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The Role of a Cap and Trade Market in Reducing NO_X and SO_X Emissions: Prospects and Benefits for ships within the Northern European ECA

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Abstract

This paper presents a financial evaluation of alternative approaches to the abatement of NOx and SOx emissions from ships operating within the Emissions Control Area (ECA) of Northern Europe. The objective of the paper is to assess the financial viability of a range of alternative technologies and fuel types, by accounting for revenue that might be generated from emissions trading within a *cap and trade* market for NOx and SOx emissions. Using a sample of real ships that operate within the ECA, NOx and SOx emissions for each alternative are estimated and the revenue generated within a *cap and trade* system is calculated under a given set of assumptions. Results suggest that distillates are not an economic solution to meeting regulatory requirements. Conservative estimates of revenue generated within any prospective *cap and trade* system suggest that sea-water scrubbers, HAM and SCR systems would all constitute financially attractive abatement options, while the use of LNG is the most financially attractive alternative. A *cap and trade* system is found to be highly efficacious in providing a relatively inexpensive source of finance for investments in improved environmental performance, as well as incentivizing such improvements; thereby removing any requirement for public sector support.

Keywords: cap and trade, emissions, NOx, SOx, ECA, abatement

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1. Introduction

1.1 Air pollution from ships

More than 95% of the world's shipping fleet has traditionally been powered by diesel engines [1,2] and, primarily as a result of the low quality of fuels used, even the most modern of marine engines produces higher emissions per power output than regulated on-road diesel engines [3], a fact recognised in regulated emissions standards worldwide [4]. In addition to CO_2 and other greenhouse gases, there are a number of other atmospheric pollutants which are of particular concern. These include:

- SOx (oxides of sulphur). The emission of this shipping pollutant is related directly to the relatively high sulphur content of marine fuel in comparison to other fuels. Indeed, the bunker fuel used in ocean-going ships has been estimated to produce over 100 times per unit volume the amount of sulphur of on-road diesel [5-7].

- NOx (oxides of nitrogen). Volumes of this emission relate directly to the temperature at which a fuel combusts and because of the low energy efficiency of marine fuels, they need to be heated to higher temperatures.

- VOC (Volatile Organic Compounds). The cargoes of tankers emit VOC during cargo loading/discharge, crude oil washing operations and during sea voyages.

- PM (Particulate Matter – typically measured in terms of PM_{10} and $PM_{2.5}$). This is produced during combustion and mainly takes the form of soot and ash. Again, this pollutant is especially prevalent from ships because of the poor quality of fuel used in comparison to other transport modes.

It has been found that ships contribute around 55-77% of total emissions in port regions [8, 9] and three of the pollutants with a very specific local impact (SOx, NOx and PM) are especially problematic in that they cause acidification, eutrophication, ground level ozone and human health problems, including cardiopulmonary mortality [10].

1.2 The regulatory context for NOx and SOx emissions from ships

Although the International Maritime Organization (IMO) has a long history of regulating ship pollution through its International Convention on the Prevention of Pollution from Ships (known as the MARPOL Convention), air emissions have been one of the last major ship pollutants to be regulated. It is MARPOL Annex VI which sets limits on NOx and SOx emissions from ship exhausts. The issue of energy efficiency and greenhouse gas emissions was only recently addressed (in July 2011), with the addition of a new chapter 4 to MARPOL Annex VI.

IMO NOx and SOx emissions standards are commonly referred to as the Tier I, Tier II and Tier III standards. The Tier I standards entered into force on 19 May 2005 and applied retrospectively to new engines greater than 130 kW installed on vessels constructed on or after January 1st 2000 or which have undergone a major conversion after that date. In anticipation of the ratification of the Annex VI provisions, most marine engine manufacturers have been building engines compliant with these Tier I standards since 2000.

Amendments to Annex VI of the MARPOL Convention were adopted in 2008 and have only relatively recently come into force on 1 July 2010. The amendments define the Tier II and Tier III standards which introduced new fuel quality requirements and Tier II and Tier III NOx emission standards for new engines, as well as a revised Tier I NOx requirement for existing pre-2000 engines. Amongst many other things, this revised version of MARPOL

Annex VI also established the concept of specific ‘Emission Control Areas’ (ECAs) and defined the first of these as the English Channel, the Baltic Sea and the North Sea, where more stringent caps on the sulphur content of marine fuel would apply; a reduction to 1.00% (10,000 ppm), effective 1 March 2010 and a reduction to 0.10% (1,000 ppm), effective 1 January 2015. Instead of using low sulphur fuel, it also allowed the use of abatement technology as an alternative means of achieving the required reductions in the sulphur oxide content of exhaust gas.

The expectation of success for the IMO’s regulations on SOx emissions is very clearly shown in the forecast figures for 2020 in Figure 1. Due in large part to the considerable reductions made in shore-based industry and other terrestrial sources within the EU, this also clearly shows that, in the absence of any regulation on the part of the IMO or the EU itself, by 2020 the shipping industry is expected to be a larger source of sulphur pollution than all other sources combined.

INSERT FIGURE 1

The IMO’S NOx emission standards are based on an engine’s maximum operating speed (in rpm) because, in general terms, the lower the rpm, the greater the propensity to generate NOx. As shown in Table 1, the limits are expressed in g/kWh, with Tier I and Tier II limits being global, while Tier III standards are to apply only within NOx Emission Control Areas. As shown in Figure 2, the level of success which these regulations are expected to achieve in reducing NOx emissions is nowhere near as high as for SOx.

INSERT TABLE 1

INSERT FIGURE 2

In the past, EU policy on the control of shipping emissions has often pre-empted the implementation of IMO regulations. For example, the 2008 amendments to Annex VI of the MARPOL Convention reinforced the EU Marine Fuel Directive by specifying a sulphur cap of 0.10% at berth within the whole of the EU. Indeed, the establishment of the Northern European ECA is itself a proactive, locally implemented EU initiative which led directly to the design and development of the globally applicable, enabling regulations of the IMO.

The EU not only has an important regulatory role in the abatement of shipping emissions within the Northern European ECA, it also plays a critical role in establishing incentives (both 'carrots and sticks') for achieving reductions in shipping emissions which are greater than the regulated minimum required for ensuring compliance. Four proposals have been considered and discussed as possible instruments for the implementation of EU policy on the reduction of shipping emissions: consortium benchmarking, environmentally differentiated charges, an environmental subsidy approach and the credit-based (*cap and trade*) approach [11]. Each approach comes with advantages and disadvantages. The levying of environmental charges is likely to prove administratively difficult, particularly given an environment where ports are increasingly privatised. Shipping consortia that revolve around environmental considerations may not be easily accepted by a predominantly private-sector international shipping industry and may also fall foul of competition regulation. Subsidies are only considered as supplementary measures.

Overall, what appears to have emerged from continuing discussions is that a *cap and trade* approach is favoured for the trading of NOx emissions and consortium benchmarking as the basis for SOx trading. This study, however, focuses solely on the use of a *cap and trade* system for both NOx and SOx trading, since it is this option which has recently received particular attention from policy makers, within both the IMO and the EU, as the most likely basis for the future trading of CO_2 emissions from the shipping industry.

1.3 Objectives and structure

Given this context and utilizing a sample of ships operating within the Northern European ECA, this paper presents a financial evaluation of alternative approaches to the abatement of NOx and SOx emissions from shipping. The nature of the sample dataset and the difficulty of collecting the required data dictate that Tier I regulations (largely pre-2010) are assumed as the baseline for comparison; simply too little time has elapsed since the entry into force of the later, more stringent, Tier II regulations to allow any meaningful collection of sample data.

The existence of a *cap and trade* market for NOx and SOx emissions is also assumed. This provides a basis for valuing the reductions in emissions achieved by each of the particular tested options for abatement. Obviously dependent upon the level of NOx and SOx reductions achieved by each of the options evaluated herein, this would theoretically provide some level of offset against (compensation for) the costs associated with deploying each of the abatement options.

The analysis contained within this paper is unique in that it facilitates the assessment of the role of, and effectiveness of actually introducing, a *cap and trade* market for the trading of shipping emissions. As will be shown, the results and conclusions confirm that the introduction of a cap and trade system for the shipping sector will reduce the financial burden of implementing environmentally less damaging technologies and operations. This is an important contribution in that at the time of writing, the possible future implementation of a *cap and trade* market is high on the agenda of the IMO in relation to reducing CO_2 and other greenhouse gas emissions from shipping. At its 63rd meeting held in February 2012, the IMO's Marine Environment Protection Committee (MEPC) continued its discussions on, and review of, possible market-based measures that could be used to complement existing technical and operational measures that are already incorporated within IMO regulations. During this meeting, the German and Japanese delegations very strongly advocated the introduction of a *cap and trade* market for shipping GHG emissions. The outcomes of this analysis support their contentions and will inform this ongoing debate which is scheduled to continue as part of the agenda for MEPC64 to be held in October 2012. In addition, with the continuing question-marks hanging over the success and/or practical effectiveness of the existing northern European ECA, the analysis presented within this paper could provide a justification for the introduction of a *cap and trade* market for shipping's SOx and NOx emissions as a supplement to existing regulations, particularly in advance of when global regulations come into effect.

