approximately a 66% reduction in the NECA scenario, and 21% reduction in the scenario without a NECA, compared to emissions in 2010.

5 Selection and analysis of additional/alternative NO_X policy instruments

5.1 Introduction

The aim of this task is to identify and analyse instruments for Member States or the EU to reduce NO_X emissions from shipping, either in addition to or instead of the North and Baltic Sea NECA.

To this end, a longlist of potential instruments is set up in the first instance and a high level assessment of these instruments is carried out. Then three instruments are shortlisted and analysed in more detail for the two scenarios, i.e. in addition to the North and Baltic Sea NECA or as an alternative instrument (see Table 14), focusing on the NO_X emission reductions and on the costs for the shipping sector. The NO_X emission projection and the NO_X abatement costs of NO_X reduction measures as presented in section 4.4 and in section 3.2, respectively, form the basis of this analysis.

Table 14 Scenarios analysed.

Scenario 1 North Sea + Baltic Sea NECA is implemented	Scenario 2. North Sea + Baltic Sea NECA is not implemented
a. Policy instrument 1	a. Policy instrument 1
b. Policy instrument 2	b. Policy instrument 2
c. Policy instrument 3	c. Policy instrument 3

5.2 Identification of possible instruments

There are different NO_X policy measures that could be introduced for existing ships if the Baltic Sea and/or North Sea were designated a NECA, or that could be introduced for all ships if the Baltic Sea and/or North Sea were not designated a NECA, such as:

1. a NO_X emissions charge/levy/tax;
2. a NO_X levy combined with a fund;
3. an Emissions Trading Scheme (ETS) for NO_X from shipping;
4. a NO_X MRV for ships;
5. regulated slow steaming;
6. financial incentives offered by ports to low-NO_X ships;
7. an EU coastal waters-NECA.

In Table 15, the principle of the measures is briefly described and relevant references are given.

Table 15 Longlist of potential NO_X reduction instruments – principle and references

Instrument	Principle	References
EU NO_X emissions charge/levy/tax	Ships could be obliged to pay an emissions charge, depending on their NO_X emissions in a certain region/on specific voyages.	- Arcadis et al., 2012 - CE Delft, 2009c
EU NO_X levy & fund	The shipping sector could be obliged to contribute to an EU NO_X fund, with the contributions to the fund depending on the ships' NO_X emissions in a certain region/on specific voyages and the income of the fund being used to subsidise the uptake of NO_X reduction measures within the sector.	- Arcadis et al., 2012 - European Commission, 2012 - Bundesregierung et al.,2015
EU NO_X emissions trading scheme	**1. Cap and trade system** For each kg NO_X emitted by a ship in a specific region/on specific voyages, an NO_X emission allowance has to be submitted. The total number of NO_X emission allowances is restricted. Emission allowances can be purchased on the primary market and can be traded on a secondary market. **2. Credit and baseline system** For each kg NO_X emitted by a ship in a specific region/on specific voyages above the required average NO_X emission requirement, an NO_X emission allowance has to be submitted; there is no centralised issuance of allowances - ships emitting less than the average NO_X emission requirement can sell allowances.	- Kågeson, P, 2009 - CE Delft, 2009c
NO_X EU MRV	In line with the EU MRV regulation for CO_2, ships could be obliged to monitor, report and verify their NO_X emissions emitted on all voyages to and from Union ports.	- European Union, 2015
Regulated slow steaming	A speed limit could be imposed on ships, leading to less fuel consumption and thus indirectly to a reduction of NO_X emissions.	- John Maggs, 2011 - CE Delft, 2012 - Boersma et al., 2015
Environmentally differentiated port dues	Ships with relative low NO_X emissions could be rewarded with a discount on port dues.	- Cleanship, 2013 - Danish Ministry of Environment, 2013 - CE Delft, 2009a - CE Delft, 2009b
EU coastal water-NECA	If the EU coastal waters were, on request of the EU/EU coastal MS, designated as a NECA by the IMO, IMO Tier III NO_X emission requirements would hold in this ECA for new built ships.	

Some of the references given above are related to CO_2 or SO_X reduction measures, because a large part of the insights gained in this field are helpful regarding the design of NO_X reduction measures too, however, there are some fundamental differences that thereby have to be taken into account:

1. NO_X emissions have a regional impact on human health and on ecosystems. This is why it makes sense to set stricter NO_X requirements for ships sailing in specific areas.

2. NO_X emissions not only depend on the fuel type used but also on the engine type and the aftertreatment of exhaust gases.

3. Unlike for CO_2 emissions, there is not a direct incentive for ship operators to reduce NO_X emissions; a CO_2 reduction is always effected by a reduction of fuel consumption and thus also associated with fuel expenditure savings. This is not necessarily the case for a NO_X reduction. If there is no policy instrument in place the NO_X emission reduction can be affected by:

    a. an improvement of the energy efficiency, the emission reduction is associated with savings for the ship operator/owner,

    b. the use of alternative fuel, the emission reduction could be associated with savings for the ship operator/owner,

    c. an end-of-pipe measure, the emission reduction is not associated with savings for the ship operator/owner.

4. Emissions monitoring: The CO_2 emissions of a ship can be determined by multiplying the fuel consumption of the ship with a fuel specific emission factor. Since the NO_X emissions of a ship depend on the engine, the condition of the engine, the engine load, ambient temperature and humidity and on after-treatment systems used, they can only be accurately established by an exhaust gas analysis. As a first approximation, they may be calculated using fuel & engine-/ship-specific NO_X emission factors.

Regarding fuel and engine/ship specific NO_X emission factors, ships with diesel engines that have been built or have undergone a major revision in January 2000 or later, have an Engine International Air Pollution Prevention (EIAPP) Certificate, and an associated NO_X technical file which specifies their NO_X emission factors at different engine loads. If this emission factor is based on the use of an aftertreatment system, emissions monitoring would also require the ship owners/operators to provide evidence that the aftertreatment system has actually been used and maintained properly. If the performance of an aftertreatment system is known to deteriorate inherently over time, the emissions factors would have to be corrected for this deterioration.

Regarding the measurement of the emissions on board, this is not equipment that ships normally have. Only ships that already are equipped with an on board end-of-pipe technology (e.g. scrubber for the reduction of SO_2 emissions or an SCR for the reduction of NO_X emissions) can be expected to be able to monitor NO_X emissions.

For all other ships one could, comparable to what Norway does regarding the Norwegian NO_X tax, either use standardized emission factors[3] or determine a ship-specific emission factor by means of on board measurements.

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[3] Regarding the main engines, the Norwegian NOx taxes works with standard values, depending on the engine's maximum revolutions per minute, differentiating four different emission factors.

It is not possible to oblige ships to install monitoring equipment, since only Flag States would have the right to oblige ships flying under their flag to do so, but the use of NO_X reduction instruments could serve as a means of incentivising the installation and use of on-board emissions monitoring equipment.

Important common general elements of potential CO_2 reduction measures and NO_X reduction measures are:

- the need for monitoring fuel consumption, at least, if the NO_X emissions are not monitored,
- the legal aspects regarding the scope of the measures (e.g. which authority has the right to impose environmental requirements on which ships and in which jurisdiction/region,
- the choice of responsible entity (ship owner, ship operator etc.),
- institutional design aspects regarding verification, enforcement etc.,
- cost incidence (who has actually got to incur the costs?)

What is further important to note is that there are mandatory and voluntary NO_X reduction measures already in place:

Mandatory NO_X reduction measures:

- Globally:
    - Diesel engines of new builds constructed in the period January 2000 – 31 December 2010 have to comply with IMO Tier I requirements.
    - Diesel engines of new builds constructed in or after January 2011 have to comply with IMO Tier II requirements.
- Regional:
    - North American NECAs: Diesel engines of new builds constructed in or after January 2016 have to comply with IMO Tier III requirements.
    - National Europe: Differentiated port dues (Sweden, Finland) and fairway dues (Sweden), NO_X tax, with a NO_X fund as alternative compliance mechanism (Norway).

Voluntary NO_X reduction measures: Differentiated port dues (ESI, CSI etc.).

When designing additional/alternative NO_X measures for the Baltic Sea and/or North Sea NECA, the mandatory measures that are in place have to be considered. If, for example, an EU NO_X emissions trading scheme was implemented which would oblige ships to submit emission allowances for all NO_X emissions emitted on voyages to and from EU ports, the question would arise whether the part of the voyage that falls into a NECA would also fall into the scope of the trading scheme, or should ships that comply with IMO Tier III requirements be exempted from an EU NO_X emissions trading scheme anyway.

5.3 Initial high-level assessment of possible instruments

In the following, we will qualitatively assess the seven above mentioned NO_X measures, using the following criteria:

1. Environmental effectiveness in terms of NO_X reduction
2. Certainty of environmental effect
3. Legal issues
4. Political feasibility
5. Costs for the responsible entity
6. Initial cost incidence
7. Impact on competitiveness
8. Enforcement
9. Administrative costs

In Table 16 an overview of the assessment is given, where plus and minus signs are indicating that a measure scores better and worse, respectively, in comparison to the other measures. Note that the impact of the measures varies depending on many design options, which is why the assessment is indicative only.

Environmental effectiveness

- We expect the environmental effectiveness of an ETS, of a NO_X charge/levy/tax and of differentiated port dues to be comparable, since all provide financial incentives to reduce NO_X emissions, at least if the rate per kg NO_X emitted is the same.
- We expect the environmental effectiveness of regulated slow steaming to be relatively higher, since it affects all ships (ships have no alternative compliance options like paying a levy etc.) and speed reduction translates directly into emission reductions, with non-financial market barriers not playing a role.
- If a levy was combined with a fund, the environmental effectiveness can be expected to be higher than without a fund, at least if the fund is used to subsidise the uptake of NO_X abatement measures by the sector.
- We expect the environmental effectiveness of an EU coastal NECA to be relatively lower, since only new ships have to comply with Tier III requirements in NECAs.
- We expect the lowest environmental effectiveness from a NO_x MRS system since it would not be associated with a reduction requirement.

	ETS	MRV	Levy & fund	Charge/ Levy/Tax	Speed limit	Differentiated port dues	EU coastal NECA
Environmental effectiveness	+	-	++	+	++	+	0

Certainty of emission reduction

- For a cap-and-trade ETS the environmental effect is, due do the cap, the most certain.
- We expect the certainty of the emission reduction to be comparable for a NO_X levy & fund, a NO_X charge/levy/tax, differentiated port dues and an EU coastal NECA, but relatively less certain compared to the cap-and-trade ETS: a growing fleet can lead to growing emissions, despite an emission reduction per ship.
- The certainty of the speed reduction is estimated to be in between a cap-and-trade ETS and the above mentioned four measures: although a growing fleet can also lead to growing emissions, all ships are obliged to reduce their emissions, i.e. have no alternative compliance option.
- The emission reduction is the most uncertain for MRV, since there is no NO_X reduction requirement.

