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NOX Abatement in the Baltic Sea

An Evaluation of Different Policy Instruments

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Preface

This report was written within the Vinnova project “New fuels and policy instruments for shipping; an analysis of the potential to reduce risks for the environment” number 2014-03560. Data for the analysis has been provided by the project partners The Swedish Shipowners Association, Stena and Chalmers University. We thank Carl Carlsson, Per Wimby, Selma Brynolf, Karin Andersson and Stefan Åström for their input.

Summary

In this report a number of policy instruments for controlling emissions of NO_X in the Baltic Sea have been studied. The background is the decision to establish a NO_X Emission Control Area (*NECA)* in the region requiring ships to follow Tier III NO_X emission regulations from 2021. To achieve further and more rapid reductions of NO_X emissions than what is expected from the NECA, additional policy instruments have been discussed. The policy instruments analysed in this study are assumed to be additional to the NECA requirements. Our study describes changes of emissions and costs for existing ships with Tier II engines when upgrading for lower NO_X emissions. Of the many existing technological alternatives to accomplish NO_X reduction, this study focuses on liquefied natural gas (LNG) engines and selective catalytic reduction (SCR) for after treatment of exhaust gas. Emissions of NO_X in 2030 are modeled for scenarios in which different policy instruments are assumed. The use of LNG and abatement equipment is modeled with the assumption that ship-owners choose the most advantageous option from a cost perspective.

The most effective policy instrument found in this study is the *refundable emission payment* (REP) scheme. The reduction of emissions depends on the fee and subsidy rate applied. For example, a subsidy rate of 60% and a fee of 1 €/kg NO_X is modelled to reduce the yearly emissions of NO_X from shipping in the Baltic Sea in 2030 by about 53 ktonnes. A NO_X tax will also have a significant effect on the NO_X emissions, but in this case the costs for ship-owners are significantly higher.

Applying a *CO_2 tax* or *environmentally differentiated port dues* in the model are found to have less impact on the NO_X emissions. Introducing slow steaming has a potential to reduce NO_X emissions In another scenario the effects on emissions from a *financial investments support* for abatement technology or LNG engines are modeled. At an interest rate of 0 % emissions are reduced significantly.

According to our model, an *extended NECA*, where also other sea areas than the Baltic and North Seas become *NECA*s, has no further impact on the NO_X emissions in the Baltic Sea. However, since the abatement equipment is used for more hours in a global NECA it will reduce the abatement cost per kg NO_X.

Sammanfattning

Ett antal styrmedel för att minska utsläppen av NO_X från sjöfart i Östersjön har studerats i denna rapport. Bakgrunden är beslutet att inrätta ett ”NOX emission control area” NECA i regionen så att fartyg måste följa Tier III NO_X-utsläppskraven från 2021. För att uppnå ytterligare minskningar av NO_X -emissioner har fler styrmedel diskuterats. De som analyserats i denna studie antas komma i tillägg till NECA-kraven. Vår studie beskriver förändringar i utsläppen och kostnaderna för existerande fartyg med Tier II-motorer som uppgraderas för lägre NO_X -utsläpp. Av de många befintliga tekniska alternativen fokuserar denna studie på motorer för förvätskad naturgas (LNG) och selektiv katalytisk reduktion (SCR) för efterbehandling av avgaser. Utsläppen av NO_X 2030 har modellerats för scenarier där olika styrmedel antas införda. Användning av LNG- och reningsutrustning har modellerats utgående från antagandet att fartygsägare väljer det mest fördelaktiga alternativet ur ett kostnadsperspektiv.

Det mest effektiva styrmedlet är systemet med NO_X-fond. Minskningen av NO_X-utsläppen beror av storleken på avgiften och subventionsgraden i systemet. En subventionsgrad på 60% och en avgift på 1 € / kg NO_X ger enligt modellen minskade utsläpp av NO_X från sjöfarten i Östersjön år 2030 med cirka 53 kton. En NO_X-skatt skulle också ha betydande inverkan på NO_X-utsläppen, men i detta fall är kostnaderna för fartygsägare betydligt högre.

Att tillämpa en CO_2-skatt eller miljödifferentierade hamnavgifter i modellen har en mindre inverkan på NO_X-utsläppen. Att införa hastighetsbegränsningar har en potential att minska NO_X-utsläppen. Även effekterna på utsläppen från finansiellt investeringsstöd för reningsutrustning eller LNG-motorer har modellerats och med en räntesats på 0% skulle utsläppen reduceras betydligt.

Enligt vår modell har ett utökad NECA, där fler områden än Östersjön och Nordsjön blir NECA, ingen ytterligare effekt på NO_X-utsläppen i Östersjön. Men eftersom reningsutrustningen används fler timmar per år i ett större NECA kommer kostnaden per reducerat kg utsläppt NO_X att minska.

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1 Introduction

The purpose of this study is to analyse policy instruments and measures in order to reduce the emissions from shipping in the Baltic Sea. The introduction of a NO_X Emissions Control Area (NECA) from 2021 will mean that in a long-term perspective the emissions will decrease but there is a need for methods to reach a more rapid decrease (see e.g. Winnes et al. (2016), Yaramenka et al. (2017)). A set of possible policy instruments have been chosen for analysis and the potential for reducing emissions is modelled by using abatement costs in combination with costs/subsidies inherent in the different instruments. The results are also discussed from a cost-efficiency perspective.

1.1 Policy Instruments for NO_X

For road traffic, mobile machinery and other sectors using combustion engines the tightening of emission regulations have been fundamental in reducing NO_X emissions. Tighter NO_X emission standard has e.g. cut the road transport sector's NO_X emission with two thirds in Sweden since 1990 (Naturvårdsverket, 2017). Also the industry in Sweden has managed to reduce their emissions with one third since 1990; one reason for that is probably the charge on NO_X that was introduced in 1992. This charge was originally set to 5.7 €/kg NO_X[1] and the money was refunded to the industry based on their output (Sterner & Isaksson, 2006).

For shipping there are less stringent emission regulations than for other sectors. The reason lies mainly in that these regulations are decided internationally by the International Maritime Organization (IMO) where agreements sometimes take a long time compared to what individual countries or states have achieved for road traffic. There have during the years been discussions about other policy instruments such as emission trading with NO_X, but this has not been realized (Nikoloulou, et al., 2012; IIASA, 2008). The following is a list of policy instruments that are or have been in place targeting NO_X emissions from shipping.

- Tier I and Tier II emission standards (World), Tier III (US Caribbean NECA)
- Emission regulations for marine engines used in inland waterway traffic (EU, US)
- The Confederation of Norwegian Enterprise NO_X fund, in Norwegian "Næringslivets Hovedorganisasjon" (NHO)
- Environmentally differentiated port and fairway dues

Emission regulations have been decided by IMO for marine diesel engines. The first regulations (Tier I) applies to engines from 2000; Tier II applies from 2011. There is also a Tier III that only applies in special NO_X emission control areas and with different starting years. There is a North American *NECA* where Tier III applies from 2016 and in the Baltic and North Seas it will be applied from 2021. This is further discussed in Section 1.2.1. Within the EU there are also emission regulations for marine engines used in inland waterway traffic (Directive 2016/1628/EU). The emission regulations are mandatory and are important drivers of methods and technologies to fulfil the standards. However, they apply to new engines only and thus significant reductions of emissions will not occur until older engines are phased out. Since marine engines and ships have lifetimes on the order of 30 years this period can be significant (see Winnes et al. (2016) for an analysis of the Baltic Sea *NECA*).

In Sweden there is since several years a system with rebate on fairway dues for ships with low emissions of NO_X. There was also a similar system for fuel sulphur content. The rebate system has stimulated ship owners with ships that operate in Swedish waters to invest and use NO_X abatement techniques. There are also several examples of ports giving rebates for ships with good environmental performance.

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[1] All currency rates in the report are first recalculated to correspond to 2016 prices and then converted to Euro

In Norway a NO_X-fund was created by the industry in 2008 as a response to the newly introduced NO_X *tax*. The original tax was set to 2.2 €/kg NO_X, but has been revised several times. This tax was perceived as rather high and the industry also argued that they could lower emission further if the revenue was refinanced to the industry. The industry and the state therefore signed an agreement in 2008, *Environmental Agreement on* NO_X *2011-2017*, which exempts all members of the agreement from the tax. All members instead pay a lower fee which goes directly to a fund (Hagem, Holtsmark, & Sterner, 2015; Sjofartsdirektoratet, 2011). The money in the fund finance investment and operation of NO_X reducing technologies. This policy instrument is called *refundable emission payment* (REP) and is further described in Section 2.2.8.

There are a number of indexes used for different purposes. They can be used for scoring to decide port fee rebates, fairway dues and in public and private procurement of transport services. Such indexes can thus be an important basis for different policy measures.

1.1.1 NECA

NO_X emissions are currently regulated by the International Maritime Organization (IMO). The regulation is divided into three different emissions standards depending on geographical area and which year the ship is built. The current regulatory framework for NO_X emission standards is illustrated in Figure 1.1. Tier I rules applies to all ships that are built between 2000 and 2011, while Tier II rules applies on all ship built from 2011 and onward. Since 2016 Tier III rules are applied in certain NO_X Emission Control Areas (*NECA*s). The North and Baltic Seas will most probably be a part of *NECA* in 2021 (MEPC 70/5, 2016). However, the decision to include Baltic Sea in *NECA* has not been officially finalized yet, that decision is expected to be taken in 2017.

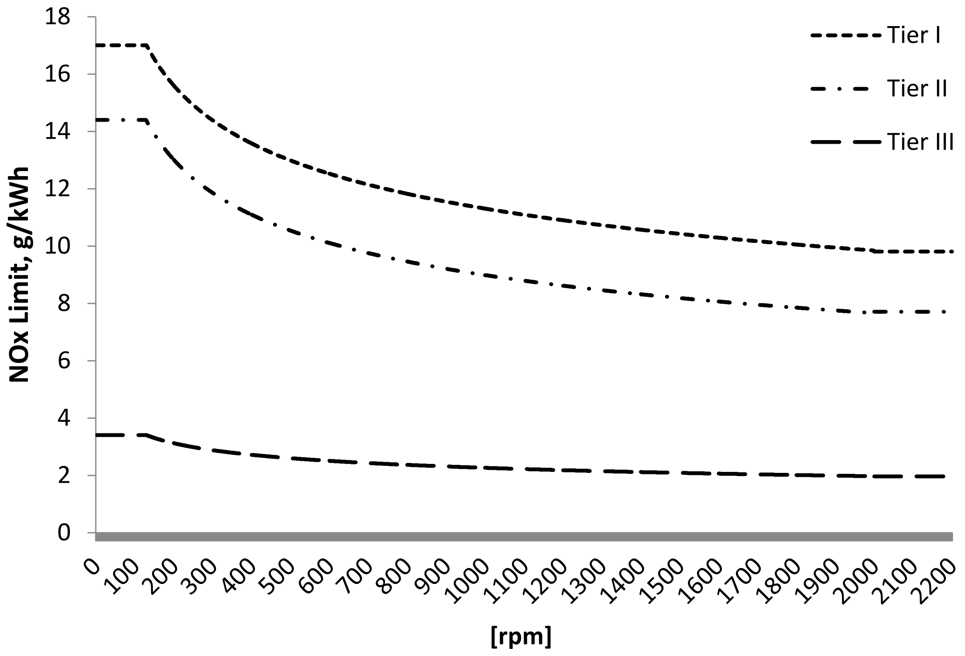

Figure 1.1 – NO_X emission standards for marine engines on ships in international shipping. The emission standard depends on engine speed (rpm) and which year the ship was built.

1.2 NO_X Emissions in the Baltic Sea

The total emission of NO_X from shipping in the Baltic Sea 2014 has been estimated to 320 ktonnes (HELCOM, 2015). The amount of NO_X emitted from shipping has been rather stable between 2008 and 2015 as can be seen in Figure 1.2. This is different from the land-based emission trend, where emissions have been decreasing steadily during the same period. The land based emissions in Sweden have, for example, dropped from 183 ktonnes in 2005 to 130 ktonnes in 2015 (Naturvårdsverket, 2017). The most significant drop has been due to reduced NO_X emissions from heavy vehicles.

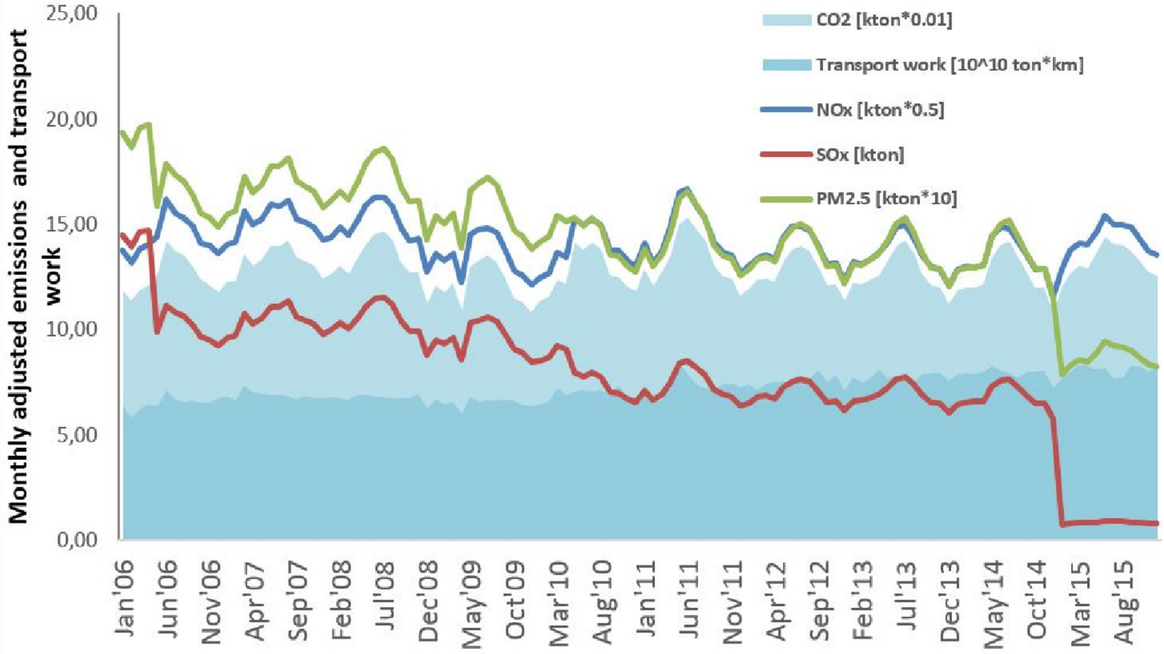

Figure 1.2 – Emissions and transport work for shipping in the Baltic Sea (Johansson & Jalkanen, 2016)

1.3 Abatement Technologies

Currently there are four fundamentally different ways to reduce NO_X emissions from marine engines: after treatment, combustion modification, fuel switch and reduced fuel consumption. A description can be found in Winnes et al. (2016). In this section the technologies studied in the analysis are described briefly.

The most frequently used after treatment method for NO_X abatement for ship engines is selective catalytic reduction (SCR) where NO_X is reduced over a base metal catalyst with an added reducing agent – normally urea which decomposes to form ammonia. The method has high activity for NO_X reduction and high selectivity towards forming N_2. The method works also for high-sulphur fuels although lower sulphur levels give better performance. There are some problems with operating SCR at low engine loads since the exhaust temperature needs to reach a certain temperature for the catalytic reactions to take place. SCR can reach 90% conversion of NO_X when the exhaust gas temperatures are 350° C and above, typically at high engine loads. The costs associated with SCR are the investment, the consumption of urea and intermittent replacement of the catalysts due to deactivation. On the other hand, the engine may be tuned to the most fuel efficient settings; this is often associated with high engines out NOX emissions which then are dealt with in the SCR system.

There are a number of different engine and combustion modifications that can be used to lower engine NO_X emissions. A number of methods introduce water to the combustion such as injection of water into the cylinders. In Exhaust Gas Recirculation (EGR) a portion of the exhausts are cooled and circulated back to the combustion chamber, which increases heat capacity of the cylinder gases and lowers the oxygen levels leading to lower combustion temperatures. EGR can be used to reach Tier III NO_X-levels and can be used on all types of diesel engines but is sensitive to fuel quality. It is preferred to have a fuel with low sulphur and impurities since high levels of particles and sulphur oxides recirculated into the engine may cause problems. Often a scrubber is used to clean the recirculated exhaust gas. Costs involved are for investments and for use of chemicals for the scrubber.