The paper is structured as follows. Following this introduction, section 2 describes the nature of a *cap and trade* system and how it might be used to help reduce NOx and SOx emissions from shipping. Section 3 elaborates the methodology which is applied for evaluating emissions reductions and how these are then taken into account in the financial appraisal of alternative abatement options. The main characteristics of each of the technologies or alternative fuels that constitute the abatement options tested within the paper are outlined in section 4, while the results of the analysis for each of these are presented in section 5. Conclusions are drawn in section 6.

2. An introduction to the *Cap and Trade* system

A *cap-and-trade* system is a policy approach for controlling a large volume of emissions from a variety of different sources over a large geographical area [14]. It is an economic instrument to limit pollution, which provides industry with a degree of flexibility in how it achieves compliance with environmental regulation. The basic concept is that emissions reductions are treated as a tradable commodity, which can be bought and sold like any other product in a market. The idea behind emissions trading is to provide an incentive for industrial players to invest in clean technologies and innovation which will increase productive efficiency. In this way, the required investment in reducing emissions will yield a tangible return.

For a *cap and trade* system to work, a central Authority (for example, this might be an agency of the EU or the EC itself) sets the emissions limits for a range of industrial installations within a ‘capped’ geographical area. For emissions trading schemes in use today, the limits are arranged in order to fulfil environmental targets. Often, the emissions of an historic year are assigned as a baseline (1990 seems to be a popular reference year). In such a case, emissions must be reduced considerably in order to reach the baseline. Not all industrial installations within a prescribed sector are capped. Instead, every implementation of a *cap and trade* system will have a minimum value established for qualification. For example, the

European CO_2 Trading Scheme targets all installations with rated thermal input exceeding 20 MW, while a local NOx and SOx programme in California targets those installations emitting more than 4 tons annually. Every targeted installation within the capped area receives emissions allowances (i.e. permission to emit *x* tons per year) that should not be exceeded. Installations have the option either to reduce emissions unilaterally (by, for example, installing cleaning systems) or to purchase supplementary allowances from other installations, over and above their initial allocation, so that they might reach compliance by the end of the relevant period. Trading occurs when an installation with a surplus of reductions or allowances sells them to an installation with growing emissions or an inability to make cost-effective reductions.

As different industrial sectors have different costs associated with unit reductions in emissions, industrial sectors with low marginal abatement costs are encouraged to reduce emissions by more than they are actually required to by regulation, so that they can then provide the market with the surplus[1]. For this service, they are rewarded with a certain profit margin on the sale of these surplus emissions reductions. Installations with high marginal abatement costs, on the other hand, benefit from savings which accrue from their effectively outsourcing what would be considerably more costly to do in-house. At the end of each assessment period, installations have to certify their reductions and hefty fines are levied (per excess ton emitted) on those that have failed to comply. Thus, overall environmental targets are attained, but are physically achieved in the least expensive manner.

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[1] Examples of emissions Exchanges are the Chicago Climate Exchange (CCX), Chicago Climate Futures Exchange (CCFE), the European Climate Exchange (ECX), Nord Pool, Powernext, the Austrian Energy Exchange (EXAA) and the New York Stock Exchange.

Trading can take place anonymously through an emissions market (i.e. a form of stock exchange for emissions) or as an over-the-counter (OTC) transaction which is a form of private sale; made either directly from one company to another, or through a dealer [15, 16]. The market mechanism of supply and demand determines the selling price of the emissions commodity and the pattern of price fluctuations over time. The market Authority does not interfere with the workings of the emissions market, but the driving determinant of the trading price is the allowable emissions limit (i.e. the level of the cap which is set by the Authority). The lower this cap, then the more expensive per ton becomes the cost of abatement and, therefore, the higher the price of the individual traded emissions. Naturally, the price of traded emissions will not exceed the level of fine per ton for non-compliance. An installation or entity can also bank emission credits for rolling-over into the next trading period, but this cannot be excessive, usually no more than 10% of the annual allowances.

The *cap and trade* system is best suited to contexts where environmental concerns occur over a relatively large area and are caused by a large number of polluting sources that have relatively different abatement costs and the ability to effectively monitor reductions. For a *cap and trade* system to succeed, however, it is vitally important that initial emissions allowances are equitably allocated and that the cap is set low enough so that companies have the incentive to invest in clean technologies. Criticism of emissions trading schemes tends not to revolve around their theoretical effectiveness, but rather the circumstances where they can be effectively and successfully applied [17]. *Cap and trade* programmes are also criticised as being regressive in that the allocation of emissions permits or allowances usually favours older and more highly polluting entities [18].

NOx and SOx *cap and trade* systems were pioneered in the USA and operate under the supervision of the US Environmental Protection Agency (EPA). Results from these American programs are reported to be remarkable, with SO_2 in particular reducing more quickly and at lower cost than anticipated. Water reserves with acid depositions are recovering in the Northeast and sulphate deposition is 25-50% lower than 1990 levels in the Northeast and the Midwest [19]. As also shown in Figure 3, results are also encouraging concerning localised high emissions (hot spots). Another interesting outcome is that the *cap and trade* system has not led to any geographical shift in emissions but, in contrast, has led to the largest emitters having the largest reductions.

INSERT FIGURE 3

The only US programme to include ships is RECLAIM; a relatively local *cap and trade* programme implemented in Los Angeles, California and which allows ships to trade NOx and SOx with installations from other industries located in the coastal area (namely ‘Zone 1’). Ships are precluded from trading with inland installations (referred to as ‘Zone 2’). The Swedish Shipowners Association has, however, proposed the voluntary participation of ships in a NOx and SOx emissions trading scheme within the EU. A Swedish government inquiry, conducted by SIKA, Sjöfartsverket, Naturvårdsverket and Energimyndighetens, has provided support for the theoretical potential of a *cap and trade* system, but is neutrally positioned otherwise [21].

The primary objective of this study is to analyze alternative approaches to NOx and SOx abatement options at sea and to investigate the costs and benefits of these alternatives for shipping companies that were to participate voluntarily in a European *cap and trade* system as proposed by the Swedish Shipowners Association.

3. Methodology

In order to facilitate such an analysis, a sample of real ships was selected which is deemed to be reasonably representative of the current shipping traffic in the waters of the northern EU. The sample comprises 37 actual identified ships that, at the time the analysis was conducted, were actively operating in northern waters. The types of ship in the sample were car carriers (4), container ships (3), cruise ships (2), general cargo (1), passenger ships (7), Ro-Ro cargo ships (9), tankers (7), supply ships/icebreakers (3) and utility vessels (1). Technical specifications for each of the sample ships were retrieved from Lloyd's Fairplay Database and supplemented in some respects from other sources. The sample can be further characterized as follows:

- It comprises a range of different sized ships, with total main engine kilowatt output ranging from 2,200kW for a product tanker to 72,000kW for a cruise ship. The average output of the sample is 20,000 kW but the median is 14,480kW, which is considered as pertaining to a medium size ship.
- Most of the sample ships were medium speed diesel (MSD), with 4 being classified as high speed diesels (HSD) and 3 as slow speed diesels (SSD).
- 7 of the 37 sample ships confirmed using distillates in their main engines at the time of inquiry.

- The annual main engine time utilization rate ranges from 1,500 hours (17% of the calendar year) to 7,780 hours (89% of the calendar year) while, on average, a ship would steam 5,077 hours (58% of the calendar year). Within the sample, low steaming times were associated with a visiting overseas cruise ship from overseas, a passenger ship (surprisingly) and short-sea tankers that have relatively long loading and unloading times.
- The average engine power utilization rate is 82%, ranging from 68-95%.
- Annual fuel consumption varies between 1,500 tons and 38,000 tons, with the average being 15,800 tons.

All ships are assumed to steam only within the northern European ECA and to operate under the ECA regulations on emissions. In reality, 10 of the sample ships operate in other waters, including all 4 of the car carriers. The rationale behind this assumption is to explore the potential use of emissions markets for shipping companies under the most stringent baselines. Another assumption made is that emissions cleaning technologies have a zero scrap value.