	ETS	MRV	Levy & fund	Charge/ Levy/Tax	Speed limit	Differentiated port dues	EU coastal NECA
Certainty of emission reduction	++	-	0	0	+	0	0

Legal issues

The implementation of all measures, except the EU coastal NECA, could be associated with legal obstacles:

- For differentiated port dues the problem could be that the EU has no influence over port dues, which are set by port authorities based on commercial and other considerations.
- Regarding ETS, the NO_X levy and fund, a NO_X tax/levy/charge and a speed limit, legal problems could arise, depending on the geographic scope of the measure chosen: coastal states can impose environmental requirements on foreign-flagged ships, with the exception of foreign-flagged ships in transit or on innocent passage, but can only enforce the requirements within their territorial waters. As an alternative, compliance with the requirement could be set as a condition for entry into ports.

- No legal issues are expected to arise regarding an EU coastal NECA.

	ETS	MRV	Levy & fund	Charge/ Levy/Tax	Speed limit	Differentiated port dues	EU coastal NECA
Legal issues	-	-	-	-	-	-	0

Political feasibility

For three of the measures, political problems might arise:

- The sector may oppose an ETS, arguing that it limits the growth of the sector.
- Regarding a NO_X MRV system, the European Parliament rejected the proposal of the EP's Environmental Committee in the context of GHG reductions, which might make the political feasibility also in the context of air quality improvement lower;
- An EU NO_X tax would require an unanimous decision by all MS, which is very hard to achieve;
- North African States could consider an EU coastal waters-NECA as a trade barrier, and the fear of distortion of competition by EU Mediterranean countries might hinder the formulation of a coordinated proposal of all EU countries.
- Moreover, the mandatory inclusion of foreign flagged ships in any measure may not be generally accepted, except for the EU Coastal NECA.

	ETS	MRV	Levy & fund	Charge/ Levy/Tax	Speed limit	Differentiated port dues	EU coastal NECA
Political feasibility	-	-	0	-	0	0	-

Impact on competitiveness

Three measures might lead to a distortion of competitive markets:

- The mandatory speed limit could be perceived to lead to modal shift (e.g. passengers flying instead of using ferries).
- The level playing field between ports inside/outside the scope of the measure could be distorted if differentiated port dues or an EU coastal NECA were implemented.

Note that these aspects could also have an impact on the political feasibility of the measures.

	ETS	MRV	Levy & fund	Charge/ Levy/Tax	Speed limit	Differentiated port dues	EU coastal NECA
Impact on competitiveness	0	0	0	0	-	-	-

Costs for responsible entity

- Given that ships could use the same monitoring methods as under the other instruments, the costs for the responsible entity can be expected to be lowest under an MRV system, since no NO_X reduction is required.
- The costs for the responsible entity can expected to be higher but still relatively low under an ETS (emission reduction costs are lowest compared to other market based instruments) and under a levy & fund (revenues are recycled back to the sector).
- The costs for the responsible entity can expected to be comparable for a NO_X charge/levy/tax and differentiated port dues, and to be higher than for ETS and a NO_X levy and fund.
- The costs of a speed limit can expected to be relatively low, since no direct NO_X abatement costs accrue, but are uncertain, since the costs highly depend on the fuel price.
- The costs for the responsible entity under an EU coastal NECA are relatively high for a ship owner considering to purchase a new ship, but are relatively low for the sector as a whole, since only new ships are affected.

	ETS	MRV	Levy & fund	Charge/ Levy/Tax	Speed limit	Differentiated port dues	EU coastal NECA
Costs for responsible entity	+	++	+	0	+/0	0	+/0

Enforcement

Regarding the enforcement of the measures, we do not see major significant differences between the measures.

Administrative costs

Regarding the administrative costs associated with the measures, we expect those measures that require the sector to make payments/to trade in allowances and that require revenues to be allocated, to be associated with higher administrative costs than the other measures.

An ETS can expected to lead to relatively higher administrative costs due to the trading of the allowances, but also in the sense that it may require high up-front costs to determine exact baseline emissions and an emission target.

	ETS	MRV	Levy & fund	Charge/ Levy/Tax	Speed limit	Differentiated port dues	EU coastal NECA
Administrative costs	--	0	-	-	0	0	0

Table 16 High-level assessment of the additional/alternative NO_X measures

	ETS	MRV	Levy & fund	Charge/Levy /Tax	Speed limit	Differentiated port dues	EU coastal NECA
Environmental effectiveness	+	-	++	+	++	+	o
Certainty of emission reduction	++	-	o	o	+	o	o
Legal issues	-	-	-	-	-	-	o
Political feasibility	-	-	o	-	o	o	-
Impact on competitiveness	o	o	o	o	-	-	-
Costs for responsible entity	+	++	+	o	+/o	o	+/o
Initial cost incidence	Sector pays; ETS revenues accrue	Sector pays	Sector pays and receives	Sector pays; revenues accrue	Sector/shipper pays or receives;	Port/sector pays; sector receives	Sector pays
Administrative costs	--	o	-	-	o	o	o

5.4 Selection of NO_X reduction instruments and supposed design

For this project several interviews have been conducted with representatives of agencies/authorities that are directly or indirectly involved in the NECA negotiations (see 2.3 for more details). The interviewees stated that none of the longlisted NO_X reduction instruments have been discussed in detail nationally or internationally as additional/alternative instruments for the Baltic and/or the North Sea NECA. The selection of the instruments that are analysed in more detail is therefore solely based on the high-level evaluation as presented in the previous section.

The following NO_X reduction instruments have been shortlisted:

1. Regulated slow steaming with a NO_X levy as alternative compliance option, where the revenues are used to fund the uptake of NO_X abatement measures.

2. A stand-alone NO_X levy whose revenues are not earmarked.

3. A NO_X levy whose revenues are used to fund the uptake of NO_X abatement measures.

An ETS system is not considered due to the relatively high administrative costs, the MRV system due to its low environmental effectiveness, the EU coastal NECA due to its political feasibility, and differentiated port dues due to the legal feasibility.

The supposed design of the selected instruments is as follows.

The first instrument requires the ships to reduce their speed by 15% under the baseline speed when sailing in the North Sea, Baltic Sea and English Channel ECAs. As an alternative compliance option, the ships that prefer to stick to their baseline speed can pay a levy, depending on their NO_X emissions in the North Sea, Baltic Sea and English Channel ECAs. The income of this levy is assumed to be used for the funding of NO_X abatement measures in the sector.

The second instrument is a stand-alone NO_X levy that the ships have to pay for their NO_X emissions in the North Sea, Baltic Sea and English Channel ECAs. The revenue of this instrument is assumed to go to the Member States and not to be earmarked.

The third instrument is a NO_X levy that ships have to pay for NO_X emissions in the North Sea, Baltic Sea and English Channel ECAs. In contrast to the second instrument, the revenue of the levy is assumed to be used for the funding of the uptake of NO_X abatement measures in the sector.

For all three instruments it is assumed that they enter into force in 2021.[4]

The following three levy rates are considered in the calculations for all three instruments:

a) €1/kg NO_X,

b) €2/kg NO_X,

c) €3/kg NO_X,

[4] In the scenario in which the instruments are used in addition to the Baltic and North Sea NECA it is assumed that the Baltic and North Sea NECAs become effective in 2021.

where the central value (approximately) coincides with the 2015 NO_X tax rate applied in Norway[5], and the other two values are higher and lower than this value.

The levy will most probably be collected by the coastal states, but an existing EU body (e.g. EIB) or a newly established international body could become responsible for the allocation of the funds, to guarantee that consistent allocation criteria are used. This is not relevant for the calculations, but will be relevant if an instrument was actually implemented.

5.5 Methodology and assumptions

For the three shortlisted NO_X reduction instruments, the emission reductions and the associated costs for the shipping sector have been calculated on the NECA-fleet level and for two scenarios, i.e. for a 'No-NECA scenario' in which the shortlisted reduction instruments are alternative instruments to North and Baltic Sea NECA requirements and for a 'NECA scenario' in which the shortlisted reduction instruments are implemented for non-Tier III ships on top of the North and Baltic Sea NECA requirements.

How and under which assumptions the effects have been calculated, is explained in more detail in the following.

5.5.1 Regulated slow steaming

Regulated slow steaming leads indirectly, i.e. via a reduction of the fuel consumption of the ships to a reduction of the NO_X emissions. In the model, the reduced fuel consumption is translated into a NO_X emission reduction using the SFOC factor and the NO_X emission factors expressed in g/kWh.

It is assumed that ferries, which sail at a certain speed in order to meet a daily schedule, and 10% of the other ship types will continue to sail at the baseline speed and will take NO_X reduction measures/pay the NO_X levy instead (see 5.5.2 for more details).

The costs for the shipping sector for regulated slow steaming, which are related to the fact that the annual transport work of a ship is reduced, are based on CE Delft (2012a). The net direct costs, i.e. the costs net of the fuel expenditure savings, used in the calculation amounts to approximately € 800/tonne NO_X reduced.[6]

5.5.2 NO_X levy (and fund)

A NO_X levy can, depending on the rate of the levy, lead to a direct NO_X emission reduction: Ships weigh the levy payment against the costs of NO_X abatement measures.[7]

The costs of the abatement measures are considered from the company perspective, differentiating between the costs for new builds and retrofits, and assuming that ships use distillates in the baseline (see section 3.2 for more details). In Table 17 and Table 18, the costs of the different measures are specified. For the calculations the central cost value has been used.

[5] The 2015 NO_X tax rate that applies in Norway amounts to €2.06/kg (Toll Customs, 2015).
[6] These costs include the costs for engine modifications, fuel expenditure savings of the baseline fleet and the additional transport costs that have to be incurred if the annual transport work is not to decline due to slow steaming.
[7] For Tier 0 ships which are relatively old in 2021 – the year in which the instrument is assumed to become effective - it is assumed that their emissions will not be reduced, but that the levy is always paid instead.