The most established ship fuel that may significantly lower NO_X-emissions is liquefied natural gas (LNG). There are different engine types where LNG can be used and common are dual fuel engines where a few percent of fuel oil is injected prior to LNG in the combustion cycle, in order to start ignition. LNG can also be used in Otto engines in which case no additional ignition fuel is needed. It is also possible to retrofit existing diesel engines for LNG. LNG engines typically reach Tier III levels. Costs are investment costs, retrofits are significantly more expensive than new builds, and fuel costs. Today only a small fraction of ships use LNG but an increase is expected.

There are different methods to reduce the fuel consumption of a ship. One important method is to reduce the speed whereupon the engine power used is also reduced. The emissions of NO_X will in general decrease, approximately following the fuel consumption. The costs are generally lower with this method through savings on fuel but costs for crew and capital may increase due to longer time spent for the same transport work.

1.4 Methods

The most important models and methods used in this work are summarised in Table 1.1. For further information see Chapter 2.

Table 1.1 – Models and methods used in this study

Method	Short description of method
Cost model	Costs are gathered from real world data for different abatement technologies. Furthermore, all costs are annualized to make different cost comparable (Bosch, et al., 2009).
Cost model for switch to LNG	The model evaluates the share of LNG given cost of fuel, abatement technologies and extra cost associated with specific policy instrument (Åström, et al., 2017).
Emission model	Emissions calculated in this study are based on the fuel consumption and emissions factors for NO_X. The emission factors are mainly based on the Tier regulations (Winnes, et al., 2016).
Ship categorization	The ships are categorized by ship type, engine size and engine speed, into what we call “ship segments” since these are associated with different costs and emission factors. Also, different ship segments are assumed to spend different amount of time in the Baltic Sea.
Stakeholder meeting	The selection of policy instruments and also some information was gathered at stakeholder meetings, involving industry and academia.
Literature review	All policy instruments in this study are studied in order to make assumption and construct possible scenarios. The emphasis on the literature search has been on real world experience of the selected policy instruments.

2 Methodology

The approach in this study is to analyse a number of policy instrument that are considered to have potential to reduce NO_X emissions from shipping in the Baltic Sea. The choice of instruments for analysis was made in collaboration with industry representatives and researchers in the project group. The instruments are analysed for the shipping in the Baltic Sea in 2030 from two aspects: expected impact on NO_X emission and costs of technology. The policy instruments studied are presented in the bullet list below.

1. *NECA*
2. *NECA5500 (NECA with extended geographical boundaries)*
3. *Slow steaming*
4. *Financial investment support (0% interest rate)*
5. *Environmentally differentiated port dues*
6. *CO_2 tax*
7. *NO_X tax*
8. *Refundable emission payment (NO_X-fund)*

2.1 General Methodology

The emissions are calculated using a previously developed model which is not described in detail here (Winnes, et al., 2016). The baseline emissions for 2012 are taken from results produced by FMI and published by HELCOM. The baseline projection up to 2030 is then produced using assumptions on increase in fuel efficiency and increase in transport work taken from Kalli et al. (2013). The model differentiates between different ship types and different engine sizes. For the different policy instruments it is assumed that the ship owners respond to the assumed regulations in a rational way in the meaning that they take actions to minimize costs. In this way the response in, e.g., conversion to Tier III standard using SCR to a NO_X-tax may be calculated and thus the change in emissions. The costs for the different abatement methods are mainly taken from Åström et al. (2017) and reflect the result of literature searches and interviews with stakeholders.

2.1.1 Ship Categories

The calculation model in this study is based on key input parameters for different ship categories. The input parameters are divided in ten different ship categories, listed in Table 2.1. This categorization is essential since the cost model described in Section 2.1.2 and emissions model in Section 2.1.3 are based on this categorization. The overall methodology for this categorization is further described in Winnes et al. (2016). Fuel consumption data for shipping in the Baltic Sea are gathered from Kalli et al. (2013) and can be found in Appendix A. All ship categories are dived into segments with three different engine sizes (Appendix A) and three different engine speeds, implying that each abatement technology is evaluated for 90 different ship segments.

Table 2.1 – Ship categories in this study.

Ship category
Bulk carrier
Chemical tanker
Container ship
General Cargo
LG tanker
Oil tanker
RoRo cargo

Ferry
Cruise
Vehicle carrier

2.1.2 Cost Model

Each abatement technology analysed in this study is accompanied with economic costs or savings for the ship owners/operators. The costs are important for the potential success of a technology on the market, although also other factors may have a significant impact on the demand of a technology. All costs are presented with minimum, central and maximum cost values. In all tables and figures this cost will be referred to as low, central and high costs. This range depends on that prices differ between different installations on similar engines and ships, but most often has to do with different characteristics of different engines. There are also price differences between new installations and retrofits. All cost components can be found in Appendix B.

The cost calculations comprise investment costs, including installation costs when available, and operation and maintenance costs (OM). For each technology, additional costs (or savings) are presented in €$_{2010}$ per kg removed NO_X, and per cost component. The calculations for SCR, EGR and the water-based technologies are based on the assumption that marine gasoil is used as fuel.

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

$$I_{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \tag{2.1}$$

Where:

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

The annual costs are calculated from what we have chosen to call "Private perspective" (PoP) and "Social perspective" (SoP) differing in assumed interest rate and investment lifetime. These two perspectives are summarized in Table 2.2. In this study, we use the private perspective to model decisions on investments.

Table 2.2 – Summary of the two different cost perspective which are used in this study

Name	Abbreviation used in tables and figures	Interest rate	Investment lifetime
Social perspective	SoP	4%	equipment lifetime[*]
Private perspective	PoP	10%	10[**] years

[*] Average lifetime for all considered technologies is the same as a vessel lifetime and assumed to be 25-29 years (Kalli, et al., 2013).

[**] The same values as used in Höglund-Isaksson 2012 that also analyses social and private cost perspectives.

Operation and maintenance (O&M) costs include different components and are described more in detail for each technology in Appendix B.

Total scenario costs are only calculated from a social cost perspective. The scenario costs include the following components:

- Technology costs (specified in Appendix B for SCR, EGR and LNG)

- Fuel costs (we use fuel price values from Danish Maritime Authority 2012 given in Appendix B)
- Port and fairway dues
- Scenario-specific components such as taxes

The main focus in this study is scenario-specific cost components associated with the abatement technologies. However, the fuel price is the most uncertain component in the 2030 scenario. The fuel price is therefore also studied in a sensitivity analysis.

2.1.3 Emission Model

The emissions in this study are derived from the fuel consumption of each ship segment, specific fuel oil consumptions in different engine types, and the emission factors for NO_X in Table 2.3. It is important to notice that also efficiency measures and increased traffic is encountered for in the model. All input data are found in Appendix A.

Table 2.3 – Emission factors for marine engines with different speeds under the three Tiers of the NO_X regulations and prior to regulations (Tier 0) (Cooper & Gustafsson, 2004a; Cooper & Gustafsson, 2004b). LNG is assumed to fulfil Tier III requirements. MD = Marine Distillate Oil

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/ MD	500	2.6	2.6	2.6	2.6

2.1.4 Share of Fuel Consumption being LNG

This study assumes that the introduction of *NECA* will result in additional investments in LNG vessels compared to the scenario where there is not a *NECA* (No-NECA). To estimate the share of new and existing vessels fuelled by LNG as response to policy instruments we use a cost-saving function, Equation (2.2), based on potential savings for a shipping company associated with this investment decision. All costs in Equation (2.2) are in € per year per vessel, calculated with respect to time of operation in *NECA*.

$$\text{Realtive cost savings} = \left(1 - \frac{\Delta LNG_{Cost}}{\Delta MGO_{Cost}}\right) \rightarrow \text{CS} = \left(1 - \frac{\Delta F_{LNG} + \Delta T_{LNG}}{\Delta F_{MGO} + \Delta T_{MGO}}\right) \qquad (2.2)$$

In the relative costs saving function described in Equation (2.2), we include extra fuel costs (ΔF), and extra cost of abatement technologies (ΔT). More precisely, extra cost of the abatement technologies include additional costs of an LNG engine compared to a conventional engine, as well as SCR-related costs for MD fuelled vessels. EGR costs are estimated to be 25-30% lower than SCR costs. Thus we apply a conservative approach to rather underestimate than overestimate the relative cost saving and compare LNG technology costs by analysing costs of SCR instead of costs for EGR.

The LNG share of the fuel consumed by ships in the Baltic Sea is derived by evaluating the potential cost savings of a switch to LNG as described in Åström et al. 2014. This analysis of additional LNG consumption and corresponding decrease in marine distillate oil (MD) consumption for 2030 is done separately for each ship segment. Furthermore, it is assumed that both new and existing vessels have the option to switch to LNG.

2.2 Different Policy Instruments

In this study we evaluate eight different policy instruments, which are listed in the beginning of this chapter. However, different features are evaluated for different policy instrument. These differences are outlined in each section.

*NECA*s in the Baltic Sea and the North Sea are assumed to be introduced meaning that new ships from 2021 will have to follow the Tier III standard. All other policy instruments are assumed complementary, i.e. on top of *NECA*. *NECA* is therefore used as a baseline scenario. The results are presented for the Baltic Sea only.

All policy instruments are assumed to result in the same transportation work (tonnes-km), implying that the fuel consumption (counted as energy content) in the Baltic Sea is the same for all scenarios except in the *slow steaming* scenario. Furthermore, we assume that retrofitting is only of interest for Tier II-vessels, not Tier 0 or Tier I since these ships are assessed to be too old for such investments.

2.2.1 NECA

The main features investigated for the introduction of *NECA* concern additional use of LNG and generating a baseline for emissions 2030. In the *NECA* scenario we assume that 50% will choose SCR and 50% will chose EGR to comply with Tier III regulations.

As a reference to the *NECA* scenario this study also analyse a scenario with the same basic assumption about traffic increase and efficiency measures, however in this scenario Tier III rules are not established. This reference scenario is referred to as No-*NECA*. Input data, assumption and methods for the No-*NECA* scenario are taken from another study (Winnes, et al., 2016), and are described in more detail there (see also Appendix A).

2.2.2 NECA with Extended Geographical Boundaries: NECA5500

As previously mentioned *NECA* is only assumed to be introduced in the North Sea and the Baltic Sea, implying that ships operating partly in that area may choose to turn of abatement equipment when operating outside the area. An introduction of *NECA* in more areas would cause ships to use abatement equipment at all times of operation, implying lower cost per kg of NO_X abated since the investment costs would be split over more usage hours.

In this scenario it is investigated how the cost per abated kg NO_X is affected if the average time spent in *NECA* is set to 5500 hours, implying that ships use their NO_X abatement technologies at all times. 5500 hours are assumed to be the average annual operational time for ships.

2.2.3 Slow Steaming

Slow steaming means that top or average speeds are restricted. *Slow steaming* is already quite common in port areas or in proximity to port areas due to safety or environmental concerns (Faber, et al., 2012). However, *slow steaming* practices have also been applied amongst shipping companies without any regulation in order to save fuel (Meyer, Stahlbock, & Voß, 2012).

A frequently sited physical relationship between the fuel consumption per time and speed is that the power of the engine is proportional to the third power of the ship speed (Corbett, et al., 2009; Doudnikoff & Lacoste, 2014; Faber, et al., 2012). A simplified relation is sometimes used to describe this relationship, see Equation (2.3) (Doudnikoff & Lacoste, 2014).

$$F_{new} \approx F_{old} \cdot \left(\frac{V_{new}}{V_{old}}\right)^3 \quad (2.3)$$

where F is the fuel consumption and v the ship speed. Meyer et al. (2012) argue the physical relation between the fuel consumption and the speed is so complex that general explanations describing the cost and benefits of slowing steaming speeds are difficult. Due to this complexity and the fact that *slow steaming* has been reviewed in many other reports, this study will only present the results from the findings in those reports. Table 2.4 summaries some key cost components, to get an idea of the complex relationship between the slow speed and cost/benefit.

Table 2.4 – Key cost components for slow steaming discussed in Faber et al. (2012)

	Cost components	Short description of the cost treated in the report	Key model assumptions
Direct costs	Higher inventory costs	The cost of the cargo is higher, since each ship spends more time at sea, e.g. cost of insurance and storage increase.	The average transit time increases with 12 days. This time is then financed by assuming an interest rate of 10%. The value of the goods that needs to be financed is assumed to correspond to 60% of global exports.
	Additional ship	More ships are needed in order to compensate for the transportation work that is lost.	Higher capital and OM costs associated with additional ships.
	Engine modification	The engine needs to be optimized for slow speeds.	A fixed cost of $200 000 is added to every ship.
	Monitoring	Speeds need to be monitored in order to ensure that the regulation is followed.	Monitoring costs are assumed to be low.
Direct benefits	Fuel savings	Less fuel is used, due to the relationship described in Equation (2.3).	Future fuel prices are based on project from European commission.
	Logistical chains	Logistical chains needs to be adapted since ships spends more time at sea	Logistical chains costs are not quantified in the report
Indirect costs	Less development of fuel-saving technologies	Slower speed will decrease the demand of fuel saving technologies. Regulated *slow steaming* may therefore distort competition and be a more costly option for society.	Not quantified in the report
	Lower direct emissions	Emissions damage society, such as global warming, eutrophication, acidification and air pollution.	The damage cost of emission is evaluated using pre-determined external costs. Discount rate is assumed to be 2.5 %
External benefits	Higher emission associated with ship building	More ships are required to compensate for lost transportation work.	Emissions from steel fabrication and the building process.
	Fewer collisions between boats and whales		Not quantified in the report

2.2.1 Financial Investment Support

One concept that has been debated is to give shipping companies 0% interest rate on their capital investment when investing in abatement or cleaner technologies. Since the lenders do not receive compensation for the loan this type of *financial investment support* could be seen as a subsidy scheme. There are mainly four costs which the lenders are subsidising in this scenario:

1. Risk
2. Inflation
3. Risk-free interest rate
4. Transaction cost

In the case of a shipping company, the most important parameter is probably the risks associated with the lending. We have developed a scenario reflecting an investment support option where the interest rate is set to zero. In this study the zero interest rate on investment is used as a proxy for 0% interest rate on a bank loan. However, in practice this interest rate includes all costs in the list above.

The private perspective costs in the cost savings calculation are modelled using 0% interest rate. We assume in the scenario that this only applies to LNG engines, not SCR or EGR technologies, in other words, this investment support is primarily aimed at increased the use of LNG rather than other NO_X abatement technologies.

2.2.2 Environmentally Differentiated Port Dues

One way of indirectly subsidizing NO_X abatement is by reducing the port due for ships arriving to the port. This system has been practiced in different formats in Sweden since 1999 (Kågeson, 2009). However, the level of the rebate varies from port to port, from technology to technology and between different types of ships (Göteborgs Hamn, 2016; Stockholms Hamnar, 2015). The port of Gothenburg for example introduced a 30% rebate on all LNG ships in 2015, in cooperation with the port of Rotterdam (Göteborgs Hamn, 2014; Göteborg Hamn, 2015; Göteborgs Stad, 2015). In the port of Stockholm a reduction of 0.05 SEK per gross ton for LNG ships was introduced in 2015 (Stockholms Hamnar, 2015).

In many ports ships that score high in Clean Shipping Index (CSI) or Environmental Ship Index (ESI) get a rebated port due. CSI will also be used as a basis for rebate of fairway dues in Sweden from 2018. In both CSI and ESI emissions to air of NO_X and other pollutants are important components. Ships that use LNG as fuel can be expected to score high in these systems and thus get a rebate on port dues.

As an example this study investigates the potential impact of an introduction of a rebate for LNG ships. In this analysis, we consider the case of 20% rebate on port fees in all Swedish ports in case vessels are LNG fuelled. This case is compared to the baseline case where we assume that no LNG-related rebate is provided. In reality, some of the ports do have LNG rebates for port fees (1-6% in Stockholm, 30% in Gothenburg, 40% in Ystad). However, to investigate the full potential of this policy instrument compared to the “no LNG-rebate” scenario (not with the actual baseline where LNG rebates already are present) we do not include the existing fees in the comparison.

This study thus investigates the effect of the additional cost component ΔA included in Equation (2.2) corresponding to the difference in the annual port dues that are lower for LNG fuelled ships than for MD fuelled ships.