For every ship in the sample, annual NOx and SOx emissions were computed in tons under the base-case assumption that there exists no cleaning technology on-board and that the ship is steaming under Tier I standards. For each ship in the sample, NOx emissions were calculated exclusively for main engine steaming on the basis of: the ship's main engine revolutions per minute (RPM); an indicator of specific fuel consumption from the NTM methodology [22]; the ship's operational characteristics (main engine time utilization rate, engine power utilization rate etc) and; using the IMO's NOx curve [23]. SOx emissions were calculated according to the sulphur content in fuel by volume. Any emissions at berth and/or during manoeuvring have been excluded from the analysis for the purpose of simplicity.

Annual NOx and SOx emissions were then calculated for each of the sample ships under a range of alternative scenarios which include the deployment of different cleaning technologies and switching to alternative fuels. Specifically, the alternatives for which such calculations were made were as follows:

1. Switching to low sulphur residual fuel.
2. Switching to marine diesel oil (MDO) as a fuel.
3. Switching to marine gas oil (MGO) as a fuel.
4. Installing a Selective Catalytic Reduction (SCR) System for NOx control.
5. Installing a Humid Air Motor (HAM) system for NOx control.
6. Installing a Sea-water Scrubber for SOx control.
7. Switching to liquefied natural gas (LNG) as a fuel.

Over an assumed five-year period of operation, the calculated reductions in NOx and SOx emissions which are below the IMO baselines (i.e. ECA Tier 1 standards) are considered tradable. These tradable emissions were calculated in tons per ship per annum for all the above alternative technologies and fuels. Thereafter, they are utilized in a supplementary analysis where implied revenues from the emissions market are calculated. In this supplementary analysis, sample ships are assumed to operate under ECA Tier 1 conditions (where the maximum sulphur content of fuel is 1.5%) and are obliged to sell all their tradable credits in the emissions markets.

After consulting the relevant literature [e.g. 24, 25] and updating the information contained therein by contacting relevant industry players (such as Wärtsilä, Aalborg, Clean Marine AS, Krystallon, Marine Exhaust Solutions Inc.), the total cost of each alternative was calculated and divided by each tradable ton of emissions to give a figure for Total Cost/tradable ton per alternative technology or fuel and per ship. Total costs include capital expenditure, maintenance, operation, monitoring and verification costs for a five year time horizon. The capital expenditure associated with the use of each alternative technology or fuel is spread equally over the five years and all numerical results thereafter consider a five year write-off.

Last but not least, the estimation of the revenues earned from the sale of tradable emissions was conducted only after reference to the marginal abatement costs of the land-based industries [26] which are expected to provide much of the market demand for emissions credits within any *cap-and-trade* programme in which shipping participates. Thereafter, revenues are calculated using the lowest marginal abatement costs of the land-based industries, corresponding to 900 Euros per traded NOx ton and 960 Euros per traded SOx ton. Because of the absence of a real operational emissions market, the revenue estimates derived in the analysis reflect this expected average selling price per unit and, as such, are likely to underestimate the revenue earned from emissions trading. Under this prudent assumption, all alternative technologies and fuels are evaluated in terms of return on investment (ROI) and the payback period required. Obviously, given the assumption on traded price, these measures will be lower and longer, respectively, than one might expect should materialize from any real participation within an emissions market as part of a *cap and trade* system.

A visual representation of the methodology expounded above can be seen in Figure 4 in the form a flow diagram. The five calculation modules shown within Figure 4 were all developed and made operational as linked excel spreadsheets.

INSERT FIGURE 4

4. Characteristics of the Alternative Technologies and Fuels Tested

4.1 General Background

The different technologies or fuels which are evaluated within this analysis reduce NOx and SOx emissions to a different degree. Despite the focus of this analysis on these two types of emissions, the particulate matter (PM) and CO_2 emissions associated with each of the alternatives are also evaluated. The former is important because of the deleterious health effects associated with PM and the latter is important because any alternative which increases greenhouse gases, while reducing NOx and SOx, would not be considered as a viable environmental option.

Within the analysis undertaken herein, each of the cleaning technologies tested is assumed to operate using residual oil with a Tier I maximum of 1.5% sulphur content, thereby satisfying the ECA Tier I standards. The maximum sulphur content of fuels sold, as defined by the ISO, is different from the actual average content in the European market. For Marine Diesel Oil

(MDO), for example, different sources report different average sulphur content, ranging between 0.2-0.5% and 1.5%[2]. For calculations concerning MDO, therefore, an approximate mid-range value of 1% sulphur content has been assumed within this analysis, despite the fact that, during the period to which the data relates, the regulated maximum sulphur content of MDO sold within the EU was 1.5% sulphur content by mass. Tradable emissions of MGO, however, have been calculated at the more stringently regulated standard of 0.1% that applied from January 1st 2008 and which was embodied within the EU Directive on Low Sulphur Fuel (2005/33/EC).

4.2 Low sulphur residuals and distillates

As of 2006 and covering the relevant period of this study, residuals with a maximum of 1.5 % sulphur by mass are sold in the European markets in 380 and 180 centistokes viscosity to provide for those ships steaming in the ECA defined as the Baltic Sea, the North Sea and the English Channel.

Low sulphur residuals may come directly from low sulphur crudes or may be derived from blending high and low sulphur crudes or by blending residuals and distillates. IFO 380 and IFO 180 fuel types can be sold either in regular or low sulphur content. The low sulphur residuals are, of course, in heavy demand for ships operating within the ECA and the average price difference between the low and regular sulphur products during the period of analysis has been as high as US$ 20 per ton, which equates to approximately 8% of the average selling

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[2] For example, Mariterm, refineries and the Swedish Environmental Research Institute – IVL.

price of regular sulphur residuals during the period. In this study, low sulphur residuals (referring to Tier I standards) constitute the baseline operating standard for comparing emissions and costs; specifically, the IFO380 LS product. All results presented are expressed, therefore, in comparison to operating using low sulphur IFO 380.

For the sample ships within this analysis, and more generally for ships operating within the northern European ECA that are willing to participate in the emissions markets, low sulphur residuals will not give any notable emissions reduction credits, either for NOx or for SOx. This is because the fundamental attribute of the IFO380 LS product is simply to satisfy Tier I ECA regulations. Any reduction credits are derived at random, therefore, from blending and represent nothing more than simply a marginal safety net for compliance. However, if ships were to switch to the distillate fuels of marine diesel oil (MDO) or marine gas oil (MGO), this would represent a proactive approach to reducing NOx and SOx emissions. As SOx emissions are proportional to the sulphur content of fuel, the use of MDO and MGO will proactively reduce SOx emissions, as well as particulate matter (PM), at sea. NOx emissions will reduce slightly, while CO_2 emissions will remain unchanged.

4.3 SCR and 1.5% sulphur residual fuel

The SCR system is a commercial product that reduces NOx. It is a catalytic exhaust treatment with an additional oxidation option to lower volatile organic compounds (VOC) and carbon monoxide (CO) [27]. Urea is injected into the hot exhaust gas and reacts with the NOx content to produce harmless nitrogen (N2) and water. The system requires space for deployment within the engine room, but the reduction rate of NOx achieved is somewhere around 90-95%.

4.4 HAM and 1.5% sulphur residual fuel

A Humid Air Motor (HAM) uses evaporated seawater to reduce the temperature in the cylinder, which is responsible for the formation of NOx. “Roughly three times as much water vapour as fuel is introduced into the engine to achieve 70-80% NOx reduction” [28]. For the analysis undertaken herein, a reduction of 70% has been assumed. Costing for the HAM technology has been implemented on the basis of information received from the engineering team of the MS Mariella which, at the time the data was collected, was the only ship to have implemented the system in practice [29].

4.5 Sea-water scrubber and 1.5% sulphur residual fuel

The sea-water scrubber is a cleaning technology that allows a ship to operate in an ECA with regular sulphur fuel and without the necessity to move to the use of another more expensive fuel that is potentially difficult to source. The scrubbing process works on the basis of a straightforward idea. Exhausts from the engine are passed through a sea-water tank, where SOx is filtered out. Upon exit, the scrubbed water is diluted with more water, in order to dissolve the high acidity, and is then discharged with a pH value of 6.5 into the sea. A sea-water scrubber removes 90-95% of the SO_2 content from ship exhaust gas and 10-20% of NOx, as well as 80% of the particulate matter and 10-20% of hydrocarbons. The use of cyclone technology ensures that the particulate material is retained on board ship and not included with the effluent sea-water which is discharged overboard [30].