Table 17 **NO_X abatement costs (€/kg NO_X, company perspective, new builds).**

		min	central	max
Tier II	WIF	0.74	1.22	1.70
Tier II	HAM	1.24	4.17	7.10
Tier II	DWI	0.92	32.06	3.19
Tier II	Methanol	-8.53	1.38	11.28
Tier III	LNG	-2.24	5.04	12.33
Tier III	SCR	0.15	1.08	2.02
Tier III	EGR	0.21	0.70	1.19

Table 18 **NO_X abatement costs (€/kg NO_X, company perspective, retrofit).**

		min	central	max
Tier II	WIF	0.74	1.22	1.70
Tier II	HAM	1.51	4.96	8.41
Tier II	DWI	1.32	3.44	5.56
Tier II	Methanol	-8.53	1.38	11.28
Tier III	SCR	0.32	1.12	1.92

For LNG and EGR it is assumed that retrofit is not an option which is why the costs for these measures are not specified in Table 18.

The costs specified in Table 17 and Table 18 are assumed to be constant over time, which implies that it is assumed that the average operational pattern of the ships and the price difference between LNG/methanol and distillates do not change over time.

The supposed NO_X reduction potentials of the different abatement measures are specified in Table 19 and are based on Incentive Partners and Litehauz (2012) and Stena (2015).

Table 19 NO_X reduction potentials.

		Reduction compared to Tier I	Reduction compared to Tier II
Tier II	WIF	55%	
Tier II	HAM	70%	
Tier II	DWI	55%	
Tier II	Methanol	60%	
Tier III	LNG	85%	80%
Tier III	SCR	95%	90%
Tier III	EGR	80%	75%

Non-financial market barriers are known to prevent the uptake of apparently cost efficient emission abatement measures. A lack of LNG infrastructure can for example frustrate the uptake of LNG-fuelled ships. To account for these non-financial market barriers, we apply a market barrier factor to the reduction potential that would be reached if there were no non-financial market barriers (e.g. only 75% of the cost effective market potential is assumed to be achieved in the case of SCR). Table 20 gives the assumed market barrier factors, which are lower (in the sense that the barrier is higher) for more innovative measures and measures like LNG and methanol that require a sufficient bunkering infrastructure. For SCR and EGR the market barrier factors are based on evidence from CO_2 abatement measures (CE Delft, 2012b), for the other measures estimations have been made relative to SCR and EGR.

Table 20 Market barrier factors.

	NO_X reduction technology	Market barrier factor
Tier II	WIF	20%
Tier II	HAM	20%
Tier II	DWI	20%
Tier II	Methanol	20%
Tier III	LNG	40%
Tier III	SCR	75%
Tier III	EGR	75%

5.5.3 Further general assumptions

The effects of the NO_X measures can only be modelled if the baseline fleet emissions and consumption are distributed over the different Tiers (0-III). The distribution of the ships over the Tiers has been estimated to this end. The underlying fleet development in terms of number of ships has been derived as follows:

- The 2010 number of ships according to Kalli et al (2013) has been distributed over Tier 0 and Tier I based on the age structure of the SECA fleet as specified in DMA (2012).
- In 2010, Tier 0 ships are at least 10 years old and assumed to be evenly distributed in terms of age.
- In 2010, Tier I ships are maximally 10 years old and assumed to be evenly distributed in terms of age.
- In no-NECA scenario, from 2011 on, only Tier II ships are added to the fleet.
- In a NECA scenario, in the period 2011-2019 only Tier II ships are added to the fleet, and from 2021 and onwards only Tier III ships.
- An annual fleet growth factor is derived from the annual traffic growth factor and the annual efficiency improvement factor.

As a result, depending on the assumed life time of the vessel type (25-28), Tier 0 ships are fully phased out between 2026 and 2029, and Tier I ships are fully phased out in the period 2036 to 2039.

The baseline fuel consumption is distributed over the tiers, based on the distribution of the number of ships, and the baseline NO_X emissions are distributed over the tiers, based on the distribution of the number of ships and assuming the average NO_X emission reduction compared to Tier 0 as specified in Table 21.

Table 21 Average NO_X reduction compared to Tier 0 per ship type.

Ship type	NO_X reduction average, Tier I	NO_X reduction average, Tier II	NO_X reduction average, Tier III
Bulk carrier	1%	16%	78%
Chemical tanker	2%	17%	72%
Container ship	1%	17%	78%
General cargo	2%	20%	79%
LG tanker	1%	18%	76%
Oil tanker	1%	17%	74%
RoRo cargo	3%	20%	77%
Ferry	3%	22%	79%
Cruise	3%	20%	76%
Vehicle Carrier	1%	17%	78%

For two instruments it is assumed that the revenues of the fund are used to incentivise the uptake of NO_X abatement measures. It is thereby assumed that:

- if *no* abatement measure was adopted without a subsidy, the use of an abatement measure would be incentivised by funding the difference between the levy rate and the abatement costs, and
- if an abatement measure was adopted without a subsidy, the use of an environmentally more effective measure would be incentivised by funding the difference between the abatement costs of the measures.

For the remaining levy revenue, it is assumed that it is refunded as a lump sum to the sector.

5.6 Results: Emission reductions and costs

The emission reduction and the associated costs for the shipping sector of the three shortlisted NO_X reduction instruments are presented for the 'No-NECA scenario' in Table 22 and for the 'NECA scenario' in Table 23 and is explained in the following.

5.6.1 Results for the 'No-NECA scenario'

If no NECA was established, the relative emission reduction associated with each of the three alternative instruments increases over time. This increase is explained by the gradual phase out of Tier 0 ships which are, because of their age, assumed, with the exemption of slow steaming, not to take any NO_X abatement measures but to pay a levy instead.[8]

Stand-alone levy:

- €1/kg NO_X levy: Only new Tier II ships reduce NO_X emissions (EGR). The associated emission reduction amounts to 25% in 2040. The total costs for the sector range from €750 million per year in 2025 to €660 million in 2040.
- €2/kg NO_X levy: Existing Tier I and II ships reduce NO_X emissions by means of SCR, while new builds by means of EGR. A significantly higher NO_X reduction (approximately 65%) can thus be achieved compared to the lower levy rate. The total costs for the sector range from €1,060 million per year in 2025 to €950 million in 2040.
- €3/kg NO_X levy: Existing Tier I and II ships and new builds reduce NOx emissions by means of SCR. The NOx reduction is slightly higher compared to the €2/kg NOX levy case. The total costs for the sector range from €1,320 million per year in 2025 to €1,200 million in 2040.

Levy and fund:

- €1/kg NO_X levy: Existing Tier I and Tier II ships are subsidised (difference between levy and SCR costs) to take up SCR – the NO_X emissions of these ships would otherwise not be reduced and the levy would be paid for the total baseline emissions. Tier II new builds are subsidised (difference between EGR and SCR compliance costs) to take up SCR and not an EGR.
- €2/kg NO_X levy: Existing Tier I and II ships would use SCR even if not funded and therefore receive no funds. Tier II new builds are subsidised (difference between EGR and SCR compliance costs) to take up SCR instead of EGR.
- €3/kg NO_X levy: Tier I and Tier II ships take up SCR without subsidies.
- Due to the funding, the NO_X emission abatement is the same for all three levy rates. The NO_X reduction (approximately 70%) is significantly higher compared to the stand-alone €1/kg NO_X levy case, slightly higher compared to the stand-alone levy €2/kg NO_X case and the same compared to the stand-alone €3/kg NO_X levy case.
- Regarding the costs, the only difference between the levy-scenarios lies in the use of the levy revenue: the higher the levy, the smaller that part of the revenue that is used to subsidise the uptake of the NOx abatement measures.
- Total costs are significantly lower compared to the stand-alone levy, especially for the higher levy rates.

Regulated slow steaming/levy and fund:

- The line of reasoning for those ships that do not slow down (ferries and 10% of others) is just as for a levy and fund (see above). The NO_X reduction effect is thus also the same for all three levy rate cases.

[8] In Table 22, the increase of the relative emission reduction does not always show, due to rounding of the numbers.

- In contrast to the other two instruments, Tier 0 ships reduce their NOx emissions (by also slowing down).

- Compared to the other two instruments, the NO_X reduction of the instrument (approximately 35%) is about half of the reduction that can be achieved with the levy & fund which means that, if compared with the stand-alone levy, the instrument gives higher NOx emissions only for the €1/kg NO_X levy case.

- Total costs are significantly lower compared to the other instruments, less than half of the costs under a levy & fund.

5.6.2 Results for the 'NECA scenario'

If a NECA was established, the relative emission reduction associated with all three additional NO_X reduction instruments decreases over time and would eventually converge to zero. This decrease can be explained by a gradually decreasing share of the ships that have to comply with the additional instruments which are the non-Tier III ships.

Stand-alone levy:

- €1/kg NO_X levy: The levy rate is too low to incentivise NO_X emission reductions – the levy is paid for the total baseline emissions. Levy costs per year then range from €590 million in 2025 to € 120 million in 2040.

- €2/kg NO_X levy: Due to the levy, existing ships are incentivised to use SCR resulting in significantly lower NO_X emissions (-60% in 2025 and -30% in 2040). Total costs per year range from €830 million in 2025 to € 170 million in 2040.

- €3/kg NO_X levy: Just as for the €2/kg NO_X levy case, existing ships are, due to the levy, incentivised to use SCR and the NOx emission reduction is therefore the same as for the €2/kg NO_X levy case. Due to the higher levy rate however, total costs are higher in this case, ranging from €1,020 million in 2025 to € 210 million in 2040.

Levy and fund:

- €1/kg NO_X levy: existing ships are subsidised (difference between levy and SCR costs) to take up SCR – the NO_X emissions of these ships would otherwise not be reduced.

- €2/kg NO_X levy and €3/kg NO_X levy: existing ships would use SCR even without a subsidy.

- Due to the funding, the NO_X emission abatement is the same for all three levy rates. Since no funds are used in the case of a €2/kg NO_X levy and a €3/kg NO_X levy, the NO_X reduction is the same as for the according stand-alone levy case (60% in 2025 and 30% in 2040). Compared to stand-alone levy, an additional reduction is thus only achieved for the €1/kg NO_X levy case.

- Total costs are significantly lower compared to the stand-alone levy, especially for the higher levy rates.

Regulated slow steaming/levy and fund:

- The line of reasoning for those ships that do not slow down (ferries and 10% of others) is just as for levy and fund (see above). The NO_X reduction effect is thus also the same for all three levy rate cases.

- In contrast to the other two instruments, Tier 0 ships reduce their NOx emissions (by also slowing down).

- Compared to the other two instruments, the NO_X reduction of the instrument (approximately 35% in 2025 and 15% in 2040) is more than half of the reduction that can be achieved with the levy & fund which means that, if compared with the stand-alone levy, the instrument gives higher NOx emissions only for the €1/kg NO_X levy case.