Annual port dues (A) for each ship category are calculated with Equation (2.4) below.

$$A = calls \cdot GT \cdot port\ dues \tag{2.4}$$

where:

$calls$: Average number of calls per ship and year (Sjöfartsverket, 2011; Kalli, et al., 2013).

$port\ dues$: The port fee per call, €/ GT

GT: Gross tonnage (GT) per ship.

Annual costs for port fees depend on the number of calls. We apply the number of calls in Swedish ports in 2030 based on the call statistics for 2009 (Sjöfartsverket, 2011), and number of ships in Kalli et al. (2013) for each ship segment, see Appendix E. We assume that there are no significant variations in the number of calls depending on ship size. Gross tonnage per ship is calculated based on the Sea-Web ship database (IHS Markit, 2016). Port fees assumed here are averaged values based on information from current price lists of several large ports in Sweden (Gothenburg, Helsingborg, Stockholm, Ystad, Malmö, Trelleborg, and Visby). All port fees and a conversion table between gross tonnage and engine sizes can be found in Appendix E.

2.2.3 CO_2 Tax

The *CO_2 tax* in this study is used as proxy for a tax on fuel. The CO_2 emissions from ships are related to the carbon content in the fuel and are therefore not directly related to NO_X emissions. However, it may affect NO_X emissions since the tax influence the end user fuel price differently. The purpose of the CO_2 tax scenario is therefore to investigate if LNG use increases and if that in turn will imply further NO_X abatement compared to the *NECA* baseline scenario. The main difference compared to the *NECA* baseline scenario is that there is an additional cost component ΔT_i included in the *Extra Cost* in Equation (2.2) corresponding to the difference in the annual tax payments that are lower for LNG fuelled ships than for MD fuelled ships.

Fuel-specific annual tax (T_i) for each ship segment is calculated with Equation (2.5) below.

$$T_i = Fuel \cdot EF_i \cdot Tax_{CO_2} \cdot CV \tag{2.5}$$

Where:

$Fuel$:	Fuel consumption per ship segment (PJ)
EF:	CO_2 emission factor for engine type i(g CO_2/kg fuel)
Tax_{CO_2}:	CO_2 tax (€/kg CO_2)
CV:	The calorific value of the fuel (PJ/kg)

Emission factors for CO_2 used in this study – 3179 g/kg for MD and 2736 g/kg for LNG – are based on Cooper & Gustafsson (2004b).

The analysed size of the tax is 0.052-0.363 €/kg CO_2, with a central value of 0.118 €/kg CO_2. These estimates are based on the numbers presented by the European Commission (EC, 2014) and the Swedish Transport Administration (Trafikverket, 2016), investigating external costs from CO_2 emissions. The central value is chosen with respect to recommendations in the latter report (Trafikverket, 2016) and represents the current value of the Swedish *CO_2 tax* for gasoline[2]. Note that the tax is assumed to apply only to CO_2 and not to other green-house gases such as methane or nitrous oxide. This is important since LNG fuelled ships emit more methane that oil fuelled ships (Trafikanalys, 2016a).

2.2.4 NO_X Tax

In this study we investigate a *NO_X tax* scheme. We assume that Tier II ships will retrofit with SCR, since SCR is the most established technology used for retrofitting. The cost for using SCR is described in Equation (2.6).

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[2] 0,27 €/l (Skatteverket, 2017), assuming that the CO_2 emissions from one litre of gasoline is 2.25 kg (EC, 2014)

$$\begin{aligned} &Cost\ of\ abatement\ with\ SCR\ per\ year \\ &\qquad = Annualized\ investment\ cost + \ labour\ cost + (urea\ cost \cdot t) \\ &\qquad + (catalyst\ cost\ \ \cdot t) \end{aligned} \tag{2.6}$$

Where:

t: time (hours)

Equation (2.6) may be divided between costs depending on fixed costs and operating costs (OM):

$$SCR_{cost}(t) = OM_{cost} \cdot t + Fixed_{cost} \tag{2.7}$$

Where:

OM_{cost}:	urea cost and catalyst replacement cost
$Fixed_{cost}$:	Annualized investment cost and labour cost

The annualized investment cost component (I_{an}) is further described in Section 2.1.2. Each shipping company may decide if they want to abate or not. One method for this decision process can be found in economic literature (Sterner & Coria, 2012). The method is derived from the function that maximizes each shipping company's (s) profit (π). The profit maximization function is described as follows:

$$max\colon \pi_s = \ P \cdot q_s - c_s(a_s, q_s) - Tax_{NO_x} \cdot e_s(q_s, a_s) \tag{2.8}$$

Where:

Tax_{NO_x}	the tax in €s per emission
P	the price per unit of output
q_s	the quantity of the output.

The output may for example by transportation work expressed in tonnes-km or passenger-km. Both the cost (c_s) and the emission (e_s) components for the shipping company is dependent on the cost of abatement (a) and the quantity (q) produced. Equation (2.8) is simplified in equation (2.9).

$$Profit = Revenue - Cost - Tax_{NO_x} \tag{2.9}$$

Two first order conditions (FOC) can be derived from equation (2.8) and those are expressed in equation (2.10) and (2.11):

$$P = c_q' + Tax_{NO_x} \cdot e_q' \tag{2.10}$$

$$c_a' = -Tax_{NO_x} \cdot e_a' \tag{2.11}$$

Equation (2.10) implies that the ship would not operate in the zone if the price of its output (product) is lower than the marginal output cost (c_q') and the marginal cost of paying the tax ($T \cdot e_q'$). Equation (2.11) implies that a vessel will abate if the marginal cost of the abatement technology (c_a') is equal to or greater than the tax times the marginal abatement. The marginal abatement cost reflects the cost of one additional unit of pollution that is abated.

In our study, the tax level where a vessel decides to abate rather than to pay the tax, the relation described in Equation (2.11), would correspond to the yearly cost of SCR divided with the yearly abatement with SCR (if the ships has no abatement equipment installed already):

$$T = -\frac{c'_a}{e'_a} \rightarrow Tax_{NO_x}(h) = \frac{OM_{cost} \cdot t + Fixed_{cost}}{t \cdot AF_{NO_x}} \qquad (2.12)$$

Where:

AF_{NO_x}: Abatement factor [kg NO_X/h].

The abatement is assumed to correspond to Tier III emission levels. This assumption is made since it is possible to extract updated investment costs for this type of retrofitting. The abatement factor, AF_{NO_x}, corresponds to the ones in Table 2.3, times the average rated power of the main and the auxiliary engines for each ship segment. The ship segments are further explained in Section 2.1.1. The cost function for each ship corresponds to Equation (2.6).

The operational costs are related to the operational time at the Baltic Sea and the fuel consumption. However, the fixed cost such as capital investments are not related to the operational time at the Baltic Sea but are instead only dependent on the installed power of the engines.

Equation (2.12) is illustrated in Figure 2.1, from the private perspective (seeTable 2.2). The emissions are based on assumed average operational time in the Baltic Sea. Each square represents a given ship segment. The width of each square on the X-axis in Figure 2.1 corresponds to each ship segment's total yearly abatement (kgNO_X) if all ships in that segment decide to abate. The Y-axis corresponds to the tax level at which that ship segment would abate rather than pay the tax.

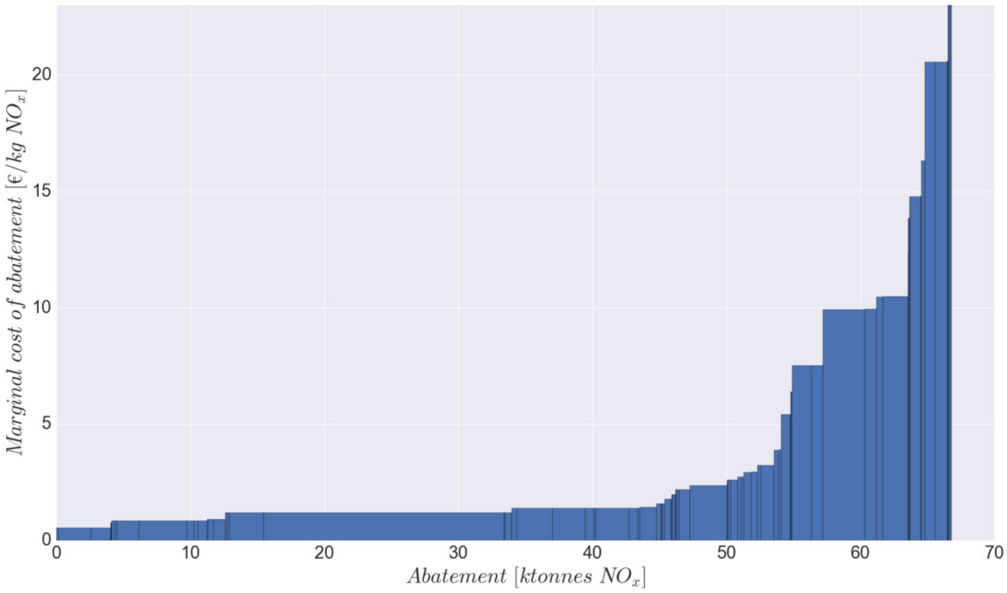

Figure 2.1 – Example on marginal cost of abatement with SCR for Tier II ships, 2030 Scenario. The length on the x-axis corresponds to the potential abatement for one ship segment. However, the cost is based on the average hours of operation in the 2030 Scenario in the Baltic Sea, see Table 2.1.

The marginal cost of abatement depends on the operational time of the ships in the area. One issue with the cost illustrated in Figure 2.1 is that this cost is based on the average operational time for each ship segment. However, each ship in every ship segment will be operating different times in the area and an average value is a poor representation of the actual situation. A theoretical function representing the data is therefore used in the analysis. If the tax is constant, Equation (2.12) may be rewritten accordingly:

$$t_{Tax} = \frac{Fixed_{cost}}{NO_x \cdot Tax_{NO_x} - OM_{cost}} \tag{2.13}$$

Under the condition that $NO_x \cdot Tax > OM_{cost}$ it is possible to calculate how many hours (h_{Tax}) a ship needs to operate in order to make the investment in SCR profitable compared to paying the tax. The details behind this calculation can be found in Appendix F.

2.2.5 NO_X Fund

The NO_X *fund* is a type of *Refundable Emissions Payment* (*REP*) and the theory behind it is explained in economic literature (Sterner & Coria, 2012, pp. 112-115). *REP* is a two-part price-type instrument including both a charge and a refund. The refund may for example be based on output or expenditures. One example on an expenditure based *REP* scheme is the Norwegian NO_X *fund* (Hagem, Holtsmark, & Sterner, 2015) and one example of the output based *REP* scheme is the one applied on energy, manufactory and incineration sectors in Sweden (Sterner & Isaksson, 2006). In this study we are modeling a *REP* scheme similar to the Norwegian NO_X fund.

The Norwegian NO_X *fund* is an Expenditure Based (EB) type of *REP* since the refund is based on expenditure on abatement technologies. The NO_X *fund* was created by the industry in 2008 as a response to the newly introduced NO_X *tax*. All members in the NO_X *fund* pay a fee of 0.44 or 1.21 €/kg NO_X directly to the fund (Hagem, Holtsmark, & Sterner, 2015; Sjofartsdirektoratet, 2011; NHO, 2016b). Approximately 99% of the companies that are obligated to pay the NO_X *tax* have joined the fund and therefore pays the fee to the NO_X *fund* instead of the tax, see Appendix C.

The following project applications have priority in the Norwegian fund:

- projects that may be implemented quickly
- projects that have a high cost-effectiveness
- projects that have high likelihood of being implemented
- complete application
- the applicant is paying the fee to the fund
- if the candidates are equal according to the criteria above, priority is given to early applicants

Also measurement of NO_X emissions are subsidized by the fund, however this is not considered in this study.

Since we are looking at the yearly emission 2030 we assume that there is enough time for all applicants to project and install SCR. However, some may install it in the beginning of the period and some in the end of the period. In our model the *REP* scheme is introduced in 2020 and ends in 2030. Due to the similarities of the tax and the *REP* scheme the same basic assumptions and conditions are used on the *REP* scheme as the tax levy described in Section 2.2.7.

The equation bellow describes the profit maximization function of a shipping company under an *REP*-scheme (Hagem, Holtsmark, & Sterner, 2015):

$$\pi_s = p \cdot q_s - c_s(q_s) - (1 - s) \cdot m_s \cdot y_s - fee_{NO_x} \cdot e_s(r_s, y_s) \tag{2.14}$$

Where:

s: the subsidy degree of the investment.

r_s: represents the reduced output.

fee_{NO_x}: the fee for members in the fond (€/kg NO_X)

A simplified version of equation (2.14) is presented in Equation (2.15).

$$Profit = Revenue - Cost - Fee + Refund \qquad (2.15)$$

If a shipping company is maximizing its profit (π_b) in Equation (2.14) the ”first order conditions” in 2.16 and 2.17 are obtained.

$$\frac{(1-s)\cdot m_i}{á_{sy}(r_s, y_s)} = fee_{NO_x} \qquad (2.16)$$

$$\frac{p_s - c'_s}{á_{sr}(r_s, y_s)} = fee_{NO_x} \qquad (2.17)$$

Equation (2.16) is the marginal private abatement cost. A comparison with the equation for marginal social cost for the fee, Equation (2.11), shows that the subsidy rate is the only factor different from the fee. Putting the factor $(1-s)$ in Equation (2.12) and then rewriting it in the same way as (2.13) gives us the equation 2.18, describing the time needed to make the SCR investment profitable over paying taxes.

$$t = \frac{Fixed_{cost}\cdot(1-s)}{NO_x\cdot fee_{NO_x} - OM_{cost}} \qquad (2.18)$$

In Equation (2.18) the subsidy is only applied on the fixed cost. Since the Norwegian NO_X *fund* has two different subsidy rates (s_{OM} and s_{Fixed}), the subsidy has also been applied on the operational cost in Equation (2.19).

$$t = \frac{Fixed_{cost}\cdot(1-s_{Fixed})}{fee_{NO_x}\cdot NO_x - OM_{cost}\cdot(1-s_{OM})} \qquad (2.19)$$

Only the *REP* scheme in Equation (2.19) is analyzed in this study. In this study: $s_{Fixed} = s_{OM}$.

There is a condition in the model representing the maximum subsidy allowed. The subsidy cannot be greater than available funding. The budget constraint is described in Equation (2.20).

$$s = \frac{fee_{NO_x}\cdot E}{\sum_{i\epsilon F}(m_b\cdot y_b)} \qquad (2.20)$$

The subsidy rate in this study is therefore limited by the total sum paid to the fund. However, in the case of the Norwegian NO_X fond the shipping sector gets more refund than they are paying to the fund. This is possible since some sectors, mainly the offshore oil and gas industry, are paying more to the fund than what is refunded to them (NHO, 2016b). This study therefore also investigates what happens if more resources are given to the fund than what is provided by the shipping industry.

The subsidy rate for a given fee level is calculated by deriving the total emission during the time period. The emissions E are the emissions for the whole Baltic fleet during the time period 2020 and 2030. However, in reality many ships are going between different ports that are not a part of the *REP* scheme, they would therefore be exempted from paying the fee. That would result in a lower subsidy level. It is also important to consider the timeframe for the *REP* scheme. In this study we assume that the *REP* scheme is carried out between 2020 and 2030, and only Tier II ships have the possibility to apply for the subsidy even though the whole fleet is paying to the fund. The total emissions for this period are given by the following relation:

$$E_{2020\to 2030} = \sum_{year=2020}^{2030} e_{year} = e_{2020} + e_{2021} + \ ... + e_{2030} \tag{2.21}$$

The subsidy level in Equation (2.20) depends on the total emission (E), however the emission each year (e_{year}) are also related to the abatement and the abatement is in turn related to the subsidy level. This study consider that the emissions depend on both the emission reduction that follows the introduction of *NECA*, but also the hypothetical abatement that will occur due to the introduction of the *REP* scheme. We therefore use the emission estimate for 2020, e_{2020}, from Kalli et al (2013) and the emission estimate 2030 for a given tax and a given subsidy level from this study, e_{2030}, to estimate the emission for the whole time period, see Equation (2.22).

$$E_{NECA\ \ 2020-2030} = \ 10 \cdot \frac{e_{2020} + e_{2030}}{2} \tag{2.22}$$

Where:

e_{2020}: 265 ktonnes NO_X, assuming that 32% of emissions in *NECA* occurs in the Baltic Sea.