There exists some concern over the effect of discharging acidic water into enclosed areas, such as ports and bays within the ECA, especially in brackish waters. The volume of water required to filter ship exhausts is also an issue, especially since the required consumption of water is non-linear with the level of reduction achieved. This means that while scrubbing the exhaust from 3% sulphur fuel down to 1.5% or 0.5% sulphur content will require similar quantities of water, a further reduction though, to say 0.2% or 0.1% sulphur content, brings with it a substantial increase in water usage. For sea-going ships, this will probably not pose much of a problem, but for ships operating in enclosed waters it could become an issue. Aeration of the water or adding a base can cut down the quantities required for scrubbing. Clearly, further studies are necessary surrounding the deployment of sea-water scrubbers in both enclosed and semi-enclosed areas, but this remains a promising technology [31].

4.6 Natural Gas

Natural gas as a marine fuel is quite a new idea, but the technology has already been long developed. However, as long as bunker fuel costs were relatively economic and in the absence of the more recent pressure for reducing emissions, it received limited attention. The transition in thinking occurred when natural gas became cheaper than residual oil in early 2006. In July 2012, the price of LNG is quoted as $1.86/MMBtu at the Nova Inventory Transfer (NIT) in Alberta and $2.23/MMBtu at the Henry Hub [32]. This compares to a price for IFO 380 at the same date of $14.76/MMBtu [33].

Natural gas may be regarded as an unusual choice for ships other than gas carriers, but in road transport, natural gas buses have been running successfully in urban areas for some time. Due to persistently high oil prices and under more stringent environmental regulation and market pressures, the possible option of burning natural gas is addressed within this study.

5. Results

5.1 Low sulphur residuals and distillates

For this study, fuel costs were examined in terms of cost-efficiency. Fuel prices per ton were acquired from Bunkerworld and a simple average taken over the sample 12 months for which the study was undertaken. This does not exactly mirror current fuel prices and trends, but does mean that the outcomes from the ensuing analysis represent actuality at the time that the sample ships were operating within the ECA under Tier I standards. It also means that the results of the analysis with respect to the financial benefits to be derived from utilizing either alternative technological solutions or LNG in tandem with a *cap and trade* market for shipping emissions are, in fact, rather understated.

INSERT TABLE 2

On the basis of Table 2, switching to MDO will clearly increase fuel costs by 61% above the cost of the baseline IFO 380 LS, while switching to MGO will increase fuel costs by 79% against the same baseline. In practice, this translates as an annual cost increase for each of the ships in the sample analysed of between 270,000 Euros and 7.3m Euros, based on a range for annual fuel consumption of 1,500 tons to 38,000 tons. This increase in cost is quite remarkable. Dividing the overall cost increase across the reductions in both NOx and SOx (as measured in combined tons) yields a unit cost of 4,600 Euros per ton of emissions reduction for switching to MDO and 6,000 Euros per ton of emissions reduction for switching to MGO.

Obviously, under these tested scenarios and compared to the, admittedly conservative, assumptions related to the unit sale price of emissions in the *cap and trade* market, the unit cost of emissions reduction per ton is far too high to have any practical selling potential in any *cap and trade* emissions market. However, if ships were to switch to distillates and did simultaneously successfully participate in the emissions market (albeit at the rather low assumed unit sales price), annual fuel costs would show a net increase of 55% on average for MDO and 66% on average for MGO across all sampled ships. It is apparent, therefore, that any earnings derived from trading NOx and SOx reductions in a *cap and trade* market are negligible compared to the annual increase in fuel costs. Switching to distillates does not, therefore, appear to be a cost-efficient solution. Hence, other alternatives need to be scrutinised.

5.2 SCR and 1.5% sulphur residual fuel

Within this analysis, the assumed cost structure for the deployment of an SCR system includes [28]:

- capital expenditure;
- operational costs – 200 Euros per ton of NOx for urea;
- maintenance costs - for every 1000 hours of operation, 6 cleaning events are required at 150 Euros per event. Within the analysis, therefore, 8,000 Euros per annum was

assumed as the maintenance cost for all ships, irrespective of the main engine time utilization rate.

- monitoring costs – 20 Euros per ton of emissions traded.

An SCR installation company was consulted and a mean estimate per ship for capital costs was calculated, together with an expected level of variation. The average capital cost used is 51,500 Euros per MW [28], which also falls within other estimates for newbuilds and retrofits [34]. As can be seen in Figure 5, the main components of the finalized cost structure for the SCR system are capital expenditure and operational costs (for urea), each of which may account for the largest share of the total, depending on the main engine time utilization rate.

INSERT FIGURE 5

Based on this set of cost assumptions, Table 3 shows that the average cost per ton of reductions in NOx emissions is evaluated as ranging between 322 and 1,124 Euros, with a mean value of 486 Euros. These results not only accord with the literature, they also show that NOx abatement costs are lower for ships than for land installations. The primary factor that determines the costs per NOx ton is the steaming time of a ship per year; the higher the time utilization rate of the main engine, the further the constant value for capital expenditure is diffused over a higher number of reduced tons of NOx emissions. Ships with a combination of small engines and a low amount of annual steaming will, therefore, find it difficult to exploit the NOx market with a SCR installed, as their NOx reductions available to trade will be insufficient to compensate for the high fixed cost of SCR installation, at least with the market estimates assumed within this study.

INSERT TABLE 3

The average rate of return is 100% with a payback period of 2.7 years. This means that, within the five year time horizon of this study, one SCR installation on a ship can support another one in the same fleet. Depending on the type of fuel used during operation, there is some evidence to suggest that the catalyst reactor may have to be rebuilt [35]. Although there is some considerable uncertainty surrounding the lifespan of a catalytic reactor, this study has opted for a strict and very conservative assumption of a 5-year time horizon for the amortization of the capital expenditure. It should be recognized that this implies that should the lifespan of the catalytic reactor prove to be longer than 5 years in practice, then the results obtained herein will underestimate the overall benefits of the system. Another potential issue of concern is the extent to which revenue generation from the trading of NOx emissions is sensitive to a changed baseline as embodied within the IMO's NOx curve. Addressing this issue explicitly, it is deduced that at a baseline value of 6 grams of NOx per kilowatt hour, ships will start to show a net loss from trading although the steaming time utilization rate is an important contributing factor in this.

5.3 HAM and 1.5% sulphur residual fuel

In contrast to the SCR system, the HAM system does not use an additive (urea in the case of SCR), which means that there are no operational costs associated with it. On the other hand, the capital expenditure per MW is three times as high, lying between 95,000 Euros per MW (for a large and new ship) and 131,000 Euros per MW (as a retrofit for a small ship) [28]. The major capital expenditure associated with the HAM system is the humidifier, which has a life span of between 12.5 to 25 years depending on the material used. As with the SCR system, and in order to make direct comparisons across all alternative options, capital expenditure has been assumed to be spread over five years, even though the practical lifespan of this technology is much longer. It should be recognized, therefore, that the calculated returns from implementing this system are likely to be underestimated. However, that said, the cost structure underpinning this analysis can be seen in Figure 6.

INSERT FIGURE 6

For the implementation of the HAM technology, Table 4 shows that the average cost per ton of reduced NOx emissions is 678 Euros for newbuilds and 750 Euros for retrofits. Utilising the *cap and trade* emissions markets, within a five year time frame the return on investment is 51% for newbuilds and 37% for retrofits, with an average payback period of 3.8 and 4.2 years respectively. Again, the main determining factor for the ship with the highest costs per ton of reduced NOx emissions was the main engine time utilization rate, with ‘idle’ ships obviously yielding the worst results.

INSERT TABLE 4

5.4 Sea-water scrubber and 1.5% sulphur residual fuel

Capital expenditure comprises about 98% of the total cost of a sea-water scrubber system. On average and under the standard assumptions for the evaluation, over the five year period of analysis, the unit cost per ton of reduced emissions is 1,470 Euros for newbuilds and 2,046

Euros for retrofits. Given the assumed market prices of 900 Euros per ton for NOx and 960 Euros per ton for SOx, it is self-evident that the investment in this system does not payback within the period of analysis. In fact, a sea-water scrubber system requires about eight years of trading the emissions savings from newbuilds and eleven years for trading the emissions savings from retrofits. This is not so much due to the high level of capital expenditure per se, but rather to the relatively low level of SOx emissions saved, with the emissions saving volume ratio between NOx and SOx emissions standing at 5:1. I any case, perhaps it is inappropriate to evaluate the technology over such a short time horizon, especially since, as shown in Table 5, with the possibility of emissions trading it does seem to provide new ships operating within the North European ECA with the potential to adapt to the regulations without compromising either on cost or the environment.