- Total costs are significantly lower compared to the other instruments, less than half of the costs under a levy & fund.

Table 22 Results for the No-NECA scenario.

	Stand-alone levy				Levy and fund				Slow steaming/levy and fund			
Levy rate: €1/kg NO_X	**2025**	**2030**	**2035**	**2040**	**2025**	**2030**	**2035**	**2040**	**2025**	**2030**	**2035**	**2040**
NO_X reduction (kt)	60	130	170	190	520	520	500	500	260	260	250	250
NO_X change	-10%	-15%	-25%	-25%	-70%	-70%	-70%	-70%	-35%	-35%	-35%	-35%
Remaining emissions (kt)	700	610	540	520	250	220	220	220	510	480	470	460
Gross abatement costs (million €)	50	90	120	130	580	580	550	550	230	230	230	230
Revenue levy (million €)	700	610	540	520	250	220	220	220	72	71	70	70
Used as subsidy (million €)	0	0	0	0	80	90	100	110	12	13	14	15
Recycled lump-sum (million €)	0	0	0	0	170	130	110	110	61	57	56	55
Total costs (million €)	750	700	660	660	580	580	550	550	230	230	230	230
Levy rate: €2/kg NO_X												
NO_X reduction (kt)	500	490	460	450	520	520	500	500	260	260	250	250
NO_X change	-65%	-65%	-65%	-65%	-70%	-70%	-70%	-70%	-35%	-35%	-35%	-35%
Remaining emissions (kt)	260	250	260	260	250	220	220	220	510	480	470	460
Gross abatement costs (million €)	540	490	440	430	580	580	550	550	230	230	230	230
Revenue levy (million €)	520	500	510	520	490	440	430	430	145	141	140	140
Used as subsidy (million €)	0	0	0	0	10	20	30	30	1	1	2	2
Recycled lump-sum (million €)	0	0	0	0	480	420	400	400	144	140	138	138
Total costs (million €)	1,060	1,000	950	950	580	580	550	550	230	230	230	230
Levy rate: €3/kg NO_X												
NO_X reduction (kt)	520	520	500	500	520	520	500	500	260	260	250	250
NO_X change	-70%	-70%	-70%	-70%	-70%	-70%	-70%	-70%	-35%	-35%	-35%	-35%
Remaining emissions (kt)	250	220	220	220	250	220	220	220	510	480	460	460
Gross abatement costs (million €)	580	580	550	550	580	580	550	550	230	230	230	230
Revenue levy (million €)	740	660	650	650	740	660	650	650	217	212	210	211
Used as subsidy (million €)	0	0	0	0	0	0	0	0	0	0	0	0
Recycled lump-sum (million €)	0	0	0	0	740	660	650	650	217	212	210	211
Total costs (million €)	1,320	1,240	1,200	1,200	580	580	550	550	230	230	230	230

Table 23 Results for the NECA scenario.

Levy rate: €1/kg NO_X	Stand-alone levy 2025	2030	2035	2040	Levy and fund 2025	2030	2035	2040	Slow steaming/levy and fund 2025	2030	2035	2040
NO_X reduction (kt)	0	0	0	0	400	290	180	90	220	130	90	50
NO_X change	0%	0%	0%	0%	-60%	-55%	-45%	-30%	-35%	-25%	-25%	-15%
Remaining emissions (kt)	640	530	410	310	250	230	230	220	420	400	320	260
Gross abatement costs (million €)	0	0	0	0	440	330	200	100	200	120	90	40
Revenue levy (million €)	590	410	250	120	190	120	70	40	50	30	20	10
Used as subsidy (million €)	0	0	0	0	50	40	20	10	10	10	10	0
Recycled lump-sum (million €)	0	0	0	0	150	90	50	30	40	20	10	10
Total costs (million €)	590	410	250	120	440	330	200	100	200	120	90	40
Levy rate: €2/kg NO_X												
NO_X reduction (kt)	400	290	180	90	400	290	180	90	220	130	90	50
NO_X change	-60%	-55%	-45%	-30%	-60%	-55%	-45%	-30%	-35%	-25%	-25%	-15%
Remaining emissions (kt)	250	230	230	220	250	230	230	220	420	400	320	260
Gross abatement costs (million €)	440	330	200	100	440	330	200	100	200	120	90	40
Revenue levy (million €)	390	240	150	70	390	240	150	70	100	60	40	20
Used as subsidy (million €)	0	0	0	0	0	0	0	0	10	10	10	0
Recycled lump-sum (million €)	0	0	0	0	390	240	150	70	90	50	30	20
Total costs (million €)	830	570	350	170	440	330	200	100	200	120	90	40
Levy rate: €3/kg NO_X												
NO_X reduction (kt)	400	290	180	90	400	290	180	90	220	130	90	50
NO_X change	-60%	-55%	-45%	-30%	-60%	-55%	-45%	-30%	-35%	-25%	-25%	-15%
Remaining emissions (kt)	250	230	230	220	250	230	230	220	420	390	310	260
Gross abatement costs (million €)	440	330	200	100	440	330	200	100	200	120	90	40
Revenue levy (million €)	580	360	220	110	580	360	220	110	150	90	50	30
Used as subsidy (million €)	0	0	0	0	0	0	0	0	0	0	0	0
Recycled lump-sum (million €)	0	0	0	0	580	360	220	110	150	90	50	30
Total costs (million €)	1,020	690	420	210	440	330	200	100	200	120	90	40

5.7 Conclusions

A levy & fund can lead to relatively high annual NO_X emission reductions in both scenarios, i.e. if used as alternative instruments to a Baltic and North Sea NECA (annual NO_X reductions of around 70%) and if used as additional instruments to a Baltic and North Sea NECA for non-Tier 3 ships (annual NO_X reduction in the range of 60-30%).

With a stand-alone levy comparable/the same high annual NO_X emission reductions can only be reached for higher levy rates and against higher costs for the sector.

With regulated slow steaming (15% below baseline speed) combined with a levy & fund about half (no-NECA case)/more than half (NECA case) of the NOx reduction achieved with a levy & fund can be realised.

In the scenario where the NO_X reduction instruments are used as additional instruments (NECA-case) to a Baltic and North Sea NECA, regulated slow steaming may, since Tier 3 ships would be exempted from the obliged speed reduction, trigger the use of more Tier 3 ships and may thus lead to higher NO_X reductions than quantified here.

For all three instruments it holds that enforcement is the crucial factor to actually achieve the estimated NO_X emission reductions.

Compared to a stand-alone levy, costs for the sector are significantly lower for both a levy & fund and regulated slow steaming combined with a levy & fund, at least if the revenue is not only used to subsidise the uptake of NO_X reduction measures, but if the remaining revenue is also recycled back to the sector.

Costs for the sector is the lowest if regulated slow steaming (15% below baseline speed) combined with a levy & fund was implemented and less than half of the costs under a levy & fund.

In terms of NOx reduction and costs for the sector, two of the three instruments thus stand out as potential additional/alternative instruments for a Baltic and North Sea NECA, i.e. a levy & fund and regulated slow steaming combined with a levy & fund. With the levy & fund relatively high NOx reduction can be achieved which is roughly twice the reduction achieved with regulated slow steaming combined with a levy & fund, at least if the baseline speed is reduced by 15%. However, costs for the sector of a levy & fund are also roughly twice the costs of regulated slow steaming combined with a levy & fund.

Note that due to a lack of more refined data, these results should be considered as indicative. If more reliable and more specific data on the costs and abatement potentials of the NO_X abatement measures were available that would allow to set up marginal NO_X abatement cost curves for the different ship types, if the market barrier factor could be quantified more precisely and if the monitoring costs for the sectors could be quantified, the decision making processes (slow steaming versus levy & fund; paying levy versus NO_X reduction) could be modelled more precisely. Experience from the North American NECA might help to fill these gaps in the near future.

In Figure 6 to Figure 9, the NO_X emissions in the analysed scenarios are illustrated. The stand-alone levy is sensitive to the levy rate. The major difference is between levy rates of 1€/kg NO_X and 2€/kg NO_X, whereas the difference between 2€/kg NO_X and 3€/kg NO_X is rather small. The scenarios with a levy of 1€/kg NO_X, and 2€/kg NO_X, are illustrated in Figure 6 and Figure 7, respectively. The levy and fund, and the slow steaming together with the levy and fund are much less sensitive to the levy rate and the effects of these economic incentives are illustrated in Figure 8 and Figure 9, respectively, for the levy rate 2€/kg NO_X.

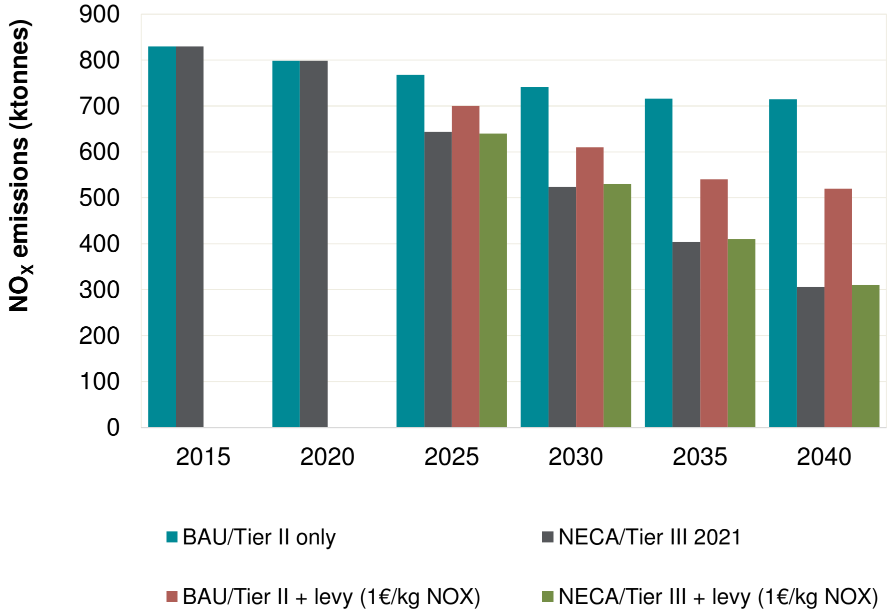

Figure 6. Projected NO_X emissions to 2040 in scenarios with a levy of 1 €/kg NO_X in scenarios with and without the NECA. NO_X emissions in reference scenarios without any economic incentive are also shown.