This estimate is uncertain. Therefore an uncertainty analysis is conducted where the upper value of the emissions is set by assuming that the emission increases with 70 ktonnes until 2030. The lower limit of the total emission is set by assuming an additional yearly average abatement of 165 ktonnes during the time period.

Upper limit of emission: $E_{2020\to 2030} = \ 10 \cdot \frac{e_{2020}+e_{2030}}{2} \to 10 \cdot \frac{265+265+70}{2} = 3000 \text{ ktonnes}$

Lower limit of emission: $E_{2020\to 2030} = (e_{2020} - 165 \text{ ktonnes }) \cdot 10 = 1000 \text{ ktonnes}$

These three emission estimates reflect the scenario where the whole fleet is paying to the fund, but only Tier II ships get refunding. However, in order to illustrate what would happen if only Tier II were paying to the fund this study also puts up a reference scenario where the total emission during the time period is 500 ktonnes of NO_X.

This study assumes that OM costs are subsidized for a 10 years period. However, the OM subsidy for the whole period must be covered by the fund from the first year. The maximal subsidy level is therefore calculated with the following equation:

$$\begin{aligned} E_{2020\to 2030} \cdot fee_{NO_x} = s_{OM} \cdot 10 \cdot \sum_{i=1}^{90} OM_{cost,i} \cdot t_i + s_{INV} \\ \cdot \sum_{i=1}^{90} Investment_i \cdot number\ of\ ships_i \cdot SCR_{\%,i} \end{aligned} \tag{2.23}$$

If we then apply $s_{OM} = s_{fixed} = s$, it is possible to calculate the maximal subsidy rate with Equation (2.24).

$$s_{max} = \frac{E_{2020\to 2030} \cdot fee_{NO_x}}{\sum_{i=1}^{90}(10 \cdot OM_{cost,i} \cdot t_i + Investment_i \cdot number\ of\ ships_i \cdot SCR_{\%,i})} \tag{2.24}$$

3 Results

The results are divided into two different sections due to their comparability. *NECA*, extended *NECA* and *slow steaming* are all direct regulations. Subsidy and tax schemes are instead price dependent market based regulations.

3.1 Direct Regulations

Under a direct regulation a shipping company has no option and has to follow the regulation. Direct regulations only affect the ships that are regulated. In the *NECA* scenario abatement occurs amongst ships built after 2021 while the entire fleet is affected in the *slow steaming* scenario.

3.1.1 Baseline: NECA

If a *NECA* is established in 2021 the yearly emissions will drop by about 28 % in 2030 compared to if No-*NECA* was introduced, since all new ships from 2021 will have significantly lower emissions.

Table 3.1 – Estimated NO_X emissions (ktonnes) in *NECA* compared to *No-NECA* scenario. Emissions are shown for different ship categories.

	No-NECA	*NECA*
Bulk carrier	16	11
Chemical tanker	29	21
Container ship	82	59
General Cargo	29	21
LG tanker	4	3
Oil tanker	16	12
RoRo cargo	15	11
Ferry	33	25
Cruise	5	3
Vehicle carrier	7	5
Baltic Sea in Total	237	171

Total costs (as social costs, see Table 2.2) for the new abatement equipment that will be in use in the Baltic Sea following an introduction of *NECA* are estimated at 79 M€. Calculated NO_X abatement costs (excluding fuel cost component) are 1.20 €/kg NO_X. It can be noted that the correspondent avoided external costs in Europe in 2030 are reported to be in the range between 621 M€ (median VOLY) to 2200 M€ (mean VSL) (Yaramenka, et al., 2017).

3.1.2 NECA5500

The abatement of NO_X in the Baltic Sea is the same in the *NECA* and the *NECA5500*, since the extra abatement in the *NECA5500* scenario occurs outside the Baltic Sea. However, the results in Table 3.2 shows that average technical abatement cost will drop significantly in the *NECA5500* scenario. This is due to the fact that investment costs per engine work are lower in the *NECA5500* scenario.

Table 3.2 – Modelled average technical cost per kg NO_X 2030 compared to the No-NECA scenario.

	Low cost [€/kg NO_X]	Central cost [€/kg NO_X]	High cost [€/kg NO_X]
NECA (SoP)	0.69	1.20	1.87
NECA5500 (SoP)	0.16	0.39	0.74

3.1.3 Slow Steaming – Results from Literature Review

The overall conclusion in Faber et al. (2012) is that 10% reduction in speed implies 19% reduction in power, and thereby in the regional NO_X emissions. However, if the speed restriction is limited to a certain region and ships speed up outside that region, in order to compensate for the time lost, the global emissions may increase instead. In Corbett et al. (2009), evaluating slow steaming on container ships, emission reduction are in line with the result in Faber et al. (2012) if ships carries more containers in order to compensate for the transportation work lost. However, if additional ships instead are used in the model, the emission reduction is lower than in Faber et al. (2012). In Corbett et al. (2009) they also concluded that a fuel tax of about 190 €/ton fuel would reduce the speed with about 20-30%.

When it comes to legal feasibility, Faber et al. (2012) argue that the best option probably is to require speed restriction for incoming ships. Another option is to regulate ships sailing under member state flag.

The design of a *slow steaming* scheme is also important. Different speed restriction for different ship types have many advantages compared to one single speed limit for all ships (Faber, et al., 2012). Different ship types have different design speeds and purpose; one single speed restriction may therefore distort competition between ships. However, one advantage with a single speed limit for all ship categories is that such a scheme would be easier to monitor and regulate. The speed restriction could either be set on top speeds or average speeds and AIS data can be used to monitor both. Further, average speeds may also be monitored though inspection of log books.

In one study comparing different policy instrument the results show that regulated *slow steaming* will reduce the emission less than a *REP* scheme if the tariff is higher than 1€/kg/NO_X (Winnes, et al., 2016). This is due to the fact that the speed restriction will only lower fuel consumption while a REP scheme will imply installation of NO_X reducing technologies.

3.2 Market Based Regulations

The results in this section show that a market based policy may complement the introduction of *NECA* and imply additional abatement if the price is set at a suitable level.

3.2.1 Financial Investment Support

The introduction of subsidy scheme where companies pay 0% interest rate on their investment leads to increased shift to LNG by both new and existing vessels, resulting in quite significant reduction in NO_X emissions in 2030. The emission reductions are presented in Table 3.3, and additional use of LNG – in Table 3.4.

Table 3.3 – Abatement for different ship categories compared to the *NECA* scenario for *financial investment support*.

	Reduced emissions [ktonnes NO_X]
Bulk carrier	1.4
Chemical tanker	2.4
Container ship	7.4
General Cargo	2.1
LG tanker	0.3
Oil tanker	1.4
RoRo cargo	0.9
Ferry	1.8
Cruise	0.3
Vehicle carrier	0.6
Total NO_X reduction	18.5

Table 3.4 – Additional LNG use compared to the *NECA* baseline scenario.

	Additional use of LNG relative *NECA*
All	17%
New installation min	16%
New installation max	20%
Retrofit min	22%
Retrofit max	29%

3.2.2 Port Dues with LNG rebate

The abatement potential of *environmental differentiated port dues* in our model seems to be limited. The NO_X emission reduction is only 0.17 ktonnes, compared to the *NECA* baseline scenario. The subsidy scheme only results in small increases in LNG share, as can be seen in Table 3.5.

Table 3.5 – Additional use of LNG

Ship category	Additional use of LNG [%], compared to *NECA*
Bulk carrier	0.01%
Chemical tanker	0.03%
Container ship	0.04%
General Cargo	0.04%
LG tanker	0.05%
Oil tanker	0.06%
RoRo cargo	0.12%
Ferry	0.86%
Cruise	0.07%
Vehicle carrier	0.25%

3.2.3 CO_2 tax

The emission results if a CO_2 *tax* is introduced are presented in Table 3.6. The results indicate that the NO_X emissions in 2030 are only affected to a small degree by the introduction of a low CO_2 *tax* compared to the 2030 *NECA* baseline scenario. However, higher tax values, especially if the tax is introduced in the entire *NECA* area and not only in the Baltic Sea, is found to cause NO_X emission reductions up to 6 ktonnes, compared to the *NECA* scenario. The central value of the tax, 0.12 €/kg CO_2, would result in 2.5 ktonnes emission decrease in the model.

Table 3.6 – Estimated emissions 2030 if CO_2 *tax* is put on the fuel above *NECA*.

Scenario		Fuel price, including CO_2 *tax* [€/t fuel]		Total emissions [ktonnes NO_X]
		MD	**LNG**	
No-NECA		885	610	237
NECA		885	610	171
CO_2 *tax NECA*	0.05 €/kg	1050	752	170
	0.12 €/kg	1261	934	169
	0.36 €/kg	2039	1603	165
CO_2 *tax* BS only	0.05 €/kg	1050	752	171
	0.12 €/kg	1261	934	170
	0.36 €/kg	2039	1603	169

NO_X emission reduction, compared to *NECA*, is 1.2-6.1 ktonnes if the tax is introduced in the whole *NECA* area. If the tax is only in the Baltic Sea the emission reductions are about 66% lower, 0.4-2.4 ktonnes. This is in line with the assumption that major part of the total fuel use in the *NECA* area is attributable to traffic in the North Sea.

The low CO_2 *tax* does not seem to cause any major increased in LNG use, see Table 3.7. A higher tax will increase the use of LNG for all ship types.

Table 3.7 – Additional LNG share compared to the *NECA* scenario

	CO_2 *tax* in the whole *NECA*			CO_2 *tax* in Baltic Sea only		
	0.05 €/kg	0.12 €/kg	0.36 €/kg	0.05 €/kg	0.12 €/kg	0.36 €/kg
Bulk carrier	0.7%	1.5%	3.7%	0.2%	0.5%	1.4%
Chemical tanker	0.8%	1.6%	4.1%	0.2%	0.5%	1.5%
Container ship	1.1%	2.4%	6.2%	0.4%	0.8%	2.3%
General Cargo	0.4%	0.9%	2.4%	0.1%	0.3%	0.8%
LG tanker	0.7%	1.6%	3.9%	0.2%	0.5%	1.5%
Oil tanker	0.9%	1.9%	4.8%	0.3%	0.6%	1.8%
RoRo cargo	1.2%	2.7%	6.9%	0.4%	0.9%	2.6%
Ferry	3.4%	6.8%	14.4%	1.1%	2.5%	6.6%
Cruise	1.2%	2.5%	6.5%	0.4%	0.8%	2.4%
Vehicle carrier	1.2%	2.7%	6.9%	0.4%	0.9%	2.6%

3.2.4 NO_X tax

As can be seen in Figure 3.1, a NO_X *tax* would result in additional NO_X abatement in the Baltic Sea. However, for a low tax level of 0.5 €/kg NO_X only about 10 ktonnes of NO_X would be avoided in the baseline. As the tax increase the different cost case converge towards 67 ktonnes of NO_X which is the maximal abatement for Tier II ships with the emission model used in this study. It is also worth noting that the relation between the tax level and abatement is non-linear. This is mainly due to fact that the ships with the most operational hours are also the ships with largest abatement potential (the relation illustrated in Figure F1).

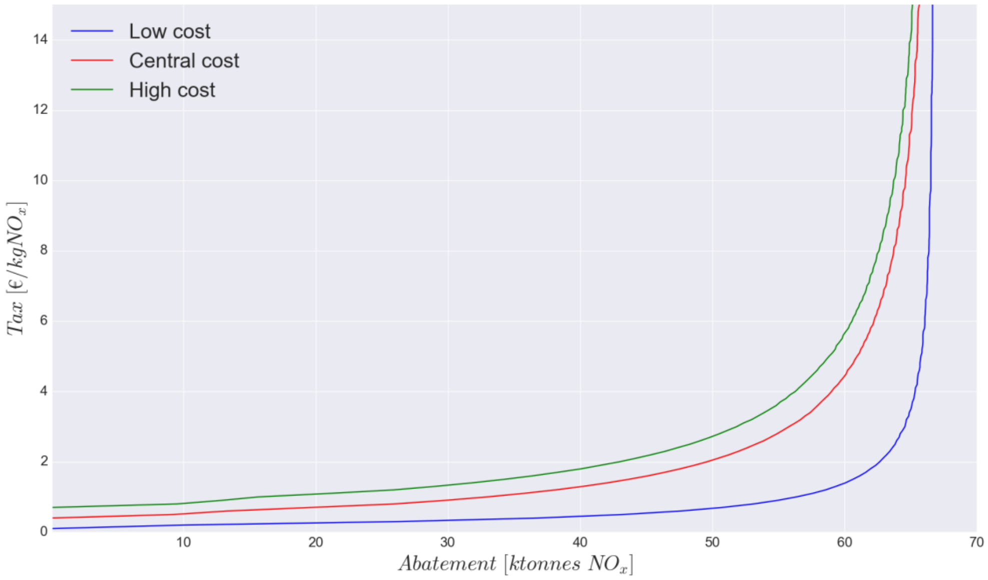

Figure 3.1 – Illustrates how the abatement in the Baltic Sea increase with increased tax level in the 2030 *NECA* baseline scenario. Only Tier II ships are included in the analysis.

The tax level on the Y-axis in Fig 3.1 is reduced to a more reasonable range for a NO_X-tax in Figure 3.2-

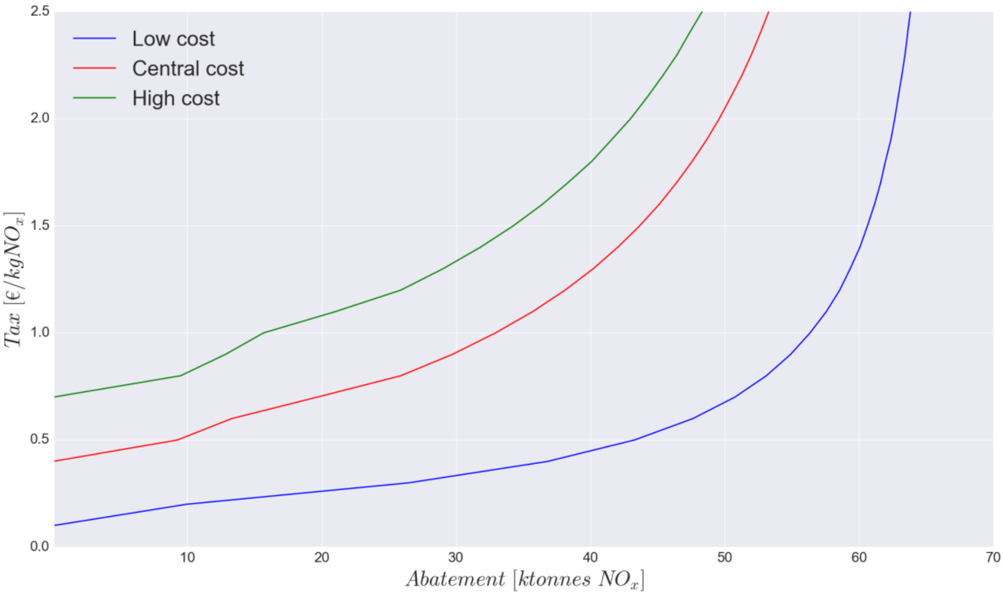

Figure 3.2 – Zoomed in version of Figure 3.1. The figure shows that NO_X abatement also can be achieved for low tax levels.

3.2.5 Refundable Emission Payment (NO_X-fund)

The *REP* scheme has great abatement potential if the NO_X price and subsidy rate is set at a proper level. Results from different combinations of fund fees and subsidy levels are presented in Table 3.8.

Table 3.8 – Estimated yearly abatement for Tier II ships in 2030 (ktonnes) for different subsidy and fee rates without budget constraint. The subsidy rates are applied on both operational and fixed cost. The fund fee in the table reflects the tariff that the industry pays to the Norwegian NO_X *fund*. The emissions estimate for 2020-2030 is used for illustrating the budget constraint. These results are very uncertain and should not be used outside that context.