INSERT TABLE 5

5.5 Natural Gas

Using liquefied natural gas (LNG) as a fuel is undoubtedly the best option in terms of environmental performance, as it emits only small amounts of NOx, SOx and PM. In addition, of all the alternatives considered within this analysis, it is the only one that yields a reduction in CO_2 emissions. NOx emissions from burning natural gas are just 1.42 grams per kilowatt hour, while SOx emissions are negligible at 0.00154 grams per kilowatt hour. For ships burning LNG, therefore, this produces a high level of emissions reduction credits (shown in Figure 7) that can be traded in the emissions markets.

INSERT FIGURE 7

Prices for LNG can vary by geographical location, but after consulting several suppliers the highest retail price found for LNG during the period covered by the analysis was 0.035 Euros per kilowatt hour. In order to take into account historical fluctuations in prices and to ensure a conservative approach was adopted, this figure was inflated by 30%, so that a price of 0.045 Euros per kilowatt hour was set for the purposes of the analysis contained herein. Under this pricing scenario, the annual cost of burning LNG is reduced to an average level of 92% of the cost of using low sulphur IFO380. In the case of ships participating in the emissions market, the revenues from trading emission reductions are notable. After accounting for this trading revenue, the annual cost of using LNG is further reduced to an average of 58% of the IFO380LS annual cost (see Figure 8).

INSERT FIGURE 8

In the absence of emissions trading, the breakeven price for LNG (where the annual fuel costs of natural gas and low sulphur residual oil (IFO380 LS) are equal) is, on average, 0.04996 Euros per kilowatt hour. If revenues from trading in the emissions market are taken into account, however, the breakeven price for LNG increases to 0.0668 Euros per kilowatt hour. In addition to lower fuel costs, the price of LNG has normally been less volatile than that of oil, with prices locked in under long-term contracts; a factor which assists with cost planning and risk reduction.

Despite the benefits in terms of fuel cost and the environment, however, there are several practical difficulties that need to be overcome in utilizing LNG as a fuel for ships. These include various technical storage and logistical issues relating to: the space requirements for natural gas, both ashore and onboard; the specialized nature of the technology required for handling LNG and; the limited number of currently available locations for supplying ships with LNG (though distribution facilities, particularly within the Northern European ECA, have been multiplying in recent years). By far the most critical difficulty lies with the fact that shipbuilding costs will be as much as 20-25% higher than ships with conventional engines [34], at least in the short-term until such point that LNG-powered ships achieve the status of an established and standard design. Clearly, this could have a significant influence over the economics of operating ships using LNG as a fuel and needs to be taken into account in this analysis. Perhaps a more attractive option in the future might be the conversion of existing ships driven by standard marine fuels to LNG operation. The first conversion of this type was conducted on the ‘BIT Viking’ and was completed in November 2011 by Wärtsilä [35]. The price paid for this conversion is commercially sensitive information and, as such, is not available. In any case, as the first of its kind, the price paid will probably prove unrepresentative of the steady state cost of such conversions in the future. For both these reasons, modelled costings were conducted solely for the newbuild option rather than the conversion option.

Shipbuilding costs were available for 12 of the 37 ships in the sample. Increased shipbuilding costs for these 12 ships were calculated on the assumption that each was built in 2006 in order to be gas driven and, in consequence, were subject to a 25% inflationary factor over and above the actual shipbuilding cost adjusted for a 2006 year of build. The calculated newbuilding cost increase has then been divided by the annual fuel cost difference between using IFO380 LS and LNG. This is done both with and without taking into account the revenues generated from trading in the emissions markets, to yield the payback period for the additional capital investment in LNG propulsion. The results are presented in Table 6 where, it can clearly be seen that emissions trading can help to finance these increased shipbuilding costs. The cruise ships are luxurious and very expensive to build, so this unsurprisingly elongates payback periods. The ‘Passenger 3’ sample ship has unusually low steaming times and any investment in such a ship will yield a low rate of return and long payback period.

INSERT TABLE 6

5.6 Cleaning technologies with 1% sulphur residual fuel

A final scenario tested was to assume that each of the cleaning technology options previously analysed are deployed in tandem with the use of 1% sulphur residual fuel. Due to a lack of precise data, a price premium of $US 25 per ton was added to both IFO380 and IFO180 1.5% sulphur bunker prices to yield a price of 257.49 Euros per ton FOB for IFO 380 1% sulphur and 273.29 Euros per ton FOB for IFO 180 1% sulphur. These represent unit costs that are respectively 8% and 14% higher than for the baseline fuel of IFO 380 1.5% sulphur. For the SCR and HAM technologies, the cost-benefit ratio is calculated as 2:1, so the cost of reducing one ton of emissions is double the estimated revenue to be derived from trading each ton of emissions reduction credits in the emissions market. For the sea-water scrubber technology, the calculated cost-benefit ratio is even worse at 8:1. Although switching to 1% sulphur residuals may still be perceived as an attractive idea compared to the other options in order to comply with regulations, it suffers from the major disadvantage that is simply does not create cost-efficient credits for trading in the emissions markets.

6. Discussion and conclusions

This study has been prompted by both the encouraging nature of findings from the US EPA on the positive impact of NOx and SOx *cap and trade* systems on achieving environmental targets and minimizing overall costs [19] and the proposal from the Swedish Shipowners Association and others for the implementation of such a system within the EU [21]. Based on a sample of real ships operating in Northern European waters under pre-2010 ECA regulations, this study has analyzed a range of alternative technologies and fuels for reducing NOx and SOx emissions at sea. The emissions reductions achieved are then evaluated in monetary terms under a scenario where they are traded on a simulated *cap and trade* market, operating under a given set of assumptions. The results of this analysis were outlined in detail in the previous section, but are summarized in Table 7.

INSERT TABLE 7

6.1 Assessing the options

The use of low sulphur residual fuel (maximum 1.5% sulphur content) does not bring about any NOx and SOx emissions reductions which can be traded in emissions markets and, therefore, merely provides the baseline for the purpose of comparing alternative technologies and fuels within this analysis. In this respect, Table 7 quite clearly shows that the use of distillate fuels increases costs disproportionately to the reductions in NOx and SOx emissions achieved and, therefore, to the revenue generated from trading in the emissions market. Under the assumptions imposed within this study, therefore, this renders the use of distillate fuels as simply not cost-efficient.

Not only are distillate fuels expensive but, in the short to medium term, they may also actually be difficult to source, particularly within the context of either a regional (as in an ECA) or global cap on NOx and SOx emissions. In the longer term, of course, as supply responds to any greater demand for distillates, then their price may not be so high. However, quite critically, under the scenario tested within this study, the estimated increase in costs from using distillate fuels is quite substantial and will influence the price of sea transportation in comparison to other modes. Obviously, where the use of alternative modes is feasible, this undermines the competitiveness of sea transport with respect to those alternative modes. The danger is then faced of a possible 'backshift' of freight traffic from sea to land transport, particularly on routes and for products where alternative modes are closely competing. By virtue of the geography of the EU with respect to the Northern European ECA and the fact that the regulation of emissions from land-based transport is already highly advanced, this is certainly a possibility within the region; particularly for medium distance hauls where shipping may be supplanted by rail and road transport. Ironically, this would then undermine the EU's policy to influence modal switching from road to less environmentally damaging modes in order to achieve reductions in road emissions, congestion and noise.

Comparing the two technologies for controlling NOx emissions over the five year timeframe of this analysis, the investment cost per ton of emissions is smaller for the SCR system than it is for the HAM system. In addition, another contributory factor to a lower rate of return on the

HAM system compared to the SCR system is that it yields lower reductions in NOx which can be traded. However, if the period of analysis is extended, the SCR system suffers, relative to the HAM system, not only from the disadvantage that operational costs are required to be incurred (for the purchase of urea), but also because it may be necessary to rebuild the reactor. Because the estimated payback period is found to be such that it covers the funding of another SCR installation within five years, then this seems to be a sustainable eventuality should it even come to fruition. On the other hand, if it does not, then this will enable a relatively inexpensive contribution to be made towards the ‘greening’ of a fleet.

It remains clear from the results of this study, however, that the existence of a *cap and trade* market (operating under the assumptions for revenue generation from emissions trading which have prevailed within this analysis) moves both the SCR and the HAM technologies from being one of a number of expensive options for complying with regulations on NOx and SOx emissions (either regional or global) to economically attractive investments in their own right. As was also found to be the case for the sea-water scrubber technology (see below), compared to the use of regular low sulphur residual fuel, the use of distillates in combination with either of these technologies was found to be economically unattractive.