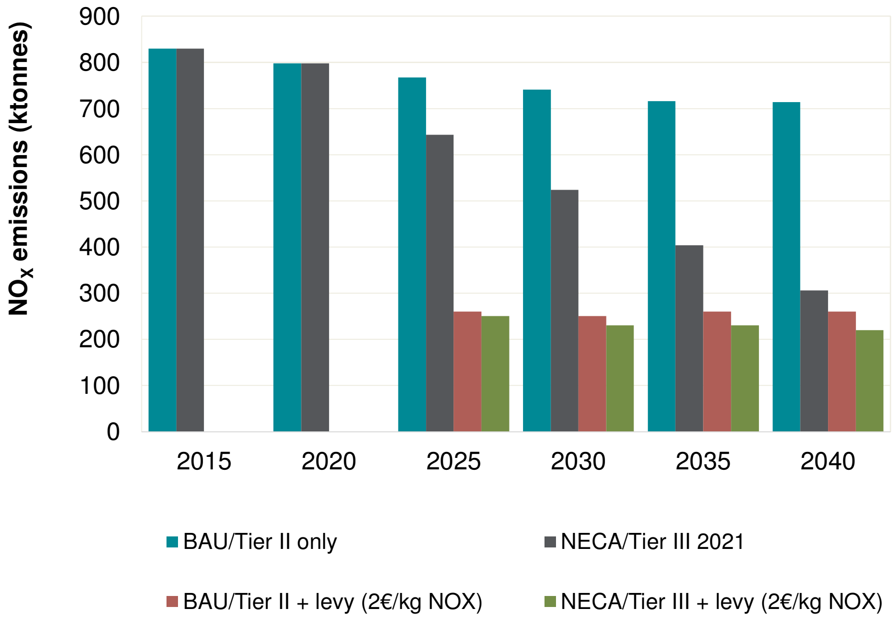

Figure 7. Projected NO_X emissions to 2040 in scenarios with a levy of 2 €/kg NO_X in scenarios with and without the NECA. NO_X emissions in reference scenarios without any economic incentive are also shown.

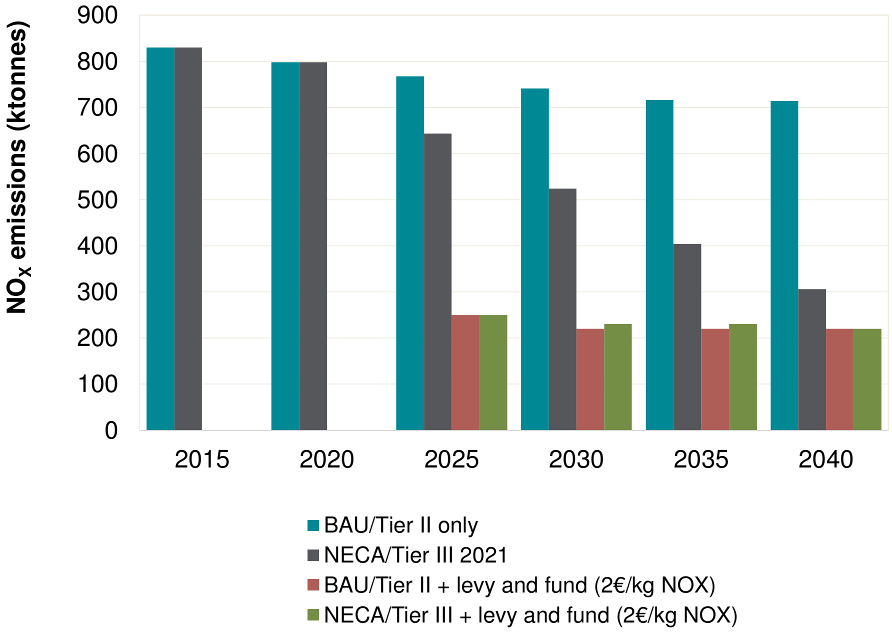

Figure 8. Projected NO_X emissions to 2040 in scenarios with a levy and fund incentive of 2 €/kg NO_X in scenarios with and without the NECA. NO_X emissions in reference scenarios without any economic incentive are also shown.

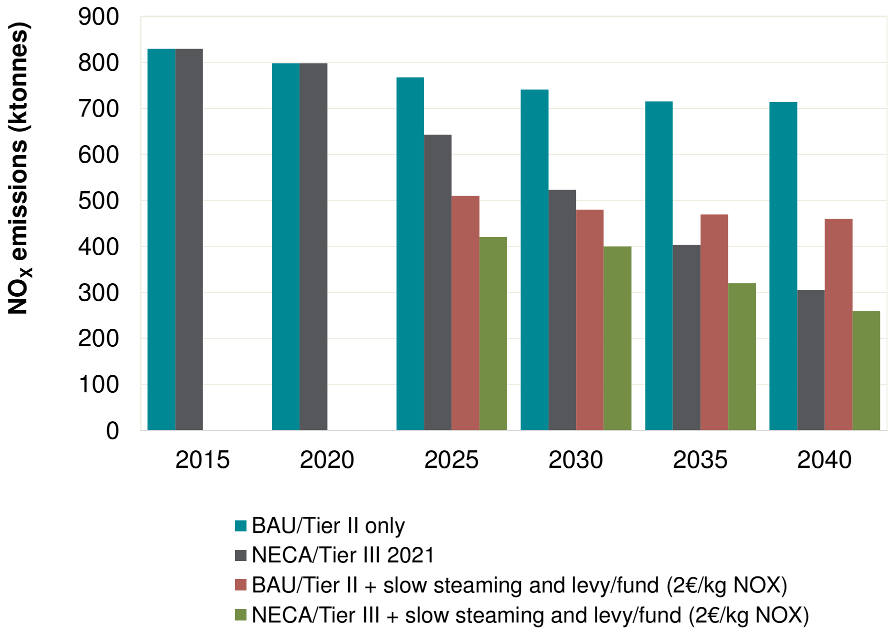

Figure 9. Projected NO_X emissions to 2040 in scenarios with a slow steaming and levy/fund incentive of 2 €/kg NO_X in scenarios with and without the NECA. NO_X emissions in reference scenarios without any economic incentive are also shown.

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Appendix A. Sensitivity analysis

This analysis is presented in order to illustrate the sensitivity to some variables on the results in the projection calculations of NO_X emissions and fuel consumption. Sensitivity to changes in three variables is tested: average lifetime of ships, efficiency increase in fuel consumption, and yearly increase in traffic.

Lifetime
One scenario using lifetimes different from those presented in Kalli et al. 2013 has been tested. Average lifetimes have then been calculated according to the following steps:

- All merchant ships (in service) in Seaweb's ship database are divided into ship categories. Ships constructed before 1960 are excluded from the analysis
- For each ship category, a linear decrease in the remaining number of ships (n_s) after different ages (a) has been assumed and linear equations for all ship categories are established ($n_s=k_s a+n_{so}$), where n_{so} is the original number of new ships (a=0), and k_s is a fitted parameter.
- The age $a_{1/2}$ corresponding to $n_s=n_{os}/2$ is taken as an approximation of the age of ships when half of the original population is dismantled

The assumptions do not take into account that production of ships has increased over time.

All other input values and variables are kept as in the base case. The results can be seen in Figure A1 a and b. Average lifetimes for all ship categories are increased in the tested scenario (Figure A1 b). The regulations will have a slower effect on NO_X emissions as the replacement rate of old ships is reduced. In the tested scenario, the NO_X emissions in 2040 are 385 ktonnes compared to the ca 300ktonnes in the original scenario.

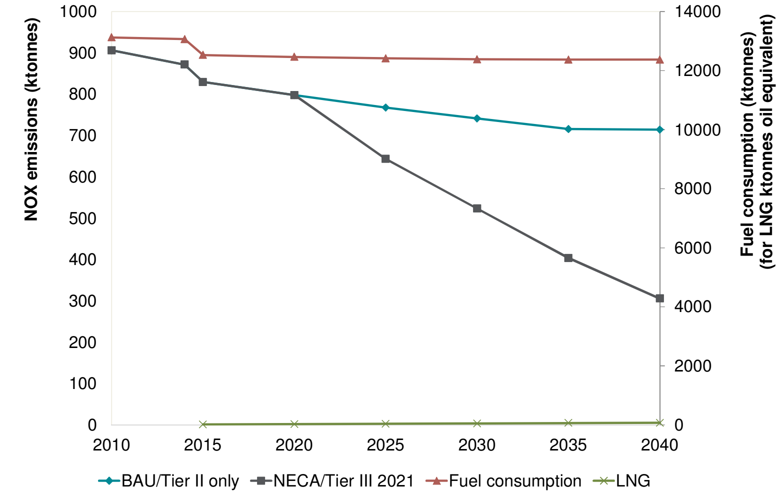
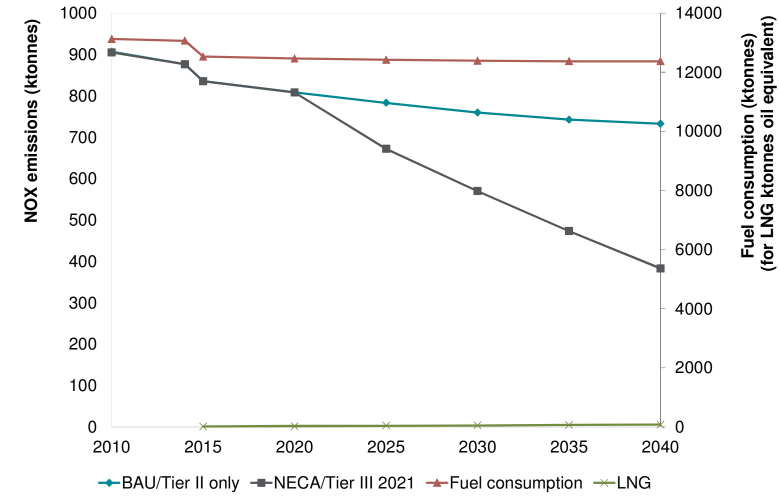
<table>
<tr><td>a)</td><td colspan="2">Original values on average lifetimes of ships (based on Kalli et al., 2013)</td></tr>
<tr><td>Bulk carrier</td><td>19</td><td rowspan="10">
</td></tr>
<tr><td>Chemical tanker</td><td>26</td></tr>
<tr><td>Container ship</td><td>25</td></tr>
<tr><td>General Cargo</td><td>26</td></tr>
<tr><td>LG tanker</td><td>28</td></tr>
<tr><td>Oil tanker</td><td>26</td></tr>
<tr><td>RoRo cargo</td><td>27</td></tr>
<tr><td>Ferry</td><td>27</td></tr>
<tr><td>Cruise</td><td>27</td></tr>
<tr><td>Vehicle carrier</td><td>27</td></tr>
<tr><td>b)</td><td colspan="2">Values calculated from linear fit of population age; half of population remaining gives average lifetime.</td></tr>
<tr><td>Bulk carrier</td><td>25</td><td rowspan="10">
</td></tr>
<tr><td>Chemical tanker</td><td>28</td></tr>
<tr><td>Container ship</td><td>38</td></tr>
<tr><td>General Cargo</td><td>21</td></tr>
<tr><td>LG tanker</td><td>29</td></tr>
<tr><td>Oil tanker</td><td>25</td></tr>
<tr><td>RoRo cargo</td><td>38</td></tr>
<tr><td>Ferry</td><td>38</td></tr>
<tr><td>Cruise</td><td>35</td></tr>
<tr><td>Vehicle carrier</td><td>20</td></tr>
</table>