Fund fee [€/kgNO_X]	Subsidy-level	Abatement [ktonnes]			Budget constraint in *NECA* 2020-2030	
		low	central	high	ktonnes NO_X	M€
0.5	20%	48	16	0	2110	1055
1.5	20%	62	48	41	1950	2925
0.5	40%	54	27	11	2050	1025
1.5	40%	64	53	48	1920	2880
0.5	60%	59	39	27	1990	995
1.5	60%	65	58	55	1900	2850
0.5	80%	64	53	48	1920	960
1.5	80%	66	63	62	1870	2805

The relation between the fund fees, the subsidy and the abatement potential in the Baltic Sea, the abatement for different subsidy rates for the baseline scenarios are illustrated in Figure 3.3. Each line represents a unique subsidy rate. The figure shows that if the desirable abatement target is 40 ktonnes and refund is set at 40 % subsidy rate, the fond fee needs to be about 0.75 €/kg NO_X to reach the target. However, if the subsidy rate instead is 80 %, the target would be reached at fee rate of 0.25 €/kg NO_X.

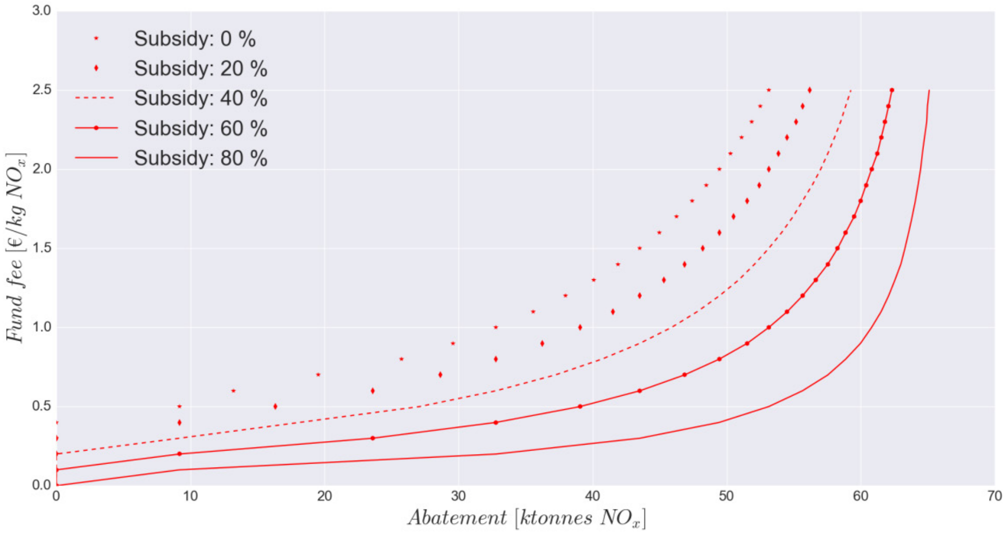

Figure 3.3 – Yearly abatement for Tier II ships in the 2030 *NECA* baseline scenario, for different subsidy rates and without budget constraint. The subsidy rates are applied on both fixed and operational costs.

Figure 3.3 do not reflect the budget constraint for refundable emissions payment. Budget restrictions for emissions ranges between 1870 and 2110 ktonnes are presented in table 3.8. A central value of 2000 ktonnes was therefore used in the calculations of how the maximum subsidy rate depends on the fund fee. The subsidy rate's relation to the paid fund fee is U-shaped with a minimum subsidy around a fee of 0.4 €/kg NOX, as illustrated in Figure 3.4. For low tax levels the main reason for the high subsidy rate is that many shipping companies do not abate, since the installation and operational cost exceeds the cost of the fee, see Equation (2.13). For high fees the budget roof is reached later since more money is given to the fund than what is refunded, due to increased fees.

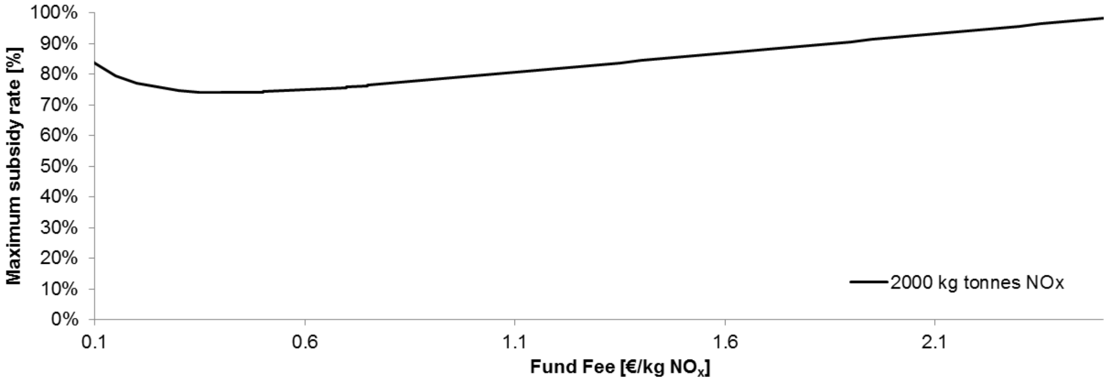

Figure 3.4 – Modelled budget constraint for different subsidy and tax levels in the baseline scenario, the line corresponds to 2000 ktonnes of emissions during the whole time period.

3.3 Comparison of Results

It is difficult to compare different policy instrument to each other since they are based on different assumptions and have different implications. However, given the assumptions in this study Figure 3.5 compares NO_X emissions in 2030 for the policy instruments evaluated. As can be seen in the figure the establishment of *NECA* implies emissions reduction corresponding to 28 %. However, additional emission reduction is also possible with a complementary policy instrument, such as *financial investment support*, a NO_X *tax*, a *REP* scheme or *slow steaming*. The comparison also shows that the abatement potential of a *CO_2 tax* and port due rebates are limited compared to the other policy instruments.

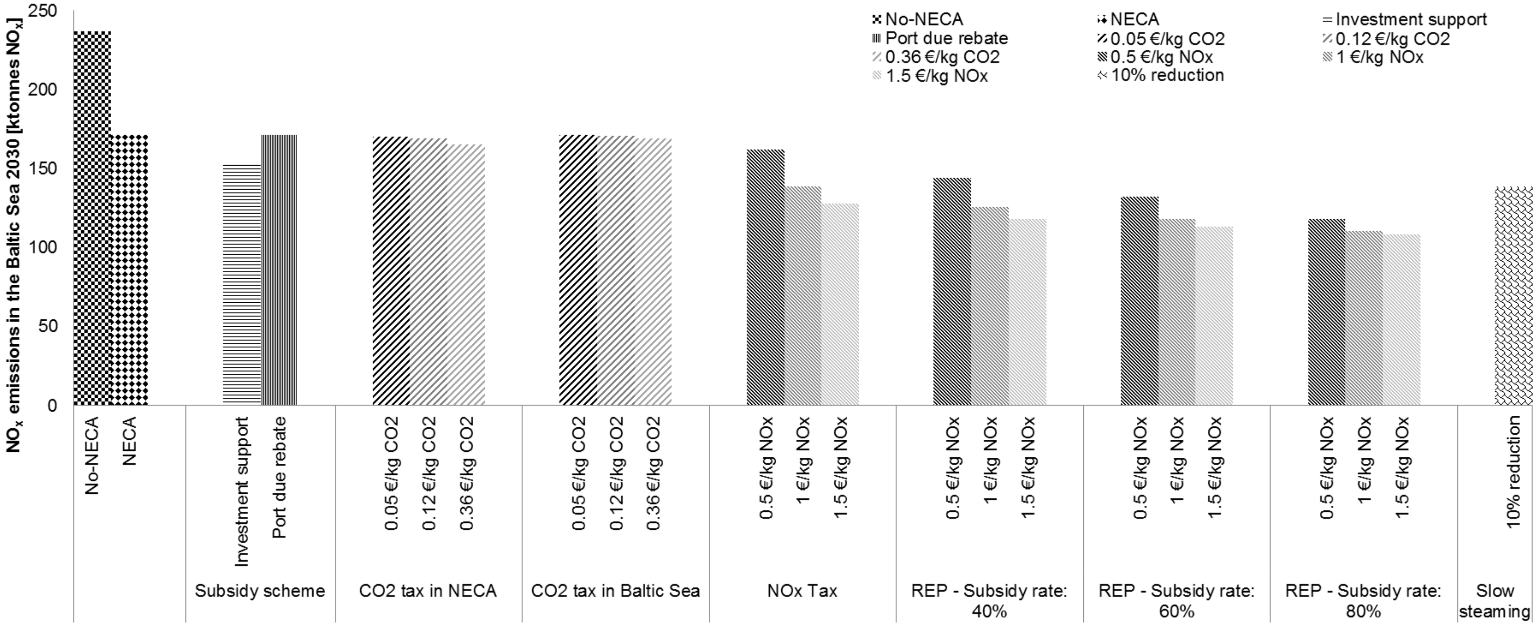

Figure 3.5 – Emission estimates for the Baltic Sea 2030 with different policy instrument. All policy instruments are assumed to be introduced on top of *NECA*.

Another way to compare the results is by looking at the additional emission reduction that is achieved compared to the *NECA* baseline scenario. This emission reduction is illustrated in Figure 3.6. In this Figure it is easier to see that the tax and *REP* schemes have the greatest abatement potential under the modelled conditions in this study.

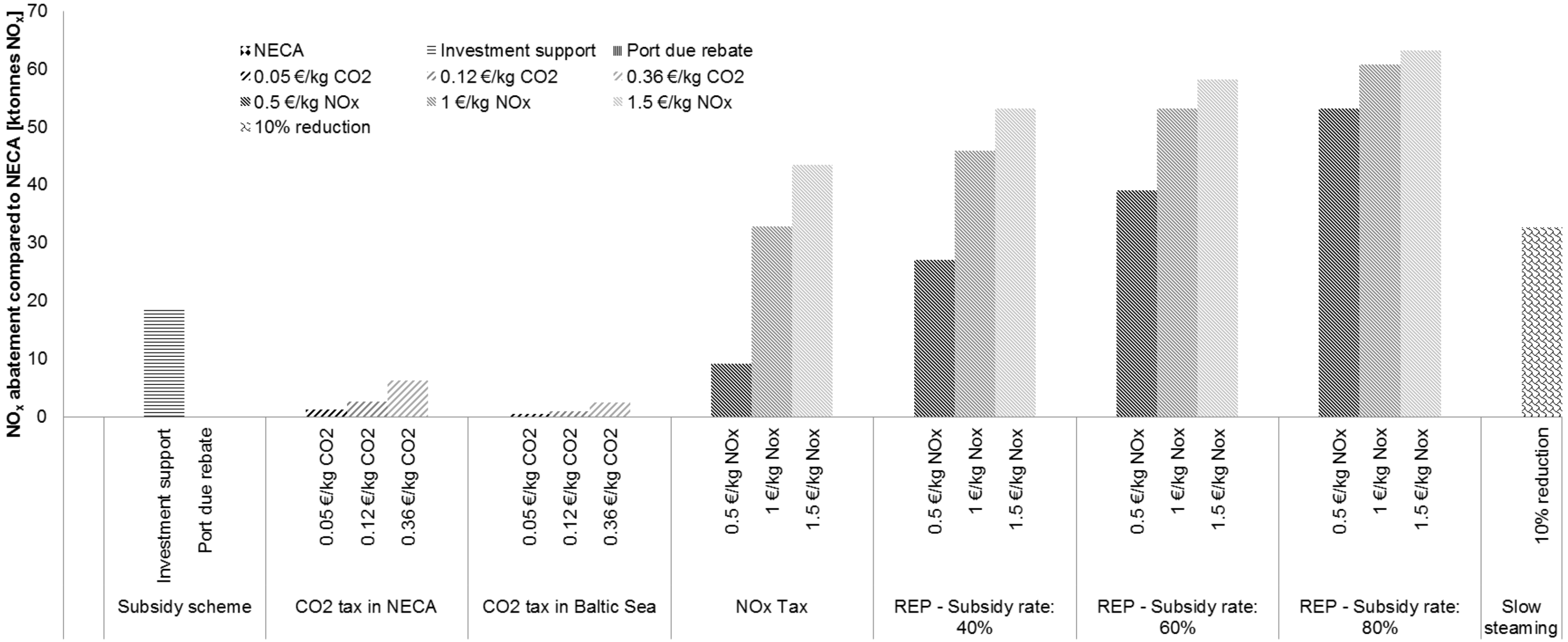

Figure 3.6 – Estimated additional emission reduction at the Baltic Sea 2030 compared to the *NECA* baseline scenario.

4 Sensitivity Analysis

This chapter presents some results from sensitivity analyses. The LNG engine price is for example one uncertain input parameter, described in Section 4.1. Furthermore, for policy instruments evaluating LNG usage the relative fuel price is a critical parameter and the LNG prices is therefore varied while the MD prices is held constant in Section 4.2. Section 4.3 instead shows model results for different interest rates and lifetimes used when companies are making investment decisions. Some comparative sensitivity analyses can be found in Appendix D.

4.1 LNG Engine Price

The LNG engine price chosen in our analysis is 736 €/kW for a new engine and 1038 €/kW for a retrofit. In the literature, however, one can find values as low as 219 €/kW (MAN 2012) and 391 €/kW for a retrofit (IMO 2015). LNG engine prices will most probably decrease by 2030 with further development and higher availability of this technology. In the sensitivity analysis, we consider price intervals 736-219 €/kW for new engines and 1038-391 €/kW for retrofits, which corresponds to up to 70% lower LNG engine price than in the main analysis.

A lower assumed price of LNG engines thus results in higher LNG use in the *NECA* baseline scenario with associated reduced NO_X emissions. This also means that the effects of additional policy instruments are lower. The modelled NO_X emission reductions due to policy instruments vary from 0.17 ktonnes (port due rebate) to 19 ktonnes (0% interest rate) for the LNG engine price used in the main analysis. This variation would decrease to 0.09 ktonnes and 12 ktonnes with lower LNG engine price, for the respective scenarios. This is because more LNG consumption by both existing and new (Tier III) ships is included in the *NECA* scenario, so the additional share of LNG is lower. However, the total NO_X emissions decrease for all considered policy instruments. The lowest NO_X emissions in 2030 might be achieved in the financial investment support scenario – 141 ktonnes. High *CO_2 tax* in the *NECA* area would reduce NO_X emissions down to 144 ktonnes. For other scenarios, additional reductions compared to the *NECA* scenario become lower with lower LNG engine price. This is because in case of the low LNG engine price significant additional LNG consumption would be seen in the *NECA* scenario even without other policy instruments, making the potential effect of policy instruments smaller.

4.2 Price Difference between LNG and MD

In the main analysis we use central fuel price values projected in a report by the Danish Maritime Authority (2012) – 610 €/ktonnes LNG and 885 €/ktonnes MD. This implies a rather high price difference of 275 €/ktonnes fuel, encouraging a number of vessels to choose LNG engine in favour of conventional engines. However, the price values are highly uncertain. For the sensitivity analysis, we vary the LNG price from 610 €/ktonnes to 485 €/ktonnes (low end estimate in the Danish Maritime Authority 2012) keeping the MD price constant. This means we consider a potential price difference increase of up to 45% compared to the main analysis.

At the low LNG price, NO_X emissions in the *NECA* scenario are modelled to 162 ktonnes – 6% decrease compared to the case of lower price spread used in the main analysis. NO_X emission reductions due to additional policy instruments supplementing *NECA* would amount to 0.09–12 ktonnes for the low LNG engine price.

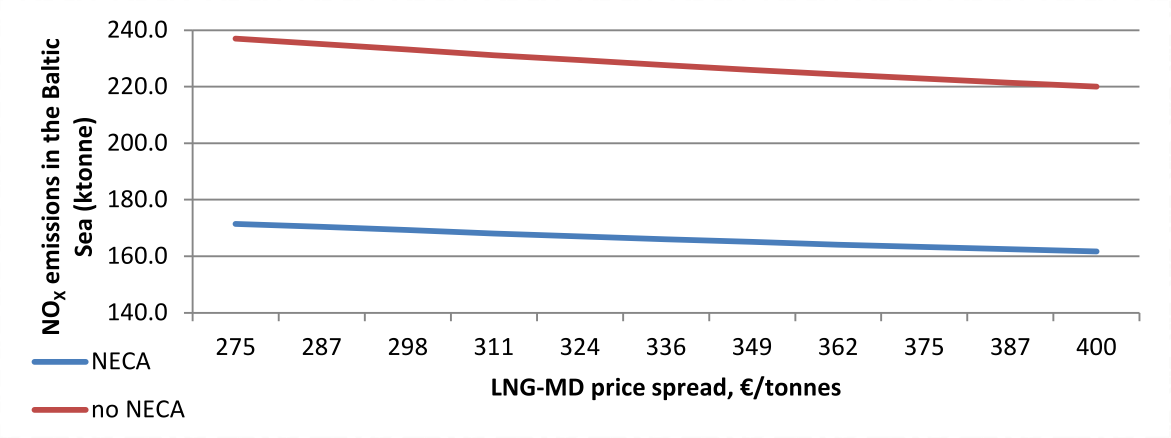

Figure 4.1 – NO_X emissions depending on the LNG-MD price spread for *No-NECA* and *NECA* cases.