It is important to bear in mind that all the estimates derived for the emissions reductions, and subsequent revenue generated from emissions trading, for these two technologies are not only dependent upon, but also sensitive to, the NOx baselines which are assumed. In this study, these have been set as the pre-2010 ECA baselines. The modelled results suggest, however, that if the NOx baseline falls below 6 grams per kilowatt hour, then the average ship operating the HAM system could not earn any revenue from the emissions markets and if it falls below 4 grams per kilowatt hour, the average ship with the SCR system will not earn any revenue either. Both are deemed to be possible future scenarios, by virtue of the fact that more stringent baseline limits than these are embodied within the Tier III NOx emissions limits, intended for implementation within any future NOx emissions control areas (see Table 1 earlier in the text).

For the sea-water scrubber, although its SOx reduction capability is significant, the modelled benefits that accrue from trading its emissions reductions do not compensate for the assumed amount of investment required under the assumed timeframe of five years for write-off. However, given the assumptions underpinning the trading model outcomes (particularly the conservative emissions prices and the five-year write-off time) and the fact that greater take-up of the technology will inevitably reduce capital costs (as has already been seen over recent years), it is likely that sea-water scrubbers could have a more important role to play than these results might imply. This is particularly the case since it is a technology which allows ships to steam within an ECA using regular fuel, thus avoiding the high prices, and potential shortages in supply, of distillates.

As the most extreme alternative fuel tested, natural gas is characterized by having the lowest level of annual fuel costs and the best environmental performance of all the options tested, thus yielding the largest level of emissions reductions. For any vessel type other than a gas carrier, a substantially higher investment in shipbuilding costs is required in order to reap these benefits. Notwithstanding the difficulty of securing the required finance, the timing and magnitude of such a cash outflow would suggest that any decision to switch to the use of natural gas as a fuel might require some sort of incentive. The results of the analysis contained herein suggest that prospective earnings from an emissions market may negate the need for the provision of a subsidy or any other form of publicly-funded incentive. With increasing take-up over time, the required LNG refuelling infrastructure will become increasingly available (a trend which has already become evident in the North and Baltic Seas) and will have the effect of further reducing operational costs. Greater use of LNG as a fuel for ships will also bring about more standard ship designs that will lead to declining shipbuilding costs in real terms, the standardisation of ship-to-ship LNG supply operations and lower risk of methane slip.

6.2 Evaluating the *cap and trade* system

As suppliers of emissions credits into the market, the level of revenue generated by shipping companies is critically dependent upon the level of liquidity on the demand side of the market. Of pivotal importance to the possible future success of a *cap and trade* system which encompasses the NOx and SOx emissions from ships is that, under current conditions, abatement costs at sea are notably lower than those on land, especially for NOx. It is this that ensures the appropriate levels of demand-side liquidity in the market; large, land-based buyers will be attracted into the market by the prospect of saving substantial sums of money by purchasing, relatively inexpensively, a volume of emissions credits that would be much more expensive to ‘earn’ unilaterally from implementing operational changes. Among the main beneficiaries would be land-based installations with large thermal output and high abatement costs, such as energy-related industries, which tend to pass their costs down the line, ultimately to household and industry consumers [36]. In many cases, buying emissions credits within a *cap and trade* system may provide the only viable means by which some land installations can inexpensively comply with European regulation and sustain flexible or increasing production levels.

The analysis contained herein has found that the alternative technologies evaluated, as well as the use of LNG as a fuel, become much more economically viable and attractive when there is financial support available for underwriting the required capital investment. The findings suggest, therefore, that the voluntary participation of shipping companies in a *cap and trade* system would generate revenue for the sector that provides both a source of funding, as well as an incentive, for investing in environmentally less damaging fuel or cleaning technologies. This constitutes a major advantage of a *cap and trade* system, in that it can attract the involvement of shipping companies in the market because the revenue generated allows investing in cleaner operations to become a self-supporting strategy. This could constitute an important motivation for the sector to unilaterally adopt a less environmentally damaging approach to shipping operations, during a time when they face simultaneously increasing regulatory and financial pressure, and to do so without recourse to financial support from the public sector.

6.3. Limitations and future research directions

As has been intimated at several points in this paper, the results from the analysis are very dependent upon the assumptions which have underpinned not only the calculation of the emissions reductions that would accrue from each of the alternative technologies and fuels tested, but also the evaluation of the revenue that would be generated from their sale in the *cap and trade* market. Although the former is certainly subject to some margin for variation and error, estimates have been based on historical physical tests from the literature. For the latter, however, estimates are derived simply from a model of what is currently an abstract reality. As such, the assumptions exert a lot of influence over the estimates derived for the revenue generated from the trading of emissions reductions.

The most important value influencing the economic evaluations of the options tested is undoubtedly the assumed price at which unit volumes of NOx and SOx are sold within the modelled *cap and trade* market. These values were assumed as being the minimum prices possible. Thus, all the revenues generated from engaging in the *cap and trade* system have been systematically estimated at their lowest possible value. In reality, on the basis of the demand for, and supply of, emissions credits, market prices are likely to fluctuate at some level above these minimum assumed levels. Thus, expected revenue to be generated is likely to be higher than assumed herein.

In similar conservative fashion, the operating and capital costs associated with each of the alternative technologies tested, as well as those associated with the use of LNG as a fuel, have been based on current market quotations and estimates. In the absence of scale production and deployment, these costs are likely to be higher than those that would occur in practice in the medium term and following a certain meaningful degree of market acceptance. Thus, again, these assumed figures serve to undervalue the benefits to be derived from shipping companies engaging with the *cap and trade* system.

Finally, the estimated cashflows associated with each option take no account of other potential schemes which incentivise the deployment of less environmentally damaging alternative technologies and fuels. For example, no account is taken of the various discounts, refunds and rebates offered by various port and maritime authorities in recognition of improved or better than benchmark environmental performance.

The limitations of the model and its estimates reported within this paper allign directly to some of the potential future research directions. For example, it would be interesting to dynamicise the estimates of revenue generated from the *cap and trade* market so that there was realistic variability in the price of emissions credits over time. It would be particularly interesting to develop and utilise a pricing pattern which was somehow related to the economic state of important demand-side players, such as the energy sector. Similarly, it might be useful to try and cater for other available incentives that might reduce the required burden on the emissions market for providing the required level of revenue to prompt ’green’ investment in shipping. Turning this on its head, encompassing such a capacility would mean that the model could also be applied to deduce what type and size of incentives should be made available to supplement any *cap and trade* system.

The sample of ships to which the economic evaluation model has been applied could be expanded and updated, particularly in light of new incoming regulations both globally and within ECAs. Not only have regulations changed, but the shipping industry has already, to some extent, anticipated such changes in terms of ship design and characteristics. Particularly noteworthy in the context of the Northern European ECA is the increasing tendency towards installing LNG-fuelled propulsion systems and the greater proliferation of the required LNG refuelling infrastructure. The regulatory contexts for ECAs are now more stringent than they were under the pre-2010 Tier I regulatory regime which was assumed in this study. Thus, this too provides a further opportunity for refining and re-applying the model, not only to assess if the *cap and trade* system still proves beneficial in that new context, but also to evaluate the overall effect of the new regulatory regime on the options for compliance and the possible implications for the future of the industry and the environment. Applying this approach to other geographical contexts is an obvious possibility for future research, even though obtaining a representative sample of ships may prove more difficult in certain circumstances. For example, the revised version of MARPOL Annex VI specified the future creation of North American and US Caribbean ECAs (for both SOx and NOx) in 2012 and 2014 respectively. Also, given the impending deadline for the IMO's imposition of Tier III standards on NOx and SOx emissions in 2015-16, as well as the verdict that is due in 2018 from an expert group on the imposition of a global SOx cap, it might prove extremely interesting to evaluate the benefits for world shipping that might accrue from the development of a global *cap and trade* market. Finally, and most topically, the approach could also be applied to the context of CO_2 emissions, particularly with respect to the prospects for global carbon trading for the shipping industry, as advocated by a number of influential shipowners associations [37].

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Table 1: MARPOL Annex VI NOx Emission Limits

Tier	Year	NOx Limit (g/kWh)		
		rpm<130	130 ≤ rpm ≤ 2000	rpm ≥ 2000
I	2000	17.0	$45 \text{ x } rpm^{-0.2}$	9.8
II	2011	14.4	$44 \text{ x } rpm^{-0.23}$	7.7
III	2016	3.4	$9 \text{ x } rpm^{-0.2}$	1.96

Source: developed by the authors on the basis of information provided by the IMO.