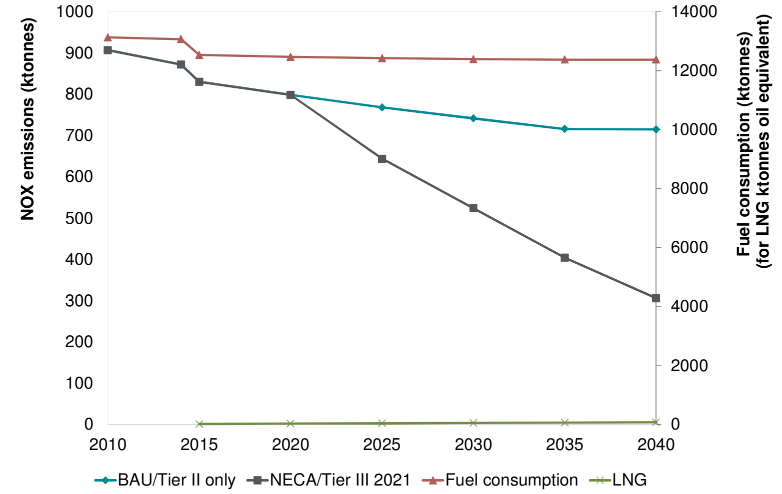
Figure A1 a) Projection of fuel consumption and NO_X in original scenario, and b) projection of fuel consumption and NO_X in scenario with lifetimes calculated from a linear fit of ship ages, for different ship categories.

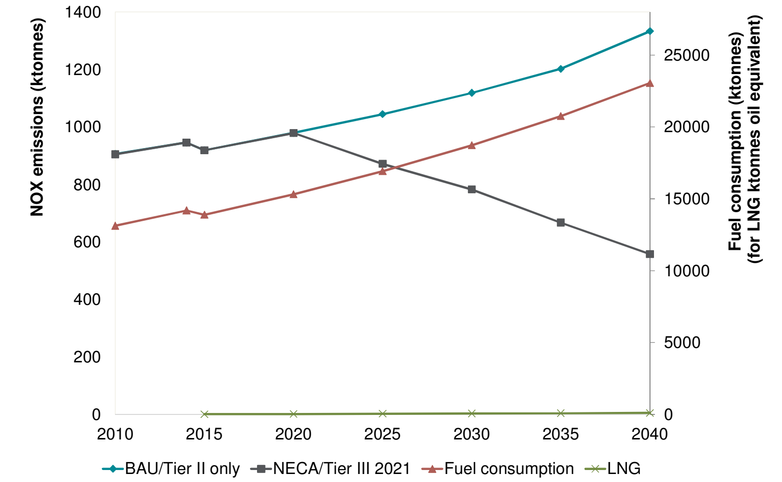
Efficiency increase of ships

Two scenarios using different assumptions on fuel efficiency increases of ships, than those presented in Kalli et al. 2013, have been tested. The annual increase in ship efficiency in Kalli would result in fuel consumption reductions of between 32% and 49% (see table below) if there had not been any traffic increase. The two alternative scenarios that have been set up include one without any efficiency improvements at all, and one that represent annual increases accomplishing 30% reduction in fuel consumption by 2040 if there had not been any traffic increase.

The one without efficiency increase must be considered as an extreme and is not a likely realistic scenario. This can be considered as a reference point. The scenario with 1.2% annual efficiency increase is loosely based on IMO's Energy Efficiency Design Index regulations. The regulation states that by 2025 all large ships (the size spans depend on ship category) should have a calculated CO_2 efficiency that is 30% lower than baseline emissions. Ships of smaller sizes have less strict requirements. Actual emissions from operations of ships are not covered in the regulation. Further, only new ships are covered by the regulation, and by 2040 there are still ships from before 2025 in service. Thus, this scenario can be argued to be an optimistic scenario despite that the annual efficiency increases of 1.2% is lower than the estimates in Kalli et al. (2013).

The results can be seen in Figure A2 a to c. Figure A2 a represents the original scenario, reaching approximately 300 ktonnes NO_X in 2040 with a NECA in effect by 2021, and a fuel consumption of around 12400 ktonnes oil. Without any efficiency measures (Figure A2 b) the NO_X would be double that amount, approximately 560 ktonnes by 2040, and the fuel consumption would increase to above 23000 ktonnes oil. The results presented in Figure A2 c build on the assumption of an annual increase in efficiency of 1.2%. In this scenario, NO_X levels with a NECA effective by 2021 are approximately 390 ktonnes, and fuel consumption is around 16000 ktonnes oil. Projections of emissions without NECAs in force are also presented in Figure A2 a, b, and c, with emission levels of approximately 710, 1300, and, 900 ktonnes NO_X, respectively, in 2040.

a)	Original values (based on Kalli et al., 2013)	
Bulk carrier	1.9%	
Chemical tanker	1.9%	
Container ship	2.0%	
General Cargo	1.3%	
LG tanker	1.9%	
Oil tanker	1.9%	
RoRo cargo	2.3%	
Ferry	2.3%	
Cruise	2.3%	
Vehicle carrier	2.3%	

b)	No efficiency increase	
Bulk carrier	0%	
Chemical tanker	0%	
Container ship	0%	
General Cargo	0%	
LG tanker	0%	
Oil tanker	0%	
RoRo cargo	0%	
Ferry	0%	
Cruise	0%	
Vehicle carrier	0%	

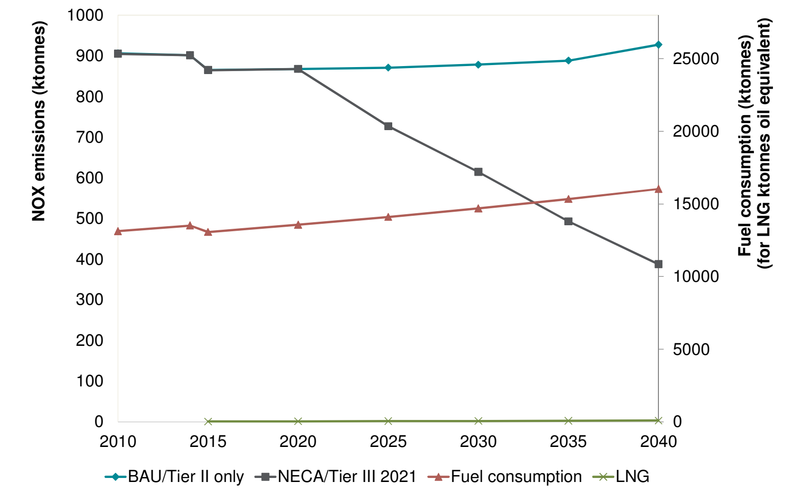
c)	Annual efficiency improvements of 1.2%.	
Bulk carrier	1.2%	
Chemical tanker	1.2%	
Container ship	1.2%	
General Cargo	1.2%	
LG tanker	1.2%	
Oil tanker	1.2%	
RoRo cargo	1.2%	
Ferry	1.2%	
Cruise	1.2%	
Vehicle carrier	1.2%	

Figure A2 a) Projection of fuel consumption and NO_X in original scenario, and b) projection of fuel consumption and NO_X in a scenario without any efficiency increase, and c) Projection of fuel consumption and NO_X in a scenario with 1.2% annual increase of fuel efficiency in shipping services.

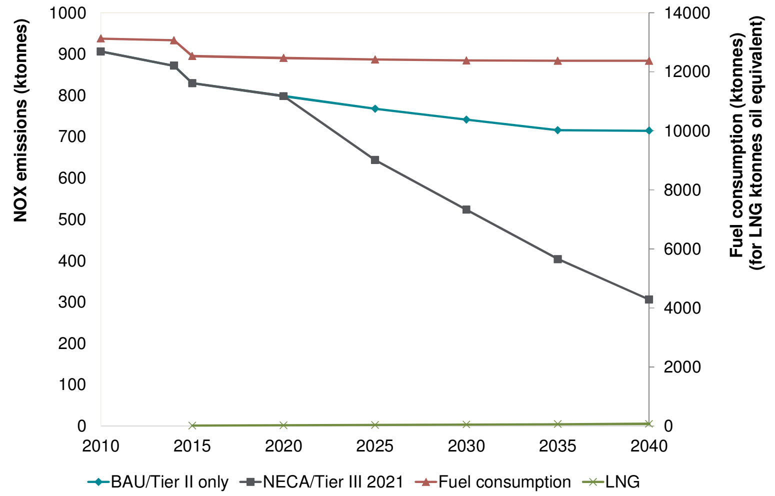
Traffic increase

In the original scenario in this study traffic change is set to an annual increase of 1.5 % for all ship categories except container ships which are assumed to have a yearly increase of 3.5% (from Kalli et al., 2013). The traffic growth is assumed to follow GDP growth and can be measured as total distance sailed per year. The same assumptions are used in Hammingh et al., 2012. The base for these assumptions is IMO estimates presented in the 2nd GHG report (IMO, 2009).