The overall trend of a high difference between LNG and MD is similar to the trend observed in the LNG engine price analysis. With low LNG price and the financial investment support with 0% interest rate on investments, emissions can reach 150 ktonnes, with high *CO_2 tax* in the *NECA* area – 158 ktonnes, and if the tax is introduced in the Baltic Sea only – 160 ktonnes. For other scenarios the relative input into emission reductions compared to the *NECA* case is much lower.

No detailed analysis of a reduced price difference has been made. The effect of such a case is expected to be that fewer vessels would choose LNG resulting in higher NO_X emissions.

4.3 Private Perspective on Cost Annualisation

There is no common agreement on what values should be used in the private perspective cost annualisation. As discussed above, in this study we have chosen to apply 10% interest rate and 10 years investment lifetime – but in reality this choice made by shipping companies is very subjective, and both interest rate and investment lifetime can vary. Interest rate decreases with investment lifetime increase – and vice versa. In the sensitivity analysis we consider the interest rate range of 10%-4% and the investment lifetime range of 10-25 years – in other words, the range from the perspective used in the main analysis to the social perspective, for which 4% and equipment lifetime are widely used.

4.3.1 NECA and No-NECA

Varying investment annualization perspective from private (10 years, 10% interest rate) to social (25 years, 4% interest rate) results in lower annual investment costs. Figure 4.3 shows this trend for NECA and no NECA scenarios. If shipping companies in their decisions use the social cost perspective, corresponding to 25 years investment lifetime, it could reduce NO_X emissions to 193 ktonnes in the *No-NECA* scenario and to 146 ktonnes – in the *NECA* scenario. This is 18% and 15% difference compared to the main analysis, respectively.

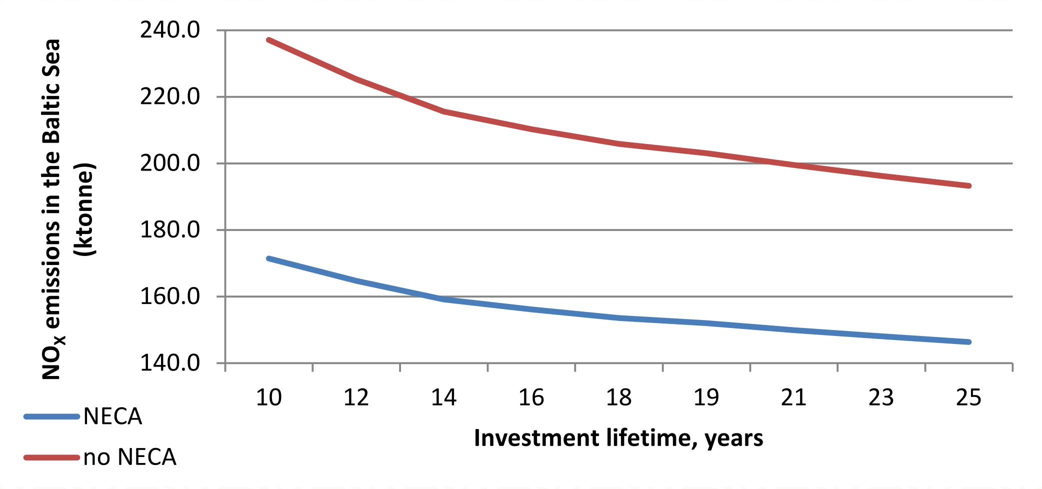

Figure 4.2 – NO_X emissions depending on the investment lifetime.

NO_X emission reductions due to additional policy instruments supplementing *NECA* would amount to 0.05-5 ktonnes for the social price perspective (see Appendix D): this view on cost annualisation, like in the cases of lower prices of LNG engine and fuel, would imply more LNG in the *NECA* and less relative effect from supplementary policy instruments – except the most efficient of them. 0% interest rate will result in 142 ktonnes NO_X, high *CO_2 tax* in the *NECA* area – in 145 ktonnes NO_X. For other scenarios the relative input into emission reductions compared to the *NECA* case is low.

The effect from shorter investment lifetime and higher interest rate is expected to be the opposite – fewer vessels would choose LNG resulting in higher NO_X emissions.

4.3.2 NO_X tax

One uncertainty in the model is that the time horizon and interest rate of the investment doesn't necessarily reflect all companies' perspective. If all companies instead have an investment perspective corresponding to the social perspective the abatement would increase due to lower annualised investment cost. This is illustrated in Figure 4.4.

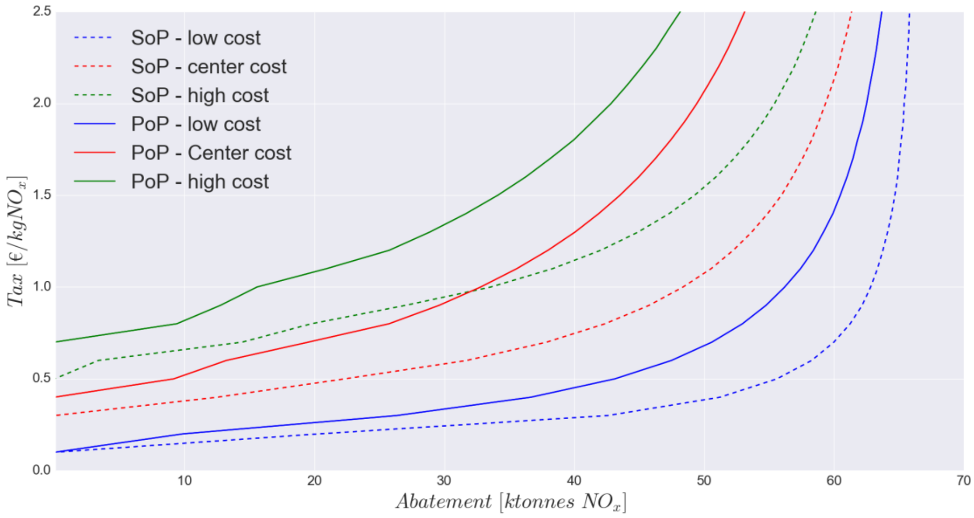

Figure 4.3 – Sensitivity analysis on the abatement potential with a NO_X *tax* in the Baltic Sea. Lines with the same colours represent the same costs for abatement technologies. The dashed line corresponds to the societal investment perspective and the solid line corresponds to the private investment perspective

Operational expenses are more important for low tax levels, since only ships with many operational hours in the area will abate. As the tax increases also ships that are operating less time in the area will install SCR, however for these ships the capital cost of installing SCR will be the major cost component. This is the reason why the dashed green line and the solid red line cross each other at about 1€/kg NO_X in Figure 4.4.

4.3.3 Refundable Emission Payment (NO_X-fund)

As can be seen in Table 4.1 the abatement potential with the refund is linked both to the cost of abatement technology and to the investment perspective. For the private perspective, PoP-central, the subsidy can make a great difference for low tax levels. However, in the SoP-low scenario it seems like the abatement potential for the subsidy is low. The sensitivity analysis shows abatement potential of the additional refund is considerably higher if the interest rate is higher and investment horizon is longer.

Table 4.1 – Sensitivity analysis of yearly abatement for Tier II ships in 2030 (ktonnes).

Tax level [€/kgNO_X]	Subsidy-level	SoP [ktonnes]			PoP [ktonnes]		
		low	central	high	low	central	high
0.5	20%	59	33	9	48	16	0
1.5	20%	65	59	54	62	48	41
0.5	40%	62	44	23	54	27	11
1.5	40%	66	61	59	64	53	48
0.5	60%	64	53	43	59	39	27
1.5	60%	66	64	62	65	58	55
0.5	80%	66	61	59	64	53	48
1.5	80%	67	66	65	66	63	62

4.4 Budget Constraint for REP

One issue with the budget constraint model is that it is based on a fixed amount of emissions during the time period. However, the amount of emissions is dependent on how much that is abated which in turn depends on both the fee and the subsidy level. The budget constraint is plotted for four different emission levels in Figure 4.5. The top line illustrates budget constraints with an emission ceiling at 3000 ktonnes NO_X. This is significantly higher emissions than the baseline. With low fees (~left in the diagram), little emission reduction can be assumed, and few ship owners will chose to apply for financial support from the fund. Those who apply, however, can get a high subsidy rate since the fund is divided only between few applicants. It is therefore likely that the top line is the best approximation of the budget constraint for low fee levels, in Figure 4.5. The second lowest solid line represents the budget constraints at total emissions of 1000 ktonnes NO_X during the period. This constraint is more probable at high fees (to the right in the diagram) since high NO_X-fees will incur more investment in abatement technology. This argumentation is valid for cases when ship owners pay fees for all active ships in the area but only refund Tier II ships. If only on Tier II ships are paying to the fund the total available funding will be considerably less. The lowest line in Fig 4.5 represents a total emission level of 500 ktonnes, which is an approximation of a situation where payments for Tier II ships finance their own installations.

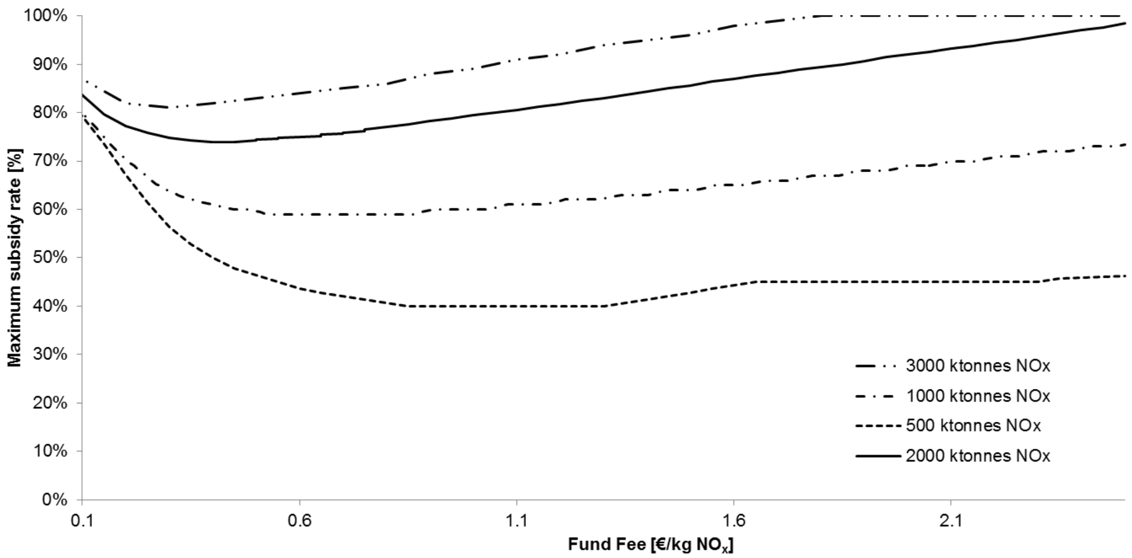

Figure 4.4 – Sensitivity analysis of budget constraint reflecting different total emission during the time period 2021-2030.

5 Discussion

This chapter contains a broader discussion of the advantages and disadvantages of each policy instrument based on the results of this study. Furthermore, the findings in this study are sometimes also discussed in the context of what other studies have shown.

This study has not investigated possible legal obstacles to introducing the studied policy instrument. Further, the assumption of ship owners applying the most cost effective solutions can be debated, since many other factors influence investment decisions, but that is not discussed in the following section.

5.1 Direct Regulations

The results from this study show that *NECA* and *slow steaming* will result in lower emissions in the Baltic Sea in 2030. Regulations are intuitive, easy to communicate, and would counteract a development of increased emission levels. However, a disadvantage with these regulations is that they do not directly regulate a total maximum emission level. The emissions may increase if the traffic increase heavily or if the vessel speeds increase due to higher transport demand.

The results in this study clearly point out that the establishment of *NECA* in 2030 would lead to lower NO_X emissions. However, since the emission potential is limited to ships built after 2021 the calculated emissions would only be about 28 % lower in 2030 than if a *NECA* was not established. The calculation model does not consider any effects of the potential for ship owners to direct more old ships to the NECA area.

The *NECA5500* scenario shows the advantage of increasing the geographical boundaries for the emission standard, which encourage vessel owners to take into consideration both higher OM costs (relevant mainly for SCR and EGR) and lower investment costs per kWh power output in their investment decisions. Total NO_X emissions are virtually the same in these two scenarios. However, more vessels would choose LNG in the *NECA5500* scenario than if *NECA* is only introduced in the Baltic Sea and the North Sea. Another benefit with a worldwide emission standard would be that the competition between different routes would not be skewed as when the emission standard only was established in the Baltic Sea.

One major advantage of *slow steaming* is that all ships may be included in such regulation and the effect of the regulation could be enforced from day one. Furthermore, *slow steaming* is the only policy instrument in this study that is lowering the actual fuel consumption. Lowering fuel consumption also has great implication in other areas, lowering all types of emissions.

5.2 Market Based Policy Instruments

The main advantage of the market based policy instruments compared to the *NECA* baseline scenario is that these policy instruments will also reduce the emissions from old ships. *Refundable emission payment* is the policy instrument with the greatest potential to additional emission reduction in this study. However, an introduction of *financial investment support* may also have certain positive benefits especially in terms of promoting immature technology. No market based policy instruments in this analysis would guarantee reduced emissions since there is no limit set on the total emissions. Also, it may be difficult to base the total emission reduction on the price (€/kg NO_X), since one never can be certain of finding the right price level (€/kg NO_X) for pre-defined abatement target. Nevertheless, the results in this study indicate the price that is necessary for achieving substantial emission reductions is somewhere between 0.5-2.5 €/kg NO_X.

The emission model in this study has some limitations for analysing market based policy instruments since the model only allows for NO_X emissions down to Tier III levels, while in reality the technology allows for further reduction. The reduction limit of the model is about 67-80%, depending on which Tier is studied. However, in reality greater NO_X reduction is possible with the technologies used in this study. Optimally, the abatement potential of the policy instrument should be related to an abatement technology's real reduction potential and its specific costs and not to an emission standard. This model will therefore underestimate the abatement potential of the instrument. Nevertheless, the results still clearly shows the advantage of combining the *NECA* with another policy instrument.

The results show that *financial investment support* of 0% interest rates will lead to a decrease in NO_X emissions, 18.5 ktonnes compared to the *NECA* scenario. More than half of this reduction is reached via retrofitting existing vessels with LNG engines hence such an investment becomes more attractive at 0% interest rate.

One advantages of a subsidy scheme is that experience show that is often politically easier to implement (Sterner & Coria, 2012), in the sense that the industry will put up less resistance. Even though it may be difficult to introduce a subsidy from a legal stand point, it is e.g. not clear if 0% interest rate even is possible in EU. Furthermore, other policy instruments may put the local/regional industry under pressure compared to other place where there are no regulations. By introducing a subsidy instead of for example a tax this distorted competition may be avoided.

There are several disadvantages with the establishment of a subsidy program in general which are also true for the investment support evaluated in this study. The institute financing the 0% interest rate is paying for the abatement and not the polluter. The so called "polluter pays principle" is therefore violated, which to a certain extent is required in law in some countries. Furthermore, with the introduction of investment support there is no incentives to further reduce the output. Also, if the investment support is establish it may also be difficult to remove, and if it is removed it may jeopardize the companies that have already invested in LNG, since they are dependent on further development of LNG. If public funding is used, one can argue that it may be in better use in other sectors, such as health care. Also, since many different governments are included in the negotiations of policy instrument, experience show that it may be difficult to agree upon which government that should pay and how much (Sterner & Coria, 2012).