Table 2: Average selling price FOB of Marine Fuels in Rotterdam (01/08/06-31/07/07)

Type of Fuel	**$/ton**	**€/ton**	**% of the unit price of using low sulphur IFO 380**	**% of the unit price of using regular IFO 380**
IFO 380 regular sulphur	291.50	220.95	93	100
IFO 380 LS max1.5%sulphur	314.70	238.54	100	108
IFO 180 regular sulphur	311.00	235.73	99	107
IFO 180 LS max1.5% sulphur	335.55	254.34	107	115
MDO max 2% sulphur	508.20	385.21	161	174
MGO max 0.2% sulphur	562.70	426.52	179	193

Note: Conversions were undertaken at the average 2006 exchange rate of US$ 1 = € 0.758.
Source: developed by the authors based on data from Bunkerworld.

Table 3: Total Cost per ton of reduced NOx emissions for the deployment of an SCR system

Vessel Type	Total main engine power (kW)	Engine type	Main engine utilization per year at cruising speed (hours)	Annual fuel consumption of main engine steaming (tons)	Total cost per NOx ton reduced (Euros) from SCR COMPANY	Total cost per NOx ton reduced (Euros) from ENTEC NEWBUILD	Total cost per NOx ton reduced (Euros) from ENTEC RETROFIT
car carrier 1	14 710	SSD	7 000	17 067	322	327	378
car carrier 2	14 480	MSD	5 737	15 040	378	385	462
car carrier 3	14 480	MSD	5 164	10 830	439	449	556
car carrier 4	14 480	MSD	6 910	17 050	359	365	434
Container and sister ships	7 200	MSD	5 034	7 334	548	406	488
Cruise 1	36 180	MDS	6 570	35 655	393	370	444
Cruise 2	72 000	MSD	2 710	31 687	502	558	725
General Cargo	3 264	MSD	5 500	3 250	491	510	631
Passenger 1	25 920	MSD	3 902	19 389	487	436	541
Passenger 2	50 400	MSD	4 000	34 353	447	449	561
Passenger 3	36 000	HSD	1 500	9 318	928	876	1 200
Passenger 4	36 000	HSD	4 690	30 568	449	433	536
Product tanker	2 200	HSD	4 250	1 424	753	777	994
Ro-Ro cargo 1	9 000	MSD	4 970	8 289	556	427	521
Ro-Ro cargo 2	14 480	MSD	6 415	13 850	385	392	474
Ro-Ro cargo 3	15 600	MSD	6 753	19 073	353	348	408
Ro-Ro cargo 4	12 000	MSD	4 830	10 494	402	424	519
Ro-Ro cargo 5	12 000	MSD	4 830	10 494	402	424	519
Ro-Ro cargo 6	18 900	MSD	4 440	15 193	445	436	540
Ro-Ro cargo 7	18 900	MSD	4 440	15 193	445	436	540
RoRo pax	44 480	MSD	4 200	31 833	446	432	536
RoRo cargo 8	23 040	MSD	5 400	18 550	433	419	514
RoRo cargo 9	9 320	MSD	7 784	13 907	432	343	399
RoRo Pax 2 and sister ship	48 000	MSD	4 730	38 688	412	414	509
supply/icebreaker and sister ships	13 440	MSD	6 132	11 711	427	423	518
Tanker 1	11 700	MSD	4 800	10 168	416	427	524
Tanker 2	9 480	SSD	6 500	9 493	427	348	406
Tanker 3	7 562	SSD	6 500	7 093	414	361	424
Tanker 4 and sister ships	4 760	MSD	2 628	2 265	1 124	1 096	1 499
Utility	6 960	HSD	4 000	4 863	563	531	669
Average	**20 231**		**5 077**	**17 067**	**479**	**467**	**582**

Notes: Capital expenditure has been spread over a five year period.

Source: Calculated by the authors.

Table 4: Total Cost per ton of reduced NOx emissions for the deployment of a HAM system

Vessel Type	Total main engine power (kW)	Engine type	Main engine utilization per year at cruising speed (hours)	Annual fuel consumption of main engin steaming (tons)	Total cost per NOx ton reduced (Euros) from ENTEC NEWBUILD	Total cost per NOx ton reduced (Euros) from ENTEC RETROFIT
car carrier 1	14 710	SSD	7 000	17 067	355	378
car carrier 2	14 480	MSD	5 737	15 040	531	566
car carrier 3	14 480	MSD	5 164	10 830	721	770
car carrier 4	14 480	MSD	6 910	17 050	473	504
Container and sister ships	7 200	MSD	5 034	7 334	564	601
Cruise 1	36 180	MDS	6 570	35 655	467	548
Cruise 2	72 000	MSD	2 710	31 687	1 011	1 194
General Cargo	3 264	MSD	5 500	3 250	681	681
Passenger 1	25 920	MSD	3 902	19 389	648	763
Passenger 2	50 400	MSD	4 000	34 353	694	818
Passenger 3	36 000	HSD	1 500	9 318	1 927	2 284
Passenger 4	36 000	HSD	4 690	30 568	647	761
Product tanker	2 200	HSD	4 250	1 424	727	727
Ro-Ro cargo 1	9 000	MSD	4 970	8 289	638	681
Ro-Ro cargo 2	14 480	MSD	6 415	13 850	553	590
Ro-Ro cargo 3	15 600	MSD	6 753	19 073	391	457
Ro-Ro cargo 4	12 000	MSD	4 830	10 494	641	684
Ro-Ro cargo 5	12 000	MSD	4 830	10 494	641	684
Ro-Ro cargo 6	18 900	MSD	4 440	15 193	642	756
Ro-Ro cargo 7	18 900	MSD	4 440	15 193	642	756
RoRo pax	44 480	MSD	4 200	31 833	644	758
RoRo cargo 8	23 040	MSD	5 400	18 550	596	702
RoRo cargo 9	9 320	MSD	7 784	13 907	396	421
RoRo Pax 2 and sister ship	48 000	MSD	4 730	38 688	594	698
supply/icebreaker and sister ships	13 440	MSD	6 132	11 711	643	685
Tanker 1	11 700	MSD	4 800	10 168	651	694
Tanker 2	9 480	SSD	6 500	9 493	406	432
Tanker 3	7 562	SSD	6 500	7 093	434	463
Tanker 4 and sister ships	4 760	MSD	2 628	2 265	1 461	1 461
Utility	6 960	HSD	4 000	4 863	915	977
Average	**20 231**		**5 077**	**17 067**	**678**	**750**

Notes: Capital expenditure has been spread over a five year period.

Source: Calculated by the authors.

Table 5: Percentage cost increases of sea-water scrubbers with different residual fuels

	Sea-water Scrubber & IFO380 LS max 1.5% Sulphur				**Sea-water Scrubber & IFO380 max 2.7% Sulphur**			
	NO TRADE		**TRADE**		**NO TRADE**		**TRADE**	
	NEW	**RETROFIT**	**NEW**	**RETROFI T**	**NEW**	**RETROFIT**	**NEW**	**RETROFIT**
Average	**114**	**119**	**105**	**110**	**106**	**112**	**97**	**103**
Median	**112**	**117**	**103**	**108**	**105**	**110**	**96**	**101**

Note: % compared to the total costs of IFO380 max 1.5% sulphur. TRADE= including revenues from the emissions market.

Source: Calculated by the authors.

Table 6: Payback periods for the increased shipbuilding costs of ships with LNG propulsion systems – with and without trading in the emissions market

		LNG price=0.035€/kWh		**LNG price=0.045€/kWh**	
Ship	**Engine output kW**	**Years to compensate WITH**	**Years to compensate WITHOUT**	**Years to compensate WITH**	**Years to compensate WITHOUT**
Car Carrier 1	14710	5	14	8	232
Cruise 1	36180	9	21	14	139
Cruise 2	72000	21	46	32	235
Passenger 1	25 920	5	10	7	32
Passenger 2	50 400	2	4	3	13
Passenger 3	36 000	10	22	16	112
Passenger 4	36 000	3	6	5	19
RoPax 1	44 480	4	8	6	25
Ro cargo 9	9320	3	6	4	19
3 Supply ships	13440	5	11	8	58
Average	-	7	15	10	88

Note: Assumes annual cost difference between LNG and IFO380 LS to be constant

Source: Calculated by the authors.