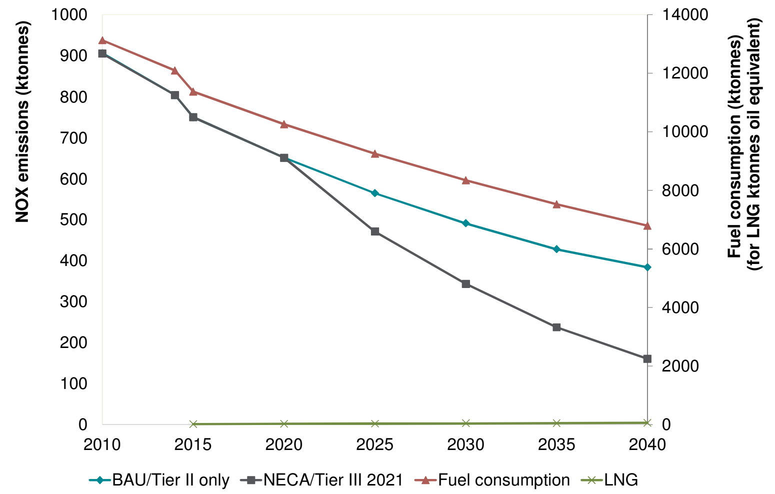
Two scenarios using growth rates different from those used by Kalli et al. has been tested. In one scenario no growth in traffic at all is assumed. This is an extreme scenario and should be considered merely as a reference point. The decrease in fuel consumption is significant and NO_X emissions have decreasing trends that follow the fuel consumption. The second scenario is loosely based on the scenario with the highest increase rates of CO_2 emissions in the 3rd GHG report by MEPC (IMO, 2014). An average traffic increase of all ship categories of 3.2% has been assumed. This results in emission increases of comparable magnitudes as those in the report. Changes in efficiency are not included in this scenario.

The results are shown in Figure A3; Figure A3 a represent the original scenario, Figure A3 b the scenario without any growth, and Figure A3 c the scenario with a high traffic increase.

a)	Original values (based on Kalli et al., 2013)
Bulk carrier	1.5%
Chemical tanker	1.5%
Container ship	3.5%
General Cargo	1.5%
LG tanker	1.5%
Oil tanker	1.5%
RoRo cargo	1.5%
Ferry	1.5%
Cruise	1.5%
Vehicle carrier	1.5%



b)	No traffic increase
Bulk carrier	0%
Chemical tanker	0%
Container ship	0%
General Cargo	0%
LG tanker	0%
Oil tanker	0%
RoRo cargo	0%
Ferry	0%
Cruise	0%
Vehicle carrier	0%



c)	High traffic increase
Bulk carrier	3.2%
Chemical tanker	3.2%
Container ship	3.2%
General Cargo	3.2%
LG tanker	3.2%
Oil tanker	3.2%
RoRo cargo	3.2%
Ferry	3.2%
Cruise	3.2%
Vehicle carrier	3.2%

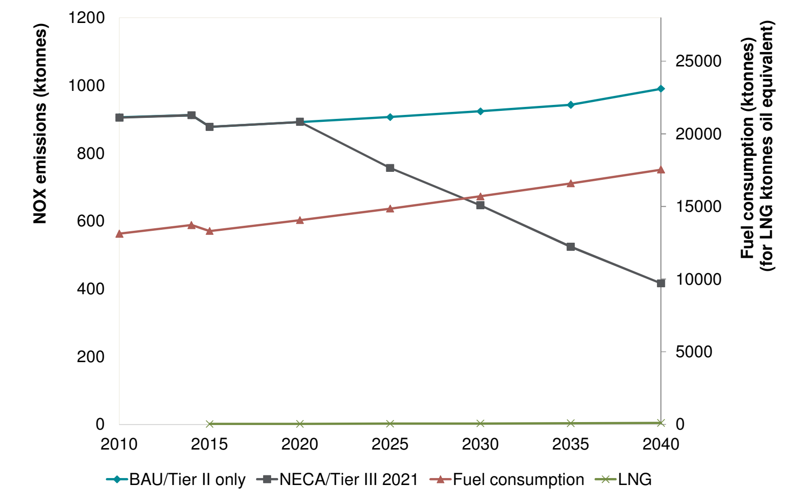


Figure A3 a) Projection of fuel consumption and NO_X in original scenario, b) Projection of fuel consumption and NO_X in a scenario without any traffic increase, and c) Projection based on future increase in CO_2 emissions from international shipping in the 3rd GHG report from MEPC; the scenario with the most increase by 2040 corresponds to annual increases of 3.2% n.b that no efficiency increase is included in this forecast.

Concluding remarks

The analysis emphasise the importance of accurate values for the three tested variables in NO_X projections; ship lifetimes, efficiency increase in shipping and traffic increase. Projections are always based on assumptions on future situations. Conclusions on definite values for input parameters should therefore be accompanied by arguments and plausible alternative developments. Of special importance to the presented study is the input parameter of efficiency increase in shipping. The values used in the original scenario seem optimistic and cause fuel consumption to be very stable over time despite an increase in ship traffic. Other projections expect fuel consumption from shipping to increase over time.

NO_X emissions follow fuel consumption. As shown in Figure A1, the Tier III regulation has a more rapid impact on reduced NO_X emissions if ships are replaced quickly. The two alternative cases tested for efficiency increase (Figure A2 b and c) are both assuming lower efficiency increases than the original scenario. Both those cases cause fuel consumption to grow over time, and the importance of the Tier III to uncouple NO_X emission trends from fuel consumption are clearly demonstrated. Similarly, the Tier III regulations are more important in a scenario with increasing ship traffic than in a scenario with slow or no ship traffic growth.

Additional reference:

International Maritime Organization (IMO) , 2009, Second IMO GHG study 2009; London, UK, Buhaug, Ø.; Corbett, J.J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K.

Appendix B. Cost details of abatement technologies

This section gives further details on costs related to Tier III technologies.

Selective Catalytic Reduction (SCR)
SCR is one of the most established and well-studied NO_X abatement technologies, which means lower uncertainties in the cost estimations compared to alternatives. SCR investment costs, per installed kW, depend on engine type and are usually lower for SSD engines than for HSD and MSD. SCR installed in new vessels cost much less than retrofit installations.

O&M costs comprise consumption of urea, catalyst replacement and labour costs. Typical costs for catalyst replacement are about 0.28-0.75 €/MWh, according to HELCOM (HELCOM, 2010). The interval for element replacement depends on various factors like operation conditions, fuel type, element type, and process control.

Available labour demand data is expressed in working hours per year. To recalculate this into $€_{2010}$/MWh, we use the interval of 1584-6648 hours spent at sea (IMO 2014), and vessel size interval of 3-25 MW (ENTEC 2005) so that the total MWh interval is between 4752 and 166200. The resulting labour costs are 0.002 - 0.06 $€_{2010}$/MWh.

Urea costs account for a large part of total O&M costs – about 80% in HELCOM, 2010, estimates and 79-81 % in this study. We use estimates for prices and consumption rates of 100% urea.

In Table B1 intervals of SCR costs parameters used in our analysis are presented, together with the number of parameter values available in the literature.

Table B1. SCR cost parameters

Cost parameter	Sub-category	Value	Original value	Original unit	Source
Investment, total, €$_{2010}$/kW	Retrofits	80-97	Used in this study		
	New	19-103			
	Not specified	97	90	€/kW	Bosch et al. 2009
		36	370 000	€/vessel ≈ 10 MW	Papadimitriou 2015
		29-97	30-100	€/kW	IMO 2013
	Both new and retrofits	52	54	€/kW	Danish Maritime Authority 2012
	New[9]	31-103	range	€/kW	NO_X fond
	SSD	27-54	28-56	€/kW	Danish EPA 2012
		36-59	36-59	€/kW	HELCOM 2010
	MSD, HSD, unspecified	24-60	25-62	€/kW	Danish EPA 2012
	MSD, HSD, new	29-70	29-70	€/kW	HELCOM 2010
	MGO	28	29	€/kW	HELCOM 2012
	new	53	49.3	€/kW	Campling et al. 2013
		19-24	40 000 -500 000	€/vessel ≈ 1.6-20 MW	Fagerlund&Ramne 2013
	retrofit	80	74	€/kW	Campling et al. 2013
Urea price, €$_{2010}$/kg	Total interval	0.17-0.18	Used in this study		
	Not specified	0.17-0.18	226	USD/tonne	HELCOM 2010
Urea consumption, kg/MWh	Total interval	6.5-16.5	Used in this study		
	Not specified	6.5	6.5	kg/MWh	IMO 2013
	Not specified	16.5	22.25	l/MWh	Bosch et al. 2009
Catalyst replacement, €$_{2010}$/MWh	Total interval	0.25-0.75	Used in this study		
	Not specified	0.25-0.75	0.25-0.75	€/MWh	HELCOM 2010
	Not specified	0.61	0.56	€/MWh	Bosch et al. 2009
Labour demand, hours/year	Total interval	8	Used in this study		
	Not specified	8	8	h/year	HELCOM 2010
Labour price, €$_{2010}$/h	Total interval	36	Used in this study		
	Not specified	36	33.3	€/h	Bosch et al. 2009

The total investment and O&M costs of SCR are estimated as ~ 110 – 820 €$_{2010}$ per tonne reduced NO_X from socio-economic perspective, and ~ 150 – 2030 €$_{2010}$ per tonne reduced NO_X from shipping company perspective

[9] Except for very small vessels with exceptionally high investment costs

Exhaust Gas Recirculation (EGR)
Investment costs of EGR depend on engine type and are usually lower for SSD engines than for HSD and MSD. O&M costs include, among other, fuel penalty and NaOH consumption costs. Other maintenance aspects might include, for instance, water treatment and handling sludge (Papadimitriou et al. 2015).

MAN tests (MAN 2010) indicate that fuel penalty of EGR alone is quite low, only about 0.3%, meaning the costs of 0.10-0.24 €$_{2010}$/MWh with fuel prices assumed in our calculations. Fuel penalty is more often assessed for combination of EGR with other technologies, such as WIF, HAM, or DWI.

In Table B2 intervals of EGR costs parameters used in our analysis are presented, together with the number of parameter values available in the literature.

Table B2. EGR cost parameters

Cost parameter	Sub-category	Value	Original value	Original unit	Source
Investment, total, €$_{2010}$/kW	New	36-60	Used in this study		
	SSD	36-43	37-45	€/kW	Danish EPA 2012
	HSD, MSD	44-53	46-55	€/kW	Danish EPA 2012
	Not specified	60	55.5	€/kW	Bosch et al. 2009
	Not specified	43-58	45-60	equation	IMO 2013
Fuel penalty, %	Total interval	0.3	Used in this study		
	Not specified	0.3	0.3	%	MAN 2010
NaOH consumption, kg/MWh	Total interval	4.5	Used in this study		
	Not specified	4.5	4.5	kg/MWh	Bosch et al. 2009
NaOH price, €$_{2010}$/kg	Total interval	0.19-0.36	Used in this study		
	Not specified	0.19-0.25	270-340	USD/ton	Reynolds 2011
	Not specified	0.36	0.5	€/kg	Bosch et al. 2009
Other maintenance, €$_{2010}$/MWh	Total interval	0.48	Used in this study		
	Not specified	0.48	0.48	€/MWh	Bosch et al. 2009

The total investment and O&M costs of EGR are estimated as ~ 140 – 490 €$_{2010}$ per tonne reduced NO_X from socio-economic perspective and ~ 210 – 1200 €$_{2010}$ per tonne reduced NO_X from shipping company perspective.