The *financial investment support* is a type of subsidy scheme, since the lender is paying for the risks associated with the investment. In the end, it will most probably be the tax payers or society as a whole that are paying for this subsidy. It is therefore especially important to address the legitimacy of this policy instrument. It may or may not be reasonable to subsidise LNG, however several factors need to be addressed in that case, and not only the NO_X emissions. It may for example be more legit with a subsidy scheme if the technology has a great potential and if there are market barriers such as absent infrastructure, actors lacking knowledge etc. Several studies suggest that a technology then may need a protected space to grow in order to compete with the current technical system (Jacobsson & Lauber, 2004; Sandén & Hillman, 2011; Bergek, Jacobsson, & Sandén, 2008; Geels, 2005). On the other hand, one can also question if a fossil fuel should be substituted with another type of fossil fuel. A fossil fuel can never be sustainable since it is a finite resource. However, LNG may still be a possible transition technology helping a new sustainable system to emerge, and may therefore still be an interesting option. Also, LNG will result in significant reduction of emissions of air pollutants such as particles and sulphur oxides and will also limit the use of heavy fuel oils. Furthermore, LNG may perhaps be a transitional technology for some other types of gases such as biogas or hydrogen, since competence about LNG may be beneficial also for these technologies. Studies evaluating system innovation, address the importance of helping several technologies to grow at the same time. More emphasis should therefore be put on also evaluating other technologies or fuels, as e.g. methanol or cold ironing. However, to make conclusions about any of the issues addressed in this section, more studies need to investigate LNG and other technologies from a system perspective (Geels, 2005; Meadows, 1997). This perspective is essential, since many different factors are interacting with each other, factors which are not purely economic or environmental. The following bullet list summaries some factors which should be further analyzed in such studies:

- how actors one the markets is interacting with each other and their role on the market
- resource boundaries
- market boundaries
- learning processes
- legitimacy

5.2.1 CO_2 Tax

As seen in the results, a *CO_2 tax* is a blunt instrument for regulating NO_X emissions. One reason for this is that the NO_X is mainly formed in the combustion process, and not necessarily proportional to the CO_2 emissions. The negative externality in this case (NO_X) is not directly included in the tax. Compared to the investment support the *CO_2 tax* implies lower shares of LNG. This may be a reflection of the reality; the *CO_2 tax* is associated with operation of the ship while the *financial investment support* is linked to the investment. A policy instrument linked to the operation has some extra uncertainty, since a tax scheme may be removed at a certain point while a policy instrument placed on the investment is given from the start. Nevertheless, as seen in the sensitivity analysis, the fuel price in itself also adds uncertainty to the operation costs of LNG regardless if it is a *CO_2 tax* or an investment support scheme.

The CO_2 emission reduction associated with a LNG switch may also be questioned since methane slip occurs from the operation of the engine. Methane is a much stronger greenhouse gas than CO_2 and one study even show that the global warming potential (GWP) of LNG is in the same range as MD (Brynolf, Fridell, & Andersson, 2014). So if the methane is included in the *CO_2 tax*, the charge would not imply any additional LNG usage. Furthermore, as previously mentioned, a switch to LNG should be analyzed from a system perspective and focus should be on the transitional processes.

Nevertheless, it is important to notice that a *CO_2 tax* could lower the total fuel consumption if it is set at a proper level, implying lower emissions of NO_X. A study by Corbett et al. (2009) showed that a *CO_2 tax* could lead to speed reductions implying reduced fuel consumption. However, that is out of the scope of this study.

5.2.2 NO_X Tax and REP

Compared to a *CO_2 tax*, a NO_X *tax* has the advantages that the negative externality (NO_X) is included in the price. As the results shows the NO_X tax and the *REP* scheme is therefore much more efficient in reducing NO_X. A price on NO_X will reduce NO_X emissions if the price is set at a sufficient level. The results in this study give support to those who argue that fee-based subsidies scheme is a cost effective way to reduce NO_X emissions (Hagem, Holtsmark, & Sterner, 2015; Kågeson, 2009). Furthermore, the result for the REP scheme and the tax is in line with for example the results in Winnes et al. (2016), but the results for the abatement costs are lower in this study.

Only SCR for Tier II ships was analyzed in this study for the NO_X *tax* and *REP* scenarios. The real abatement costs could be lower and abatement greater if also other technologies were included in the analysis. The results should therefore be used with great caution in terms of finding an exact level of the tax or fee. Also, real-world experiences show that a tax often is adjusted several times in order to achieve desired targets with a trial and error approach. However, that may create instability and resistance towards the tax. Companies may e.g. first invest in abatement technologies at a small scale if the tax is set at a low level. When the tax later is raised to a higher level, the shipping company needs to make a larger investment making the old one unnecessary.

The subsidy rates set in a *REP* scheme may also be changed. The Norwegian NO_X *fund* has revised its subsidy rates during its existence. In the Norwegian case, SCR was popular in the beginning, but as the subsidy rate increased for some particular investments, LNG has also become popular. One argument in favor of the refund is that the Norwegian NO_X *fund* has showed that it is possible for the industry to agree amongst each other (Sterner & Coria, 2012). This is good since acceptance seems to be high for a *REP* scheme, at least in Norway. Kågesson (2009) also argues in favor of the refunding scheme in order to avoid to be "legally challenged by third parties". Nevertheless, it is important to note that the Norwegian shipping industry doesn't necessarily reflect the European shipping industry, since only the domestic shipping is regulated. Furthermore, many Norwegian ships are associated with the oil and gas industry, and shuttle traffic between rigs and ports are easier to regulate.

It is essential that the refund is supporting operational cost when SCR is installed, since that would lower the risk of cheating with the abatement equipment. With only a tax it would be harder to control if the SCRs are used or not. The reduction of NO_X with SCR has been calculated for the Norwegian NO_X *fund* from reported information on urea consumption. The actual NO_X reduction for these installations is calculated to be about 64% instead of the assumed reduction of 87%. This could be due to bad documentation, however since the documentation is necessary in order to get the refund, it is probably not the only reason.

Budget constraint

The budget constraint model in this study is very limited; this is due to the fact that it is hard to evaluate how much that will be emitted during the fund's 10 year period, since it depends on the adaptation rate of abatement technologies. A comparison between Figure 3.3 and Figure 3.4 shows that with a tariff of 0.5 €/kg NO_X it is still possible to abate 50 ktonnes NO_X, if the emissions during the time period is 2000 ktonnes. However if the budget roof is decided by a total emission level of only 500 ktonnes during the time period, only about 25 ktonnes of yearly NO_X abatement would be reached. With this in mind, one could argue that it is better to start at a low subsidy level the first years and later increase the subsidy level if it seems like the desired abatement isn't reached and there is money in the fund.

The results from this study indicate great abatement potentials for both a tax scheme and an *REP* scheme. The refund seems to be especially efficient for low fee rates. A conclusion is therefore that it is better to select a low fee with a high subsidy rate rather than a high fee with a low subsidy rate if maximum abatement is the desirable goal. Yet, if the revenue from the tax can be better used in another sector, perhaps a NO_X *tax* is a better option. Nevertheless, a tax will most likely be harder to implement and control than a *REP* scheme.

6 Conclusions

In this report a number of policy instruments for controlling emissions of NO_X in the Baltic Sea have been studied. The background is the decision to establish a *NECA* in the region requiring ships to follow Tier III regulations from 2021. To achieve further and more rapid reductions of NO_X emissions than what is expected from the NECA, additional policy instruments have been discussed. The policy instruments analysed in this study are additional to NECA requirements. Our study describes changes of emissions and costs for existing ships with Tier II engines. Of the many existing technological alternatives to accomplish NO_X reduction, this study focuses LNG-engines and SCR for after treatment of exhaust gas. Emissions of NO_X in 2030 are modeled for scenarios in which different policy instruments are assumed. The use of LNG and abatement equipment is modeled with the assumption that ship-owners choose the most advantageous option from a cost perspective.

According to our model, an *extended NECA*, where also other sea areas than the Baltic and North Seas become *NECA*s, has no further impact on the NO_X emissions in the Baltic Sea. However, since the abatement equipment is used for more hours in a global NECA it will reduce the abatement cost per kg NO_X.

The most effective policy instrument found in this study is the *refundable emission payment* (REP) scheme. The reduced emissions depend on the fee and subsidy rate applied. For example, a subsidy rate of 60% and a fee of 1 €/kgNO_X is modelled to reduce the yearly emissions of NO_X from shipping in the Baltic Sea in 2030 by about 53 ktonnes. A NO_X tax will also have a significant effect on the NO_X emissions, but in this case the costs for ship-owners are significantly higher.

Applying a *CO_2 tax* or *environmentally differentiated port dues* are found to have less impact on the NO_X emissions in the model. Introducing slow steaming has a potential to reduce NO_X, however, the reduction of NOx is dependent on that vessels are not driving at more irregular speed. In another scenario the effects on emissions from a *financial investments support* for abatement technology or LNG engines were modeled. At an interest rate of 0 % emissions were reduced significantly.

This study has not investigated possible legal obstacles to introducing the studied policy instrument. Further, the assumption of ship owners applying the most cost effective solutions can be debated, since many other factors influence investment decisions.

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Abbreviations and currency rates

CSI	Clean Shipping Index
PoP	Private Perspective
CS	Cost Saving
EB	Expenditure based
EGR	Exhaust Gas Recirculation
ESI	Environmental Ship Index
GAINS	Greenhouse Gas - Air Pollution Interactions and Synergies
GT	Gross Tonnage
GWP	Global Warming Potential
LNG	Liquefied Natural Gas
MD	Marine Distillate Oil
NECA	NO_X Emission Control Area
NHO	The Confederation of Norwegian Enterprise (in Norwegian Næringslivets Hovedorganisasjon)
NO_X	Nitrogen oxides
NOK	Norwegian Krone, currency rate 2017-01-02: 9.08 NOK/€
REP	Refundable Emission PaymentsSCR
SCR	Selective catalytic reduction
SEK	Swedish Krona, currency rate 2017-01-02: 9.56 SEK/€
SoP	Societal perspective
VOLY	Value of life lost
VSL	Value of statistical life
USD	United States Dollar, currency rate 2017-01-02: 1.05 USD/€

Appendix A – General Input Data

Table A1 – Input values on fuel consumption, efficiency increase and traffic increase, for the NO_X calculation model.

Ship categories	Fuel consumption 2010 (ktonnes MD and HF)	Fuel consumption 2030, ktonnes MD	Fuel consumption 2030, ktonnes LNG	Annual efficiency increase	Annual traffic increase
Bulk carrier	807	697	14	1.9%	1.5%
Chemical tanker	1778	1534	32	1.9%	1.5%
Container ship	3272	3752	84	2.25%	3.5%
General Cargo	1624	1595	31	1.3%	1.5%
LG tanker	257	222	4	1.9%	1.5%
Oil tanker	891	769	16	1.9%	1.5%
RoRo cargo	1089	875	25	2.25%	1.5%
Ferry	2632	2114	44	2.25%	1.5%
Cruise	370	298	6	2.25%	1.5%
Vehicle carrier	407	327	18	2.25%	1.5%

Table A2 – Input values on number of vessels in 2030 and their average lifetime (Kalli 2013)

Ship categories	Number of vessels	Average lifetime (years)
Bulk carrier	2 929	26
Chemical tanker	2 885	26
Container ship	1 186	25
General Cargo	3 598	26
LG tanker	397	28
Oil tanker	545	26
RoRo cargo	322	27
Ferry	276	27
Cruise	76	27
Vehicle carrier	119	27

Table A3 – 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%

Table A4 – Vessel size definitions based on the engine effect (ENTEC 2005).

	Small	Medium	Large
ME effect, range, kW	<6000	6000 - 15000	>15000
ME effect, average, kW	3000	1000	25000
AE effect, average, kW	560	1480	3800

Table A5. Ship categories in this study and some key input data (Winnes, et al., 2016).

	Weighted average hours in *NECA* 2030		
Ship category	**Small**	**Medium**	**Large**
Bulk carrier	2750	110	110
Chemical tanker	2750	220	220
Container ship	2750	935	935
General Cargo	1375	110	110
LG tanker	2750	165	165
Oil tanker	2750	440	440
RoRo cargo	2750	1210	1210
Ferry	5500	5500	5500
Cruise	2750	1045	1045
Vehicle carrier	2750	1210	1210

Appendix B – Costs of Different Abatement 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.

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 (24-97)[3]	Used in this study		
	New	59 (19-100)			
	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[4]	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
	MD	28	29	€/kW	HELCOM 2012

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[3] Low-high values, if different from the central values, are given in parenthesis

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

Cost parameter	Sub-category	Value	Original value	Original unit	Source
	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	0.21 (0.17-0.29)	Used in this study		
	Not specified	0.17-0.18	226	USD/tonne	HELCOM 2010
	Not specified	0.29	300	€/tonne	Trafikanalys 2016-20
Urea consumption, kg/MWh	Total interval	10.9 (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	0.55 (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

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%. 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, SSD small	45	Used in this study		
	New, SSD medium	43			
	New, SSD large	40			
	New, HSD, MSD small	54			
	New, HSD, MSD medium	51			
	New, HSD, MSD large	42			
	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	0.9 (0.3-2.0)	Used in this study		
	Not specified	0.3	0.3	%	MAN 2010
	Not specified	1-2	1-2	%	Papadimitriou 2015
NaOH consumption, kg/MWh	MD	0.2	Used in this study		
	MD	0.2	0.1	l/MWh	Bosch et al. 2009
	HF	4.6	3	l/MWh	Bosch et al. 2009
NaOH price, €$_{2010}$/kg	Total interval	0.26 (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,	Total interval	0.48	Used in this study		

Cost parameter	Sub-category	Value	Original value	Original unit	Source
€$_{2010}$/MWh	Not specified	0.48	0.48	€/MWh	Bosch et al. 2009

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.

In Table B3 prices are expressed in €$_{2010}$/MWh; for recalculation we use specific fuel oil consumption from IMO 2014[5]. Both MAN 2012 and Danish Maritime Authority 2012 assume that the future LNG price will be lower than MD price. 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**
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	1038 (391-1603)	Used in this study		
	New	736 (219-940)			
	New[6]	539-940	range	€/kW	NO$_X$ fond
	Not specified	219-329	300-450	USD/kW	MAN 2012
	Retrofit	1603	32 000 000	USD/vessel ≈ 14 MW	IMO 2016
	Retrofit	391-554	5 350 000 – 7 580 000	USD/vessel ≈ 10 MW	IMO 2015
	New	333-379	4 550 000 – 5 180 000	USD/vessel ≈ 10 MW	IMO 2015

LNG installation costs are not included in the cost estimates above. According to IMO 2015, they constitute about 10% of additional crewing costs.

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[5] 166 g/kWh for LNG;195-215 g/kWh for MGO vessels

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

Appendix C – Main Results for Selected Policy Instruments

Table C1 – Main results for selected policy instruments

Result, unit	***NECA***	***NECA5500***	**CO2 in Baltic Sea and North Sea**			**CO2 in Baltic Sea only**			**Loan with 0% interest rate**	**Port rebate on LNG**	**More?**
			low	**medium**	**high**	**low**	**medium**	**high**			
On top of *No-NECA*											
NO_X emission reductions, kt	65.6	65.6	66.7	68.0	71.7	65.9	66.4	67.9	84.1	65.7	
Average share of extra LNG, new %	4%	7%	5%	7%	10%	5%	5%	7%	21%	4%	
Average share of extra LNG, retrofits %	-	-	1.9%	4.0%	9.8%	0.6%	1.4%	3.8%	24.1%	0.3%	
Total technology costs (social), MEuro	78.5	25.7	81.4	84.5	92.9	79.5	80.6	84.3	110.4	79.0	
Technology costs, €/kg NO_XNO_X	1.20	0.39	1.22	1.24	1.30	1.20	1.21	1.24	1.31	1.20	
On top of *NECA*											
NO_XNO_X emission reductions, kt	-	0.11	1.162	2.457	6.134	0.377	0.835	2.4	18.53	0.17	
Average share of extra LNG, new, %	-	3%	1%	2%	6%	0%	1%	2%	17%	0%	
Average share of extra LNG, retrofits, %	-	-	1.9%	4.0%	9.8%	0.6%	1.4%	3.8%	24.1%	0.3%	
Total technology costs (social), MEuro	-	-52.8	2.9	6.0	14.4	0.9	2.1	5.8	31.9	0.5	
Technology costs, €/kg NO_XNO_X	-	-	2.48	2.45	2.35	2.50	2.49	2.45	1.72	2.66	

Appendix D – Sensitivity Analysis for some Policy Instruments

Comparative Sensitivity Analysis

In Appendix D the following considered policy instruments have been analysed together:

- *NECA* and *NECA5500*
- *CO_2 tax*
- Loan with 0% interest rate
- Port due rebate

We have investigated how the extra LNG consumption, NO_X emission reduction compared to *NECA* scenario, and the total NO_X emissions change with variations in the three key parameters:

- Additional LNG engine price
- Price spread between LNG and MD
- Parameters used for cost annualization in the private cost perspective – investment lifetime and interest rate.

Changes in the No-NECA and NECA scenarios

Our calculation model is based on the assumption on cost efficiency as a basis for investment choice. It applies to all considered policy instruments as well as to the *No-NECA* case. This means, if one or more of the key parameters changes – not only emissions compared to the NECA scenarios would change but also emissions in the *No-NECA* and *NECA* scenarios.

Price of LNG Engine

Table D1 – Extra LNG on top of *NECA*, PJ

Engine price, €/kW		*CO_2 tax* in the *NECA* area			*CO_2 tax* in the Baltic Sea only			0% interest rate	Port due rebate
New	Retrofit	low	central	high	low	central	high		
736	1038	1.82	3.80	9.22	0.59	1.31	3.64	25.56	0.29
650	918	1.50	3.15	7.63	0.49	1.08	3.01	21.27	0.24
564	798	1.22	2.54	6.17	0.40	0.88	2.44	17.34	0.19
478	679	0.95	2.00	4.84	0.31	0.69	1.91	13.76	0.15
391	559	0.71	1.49	3.63	0.23	0.52	1.43	10.50	0.11
305	439	0.50	1.05	2.54	0.16	0.36	1.00	7.60	0.08
219	391	0.38	0.79	1.91	0.12	0.27	0.75	5.90	0.06

Table D2 – NO_X reduction on top of *NECA*, kt

Engine price, €/kW		*CO_2 tax* in the *NECA* area			*CO_2 tax* in the Baltic Sea only			0% interest rate	Port due rebate
New	Retrofit	low	central	high	low	central	high		
736	1038	1.16	2.46	6.13	0.38	0.84	2.35	18.53	0.17
650	918	0.96	2.03	5.07	0.31	0.69	1.95	15.28	0.14
564	798	0.78	1.65	4.10	0.25	0.56	1.58	12.31	0.12
478	679	0.61	1.30	3.23	0.20	0.44	1.24	9.66	0.09
391	559	0.47	0.98	2.44	0.15	0.34	0.94	7.27	0.07
305	439	0.33	0.71	1.75	0.11	0.24	0.68	5.18	0.05
219	391	0.29	0.60	1.49	0.09	0.21	0.58	4.39	0.04

NO_X emissions, kt

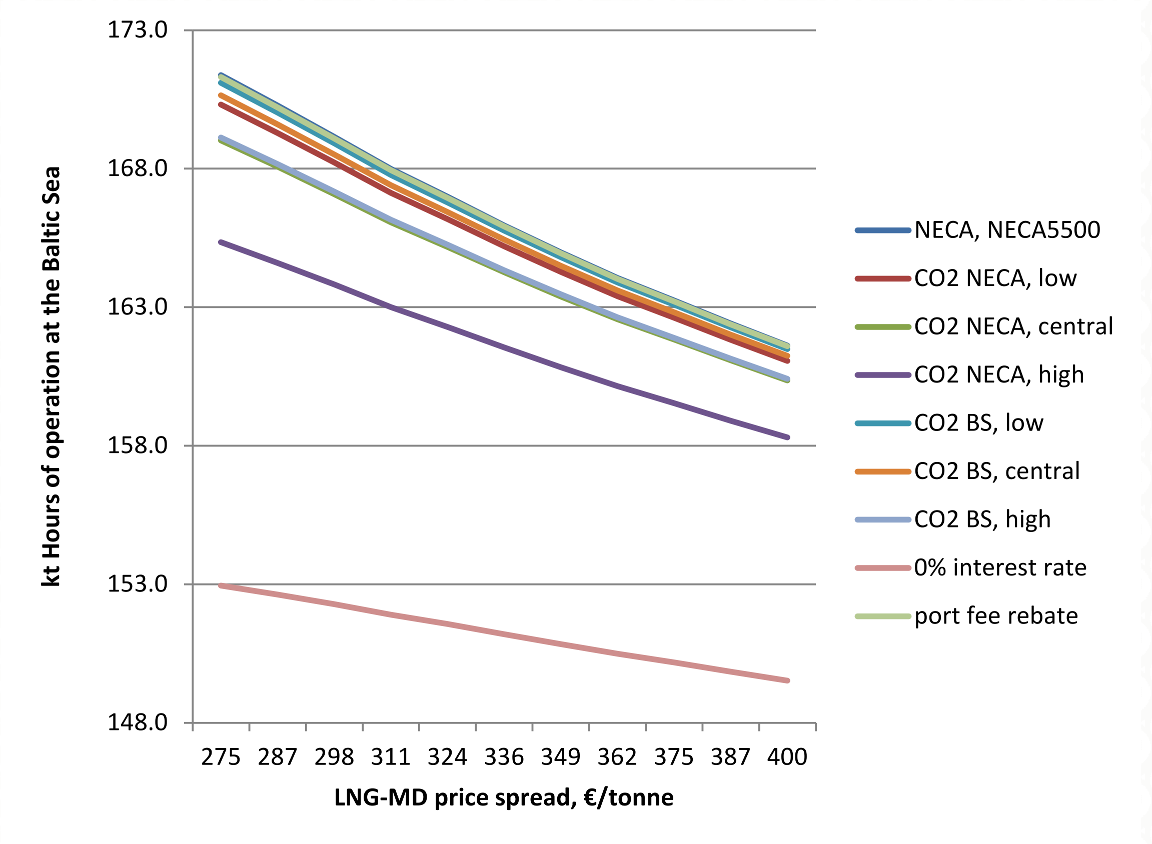
Price Spread between LNG and MD

Table D3 – Extra LNG on top of *NECA*, PJ

LNG price, €/t	**Price spread, €/t**	***CO_2 tax* in the *NECA* area**			***CO_2 tax* in the Baltic Sea only**			**0% interest rate**	**Port due rebate**
		low	central	high	low	central	high		
610	275	1.82	3.80	9.22	0.59	1.31	3.64	25.56	0.29
587	298	1.61	3.38	8.24	0.52	1.16	3.23	23.58	0.26
562	324	1.42	2.99	7.34	0.46	1.02	2.86	21.73	0.23
536	349	1.26	2.66	6.56	0.41	0.91	2.54	20.07	0.20
511	375	1.13	2.38	5.92	0.37	0.81	2.28	18.68	0.18
485	400	1.01	2.14	5.35	0.33	0.73	2.05	17.41	0.16

Table D4– NO_X reduction on top of *NECA*, kt

LNG price, €/t	**Price spread, €/t**	***CO_2 tax* in the *NECA* area**			***CO_2 tax* in the Baltic Sea only**			**0% interest rate**	**Port due rebate**
		low	central	high	low	central	high		
610	275	1.16	2.46	6.13	0.38	0.84	2.35	18.53	0.17
587	298	1.02	2.16	5.42	0.33	0.73	2.07	16.97	0.15
562	324	0.89	1.90	4.78	0.29	0.64	1.82	15.51	0.13
536	349	0.78	1.67	4.23	0.25	0.56	1.60	14.22	0.12
511	375	0.70	1.49	3.78	0.22	0.50	1.42	13.14	0.10
485	400	0.62	1.33	3.39	0.20	0.44	1.27	12.17	0.09



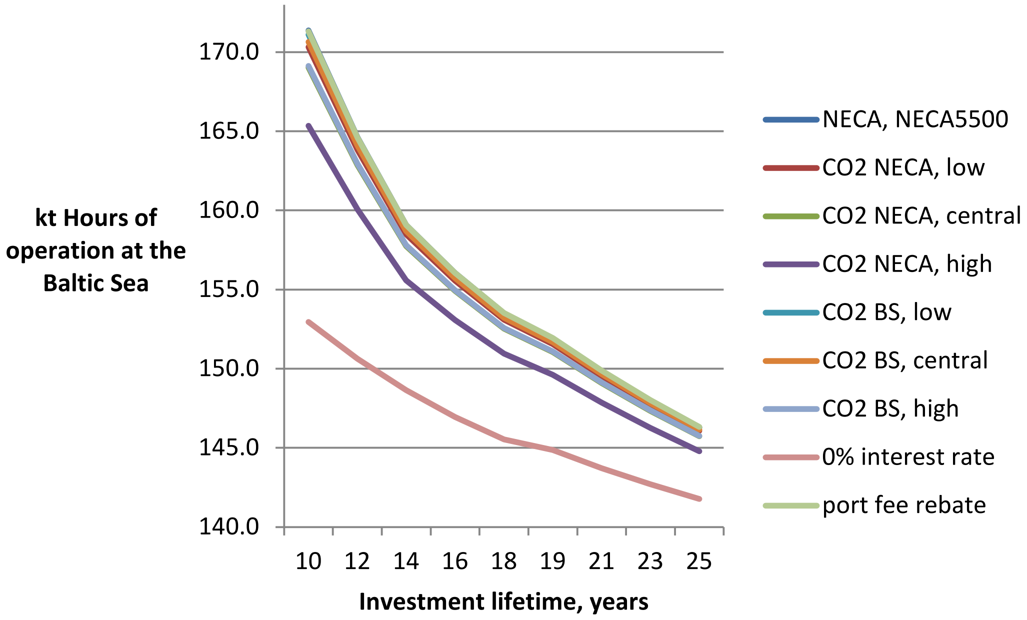
Interest Rate and Investment Lifetime in the Private Cost Perspective

Table D5– Extra LNG on top of *NECA*, PJ

Investment rate, %	Investment lifetime, years	***CO_2 tax*** **in the *NECA* area**			***CO_2 tax*** **in the Baltic Sea only**			0% interest rate	Port due rebate
		low	central	high	low	central	high		
10	10	1.82	3.80	9.22	0.59	1.31	3.64	25.56	0.29
7	14	1.08	2.26	5.49	0.35	0.78	2.17	14.96	0.17
6	18	0.80	1.67	4.06	0.26	0.58	1.60	11.65	0.13
5	21	0.63	1.33	3.22	0.21	0.46	1.27	9.12	0.10
4	25	0.48	1.01	2.46	0.16	0.35	0.97	6.85	0.08

Table D6 – NO_X reduction on top of *NECA*, kt

Investment rate, %	Investment lifetime, years	***CO_2 tax*** **in the *NECA* area**			***CO_2 tax*** **in the Baltic Sea only**			0% interest rate	Port due rebate
		low	central	high	low	central	high		
10	10	1.16	2.46	6.13	0.38	0.84	2.35	18.53	0.17
7	14	0.68	1.44	3.59	0.22	0.49	1.38	10.53	0.10
6	18	0.50	1.06	2.64	0.16	0.36	1.02	8.05	0.08
5	21	0.40	0.84	2.08	0.13	0.29	0.80	6.22	0.06
4	25	0.30	0.64	1.59	0.10	0.22	0.61	4.60	0.05


kt Hours of operation at the Baltic Sea
170.0
165.0
160.0
155.0
150.0
145.0
140.0
10
12
14
16
18
19
21
23
25
Investment lifetime, years
NECA, NECA5500
CO2 NECA, low
CO2 NECA, central
CO2 NECA, high
CO2 BS, low
CO2 BS, central
CO2 BS, high
0% interest rate
port fee rebate

Appendix E – Relation between Port Fee and Engine Size

Port fees are generally related to gross tonnage and this study has therefore developed a conversion table between gross tonnage and engine sizes, see Table E5. The relation is based on statistics from the ship database Sea-Web (IHS Markit, 2016).

Table E1 – Average gross tonnage per ship segment for different engines sizes according to ship statistics.

Ship category	**Annual average number of calls/vessel (Sweden)**	**GT, tonnes**			
		Small engine (<6 kW)	Medium engine (6-15 kW)	Large engine (>15 kW)	Port registration fee, €/year
Bulk carrier	0.2	8 500	34 300	100 900	5
Chemical tanker	1.2	3 300	26 700	64 400	5
Container ship	2.1	6 000	11 100	49 000	5
General Cargo	3.1	2 400	15 500	22 900	5
LG tanker	1.7	3 400	30 900	105 300	5
Oil tanker	1.7	1 300	50 700	122 700	5
RoRo cargo	8	4 900	14 300	30 600	5
Ferry	261.7	800	8 600	22 400	5
Cruise	5.3	1 300	17 000	84 500	2.7
Vehicle carrier	8	7 500	45 200	58 600	3.5

Appendix F – Calculating distribution for NO_X tax

The cumulative function of the lognormal distribution is given by the function $D(x)$:

$$D(x) = \frac{1}{2} \cdot \left[1 + \text{erf}\left(\frac{\ln(x) - \mu}{\sigma \cdot \sqrt{2}}\right)\right] \tag{6.1}$$

The mean (μ) and the standard deviation (σ) is given by the fitted lognormal function, the red line in Figure 2.2 . The error function (erf) and the cumulative distribution function (D) is further explained in statistical literature, e.g. (Milton & Arnold, 2003). The distribution of operating time (h_{Tax}) in the Baltic Sea is assumed to be the same in Equation . The equation therefore gives the fraction of ships that won't install SCR for a give tax level. Consequently, Equation will give the fraction of ships that will install SCR for a given tax level.

$$ships\ that\ will\ install\ SCR = SCR_{\%} = 1 - \frac{1}{2} \cdot \left[1 + \text{erf}\left(\frac{\ln(h_{Tax}) - \mu}{\sigma \cdot \sqrt{2}}\right)\right] \tag{6.2}$$

However, the emissions from all ships are related to the actual number of hours that a ship operates with SCR and not the number of ships that operates with SCR. The cumulative distribution is illustrated in , where also the cumulative version of the probability distribution in Figure 2.2 is plotted. for example shows that only the top 5 % of the fleet operates more than 5500 hours. However this top 5% stands for about 30 % of the total operational time at the Baltic Sea. Since the calculated distribution of ships is a lognormal function the amount of hours may go to infinity, however we have put up a cut of level at 8760 h (one year). The percentage above this threshold is equally distributed on all hours below 8760 h.

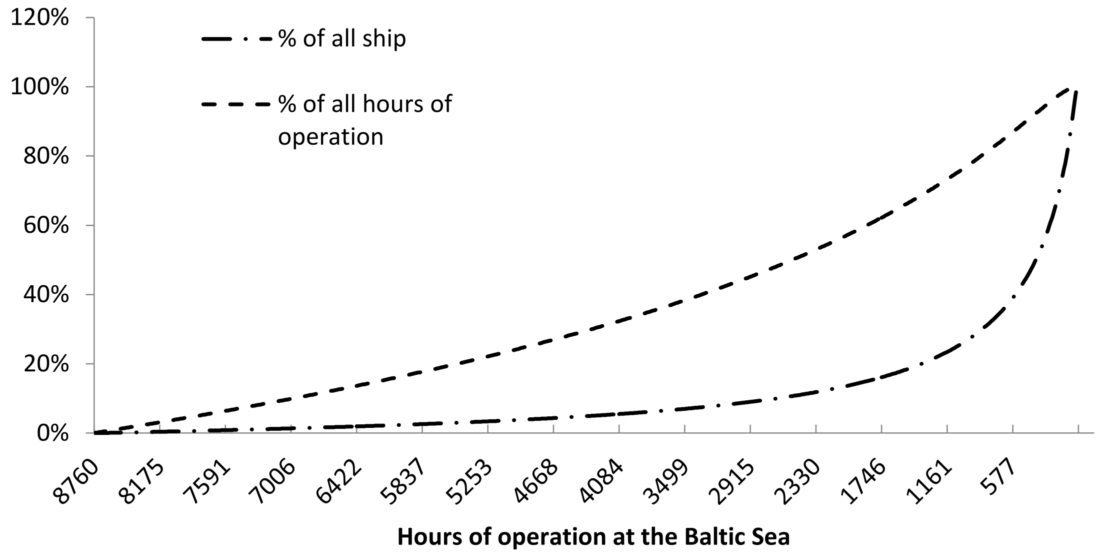


Figure F1 – Relationship between the distribution curve for all ships and the distribution curve for total hours of operation at the Baltic Sea

If each ship category (s) is assumed to have the same type of distribution of operating hours as for all ships in the Baltic Sea 2013 the fuel use under the time that Tier II ships operate with SCR would correspond to Equation .

$$Fuel_{s,SCR} = Fuel_s \cdot \%\, SCR_{hour} \tag{6.3}$$

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