LNG
One of the available data sources for investment cost estimates for LNG engines is applications to the Norwegian NO_X-fond that show a cost span from 539 to 2280 €/kW. Rather low value (about 219 €/kW) is reported in MAN 2012. Retrofitting of existing vessels with LNG engines is an alternative option to new-builds, although it is very costly.

Historically, LNG price expressed per energy follows the HF price and lies slightly below it. However, since calorific value of LNG is about 22% higher than that of HF

(IMO 2014, Kristensen 2012), LNG prices per MWh are usually higher than for HF. In our calculations we use the LNG prices summarized in Table 6. Under the current assumptions (large price difference between LNG and MGO) shift from MGO to LNG results in cost savings whereas shift from HF to LNG brings additional fuel costs. However, since LNG is a SO_X abatement option, avoided scrubber costs in SECAs for HF vessels would at least partly compensate for extra fuel costs. The same applies to methanol vessels.

MGO prices are assumed to increase much more rapidly that HF prices since global demand for distillates will most likely increase. In Table B3 prices are expressed in €$_{2010}$/MWh; for recalculation we use specific fuel oil consumption from IMO 2014[10]. Both MAN 2012 and DMA 2012 assume that the future LNG price will be lower than both MGO and HF prices. Table B4 presents the operational costs associated with LNG fuel.

Table B3. Estimates of fuel prices in 2030

Source	Danish Maritime Authority 2012		MAN 2012		
Fuel	**€$_{2010}$/MWh**	**€$_{2010}$/tonne**	**€$_{2010}$/MWh**	**€$_{2010}$/tonne**	**USD/MMBtu**
HF	135-210	530	86-134	557	19
MGO	164-266	885	119-193	978	32
LNG	101	610	77	537	15

In Table B4 below, intervals of LNG operation costs parameters used in our analysis are presented, together with parameter values available in the literature.

Table B4. LNG operation cost parameters

Cost parameter	Sub-category	Value	Original value	Original unit	Source
Investment, total, €$_{2010}$/kW	Retrofits	1260	Used in this study		
	New	219-940			
	New[11]	539-940	range	€/kW	NO_X fond vessels
	Not specified	219-329	300-450	USD/kW	MAN 2012
	Retrofit	1260	74 000 000	USD/vessel ≈ 48 MW	DNV GL 2014
Extra fuel cost, €$_{2010}$/MWh	Total interval	43	Used in this study		

The total investment costs of LNG vessels are estimated as ~ 140 – 5200 €$_{2010}$ per tonne reduced NO_X from socio-economic perspective, and ~ 590 – 20000 €$_{2010}$ per tonne reduced NO_X from shipping company perspective. Fuel savings from switch from marine gasoil to LNG are estimated as 25 – 39 €$_{2010}$ /MWh. Profitability of LNG drift depends on the investment costs and fuel price development. With our assumptions, both profitable (at low investment price and large fuel price difference) and costly (at high investment price and small fuel price difference) options are possible.

[10] 166 g/kWh for LNG; 185-205 g/kWh for HF vessels; 195-215 g/kWh for MGO vessels
[11] Except for very small vessels with exceptionally high investment costs

Methanol
Since there are very few methanol vessel projects, cost data are scarce and uncertain. We use Stena 2014 estimates for engine conversion costs in €/kW. Important to note is that the cost calculations assume that only Tier II levels can be reached with methanol. However, with further development of the technology and tuning of the engine, it seems likely that Tier III levels will be reached in the future. For the cost calculations, reaching Tier III levels would reduce the costs per tonne NO_X.

Fuel-related costs or savings due to alternative fuel use depend greatly on price relationships between available fuels. Historically, methanol price has been following prices for HF and MGO although there is in general weaker correlation between methanol and diesel fuels than between HF and MGO. This is because methanol price follows pipeline natural gas price rather than crude oil price. Prior to 2008-2009, methanol prices per energy unit tended to be higher than MGO prices. Between 2009 and 2013 the global average methanol price was lower than that of MGO, but after 2013 methanol prices rose, and methanol became more expensive that MGO again.

Whether alternative fuels (methanol, LNG) are more or less expensive than conventional fuels (HF, MGO) is a crucial factor determining cost efficiency of fuel shift in terms of fuel expenses. In average, methanol and MGO are the most expensive fuels, whereas HF and LNG are less expensive. Our fuel price ranking based on European prices observed in November 2015 is very similar to the one presented in Fagerlund&Ramne 2013 – a recent study investigating LNG and methanol alternatives. However, the ranking might change over time, together with potential cost savings or extra costs related to fuel shift.

It can be assumed that, if the infrastructure around methanol as a marine fuel is further developed, the bunkering methanol prices will not be as high as for the first methanol vessels. It is also reasonable to assume that methanol price will continue to follow the natural gas price and thus crude-oil gas price relations will be crucial for future methanol-MGO price relations. The exact development of fuel prices (especially for methanol) is, however, very hard to predict.

In Table B5 intervals of methanol operational costs parameters used in our analysis are presented, together with the number of parameter values available in the literature.

Table B5. Methanol operations cost parameters

Cost parameter	Sub-category	Value	Original value	Original unit	Source
Investment, total, $€_{2010}$/kW	Retrofits/new	290-339	Used in this study		
	Conversion	290-339	300-350	€/kW	Stena 2014
Fuel price, $€_{2010}$/MWh	Total interval	45	Used in this study		

The total investment costs of methanol vessels are estimated as ~ 860 – 5300 $€_{2010}$ per tonne reduced NO_X from socio-economic perspective, and ~ 3500 – 20000 $€_{2010}$ per tonne reduced NO_X from shipping company perspective. Fuel savings from switch from marine gasoil to methanol are estimated as 23 – 36 $€_{2010}$ /MWh. From socio-economic perspective, methanol as marine fuel would be profitable even at higher investment costs if the fuel price difference remains substantial. From shipping company perspective, high investment costs may not always be compensated by fuel savings.

Slow steaming

From a vessel perspective, slow steaming economy is mostly associated with fuel savings and investment costs for engine upgrade kits (technical solutions that some engine producers offer for more efficient slow steaming). From a shipping company perspective, slow steaming results in additional investments costs for extra vessels needed to compensate reduced transport efficiency in tonne-km per year.

Since emission reductions from slow-steaming depend greatly on engine operation mode, it's impossible to analyse this option in terms of Tier-associated NO_X emission reductions, like it's done for other NO_X abatement alternatives. Profitability of this technology from a shipping company perspective depends on relations between fuel savings per ship and additional investment costs for engine upgrades and new ships. However, slow steaming's effect on the shipping service, which is probably the main factor influencing profitability.

Water-based technologies

There are three water-based technologies that can be used in combination with EGR if the EGR in itself does not fulfil Tier III requirements. Used without EGR, these technologies reach Tier II levels.

Humid Air Motors (HAM)

Cost data on HAM is very scarce and uncertain. ENTEC (2005) estimates investment costs for new and retrofitted units, as well as O&M cost intervals. These estimates are summarized in Table B6 below.

Table B6. HAM cost parameters

Cost parameter	Sub-category	Value	Original value	Original unit	Source
Investment, total, €$_{2010}$/kW	Retrofits	119-141	Used in this study		
	New	97-119			
	Retrofit	119-141	110-130	€/kW	ENTEC 2005
	New	97-119	90-130	€/kW	ENTEC 2005
OM, €$_{2010}$/MWh	Total interval	0.15	Used in this study		
	Not specified	0.15	0.15	€/MWh	ENTEC 2005

The total investment and O&M costs of HAM are estimated as ~ 340– 2200 €$_{2010}$ per tonne reduced NO_X from socio-economic perspective, and ~ 1200 – 8400 €$_{2010}$ per tonne reduced NO_X from shipping company perspective.

Direct Water Injection (DWI)

Main costs parameter for DWI is investments. Retrofitting an engine may require installation of additional cylinder heads for 4 stroke engines (ENTEC 2005), which significantly increase costs compared to DWI integrated into a new vessel. OM costs associated with consumption of distillate water. Available data on DWI costs parameters is summarized in Table B7 below. According to ENTEC (2005), costs data for DWI are highly uncertain.

Table B7. DWI cost parameters

Cost parameter	Sub-category	Value	Original value	Original unit	Source
Investment, total, €$_{2010}$/kW	Retrofits	54-81	Used in this study		
	New	21-41			
	Retrofit	54-81	50-75	€/kW	ENTEC 2005
	New	21-41	19-38	€/kW	ENTEC 2005
Water consumption, kg/MWh	Total interval	90	Used in this study		
	Not specified	90	90	g/kWh	ENTEC 2005
Water price, €$_{2010}$/kg	Total interval	0.022	Used in this study		
	Not specified	0.022	20	€/ton	Bosch et al. 2009

The total investment and O&M costs of DWI are estimated as ~ 700 – 2000 €$_{2010}$ per tonne reduced NO_X from socio-economic perspective, and ~ 900 – 5600 €$_{2010}$ per tonne reduced NO_X from shipping company perspective.

Water in fuel (WIF)

Data on investment costs for WIF is very scarce. OM costs include fuel penalty, which is often available only for combination of WIF and EGR. MAN (2010) gives estimates for WIF and EGR separately, and the test results indicate that the total fuel penalty of the combination cannot be calculated as a sum of the components. We note estimates for EGR+WIF combination but use MAN (2010) test numbers for WIF alone in calculations... Available data on WIF costs parameters is summarized in Table B8 below.

Table B8. WIF cost parameters

Cost parameter	Sub-category	Value	Original value	Original unit	Source
Investment, total, €$_{2010}$/kW	Retrofits/new	16	Used in this study		
	Not specified	16	15	€/kW	Bosch et al. 2009
Fuel penalty, %	Total interval	2.4	Used in this study		
	WIF only (50%)	2.4	2.4	%	MAN 2010
	WIF+EGR	2.5-3.9	2.5-3.9	%	MAN 2010
	WIF+EGR	1-2	1-2	%	Papadimitriou 2015
	WIF+EGR	4.7	5	%	Bosch et al. 2009

The total investment and O&M costs of WIF are estimated as ~ 590 – 1000 €$_{2010}$ per tonne reduced NO_X from socio-economic perspective, and ~ 740 – 1700 €$_{2010}$ per tonne reduced NO_X from shipping company perspective.

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