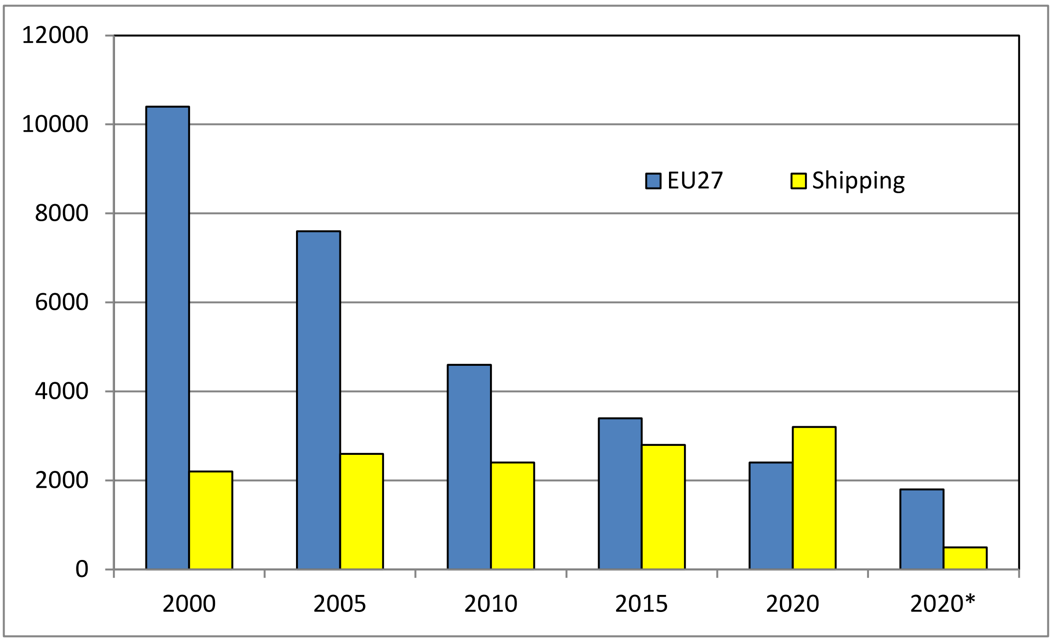
Table 7: Summary of indices for emissions reductions and costs for each tested option (percentages) compared to the baseline case of using low sulphur IFO 380

Alternatives	SOx	NOx	PM		CO_2	Bunker costs per year	Total costs per year WITHOUT	Total costs per year WITH
			SSD	MSD				
IFO max 1.5 % sulphur residual	100	100	100	100	100	100	100	100
IFO max 1 % sulphur residual	67	100	100*	100*	100	108	108	104
MDO 1% sulphur	67	94*	40*	15*	100	161	161	156
Sea-water scrubber & IFO max 1.5% sulphur**	25	100	75	75	100	100	117	108
Sea-water scrubber & IFO max 1% sulphur**	17	100	100	100	100	108	124	114
SCR & IFO max 1.5% sulphur**	100	10	100	100	100	100	111	90
SCR & IFO max 1% sulphur**	67	10	100	100	100	108	119	94
HAM & IFO max 1.5% sulphur**	100	30	100	100	100	100	113	96
HAM & IFO max 1% sulphur**	67	30	100	100	100	108	121	100
LNG	0	10	3	1	75	81	92-138 (137)	58-105 (87)

Notes: Estimated average market price: NOx = 900 €/ton, SOx = 960 €/ton. *Based on imprecise data, so results are inconclusive. **Capital expenditure is spread over 5 years. LNG price = 0.042 €/kWh. Number in (parenthesis) includes a shipbuilding cost increase spread over 15 years. WITH = with emissions trading. WITHOUT = without emissions trading.

Source: Calculated by the authors.

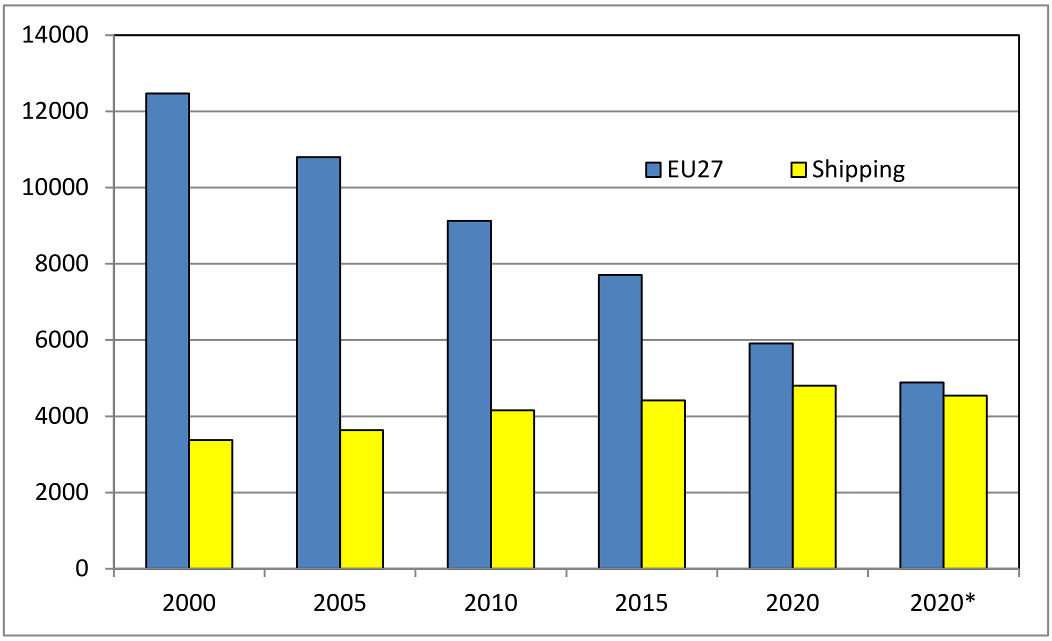
Figure 1: Forecast of SO_2 Emissions in the EU 2000-2020 (ktonnes)



Notes: * This is the TSAP – EU Target for the "EU27" and the IMO Expected Outcome after Regulation for "Shipping". The forecast methodology is a scenario analysis employing an extended version of the RAINS model called GAINS that allows the analysis of interactions between air pollution control and greenhouse gas mitigation. The methodology of the GAINS model and the differences to the RAINS methodology are summarized in Amann et al (2006), with the different optimization approaches documented in Wagner et al (2006) and Wagner et al (2007). Emission figures include updated projections for shipping for 2020, based on the IMO-MEPC decision from 9 October 2008 on a revised MARPOL Annex VI.

Source: drawn by the authors from data contained in [11] and [12]

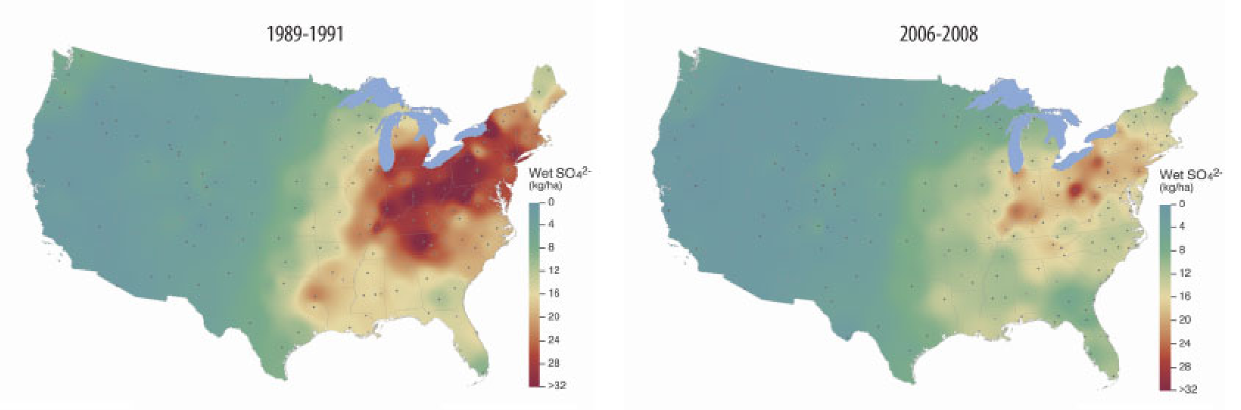
Figure 2: Forecast of NO_x Emissions in the EU 2000-2020



Notes: * This is the TSAP – EU Target for the "EU27" and the IMO Expected Outcome after Regulation for "Shipping". The forecast methodology is a scenario analysis employing an extended version of the RAINS model called GAINS that allows the analysis of interactions between air pollution control and greenhouse gas mitigation. The methodology of the GAINS model and the differences to the RAINS methodology are summarized in Amann et al (2006), with the different optimization approaches documented in Wagner et al (2006) and Wagner et al (2007). Emission figures include updated projections for shipping for 2020, based on the IMO-MEPC decision from 9 October 2008 on a revised MARPOL Annex VI.

Source: drawn by the author from data contained in [11] and [12]

Figure 3: Decrease in sulphate depositions and sulphur *hot spots* over time



Source: [20]

Figure 4: Flow Diagram of the Methodology

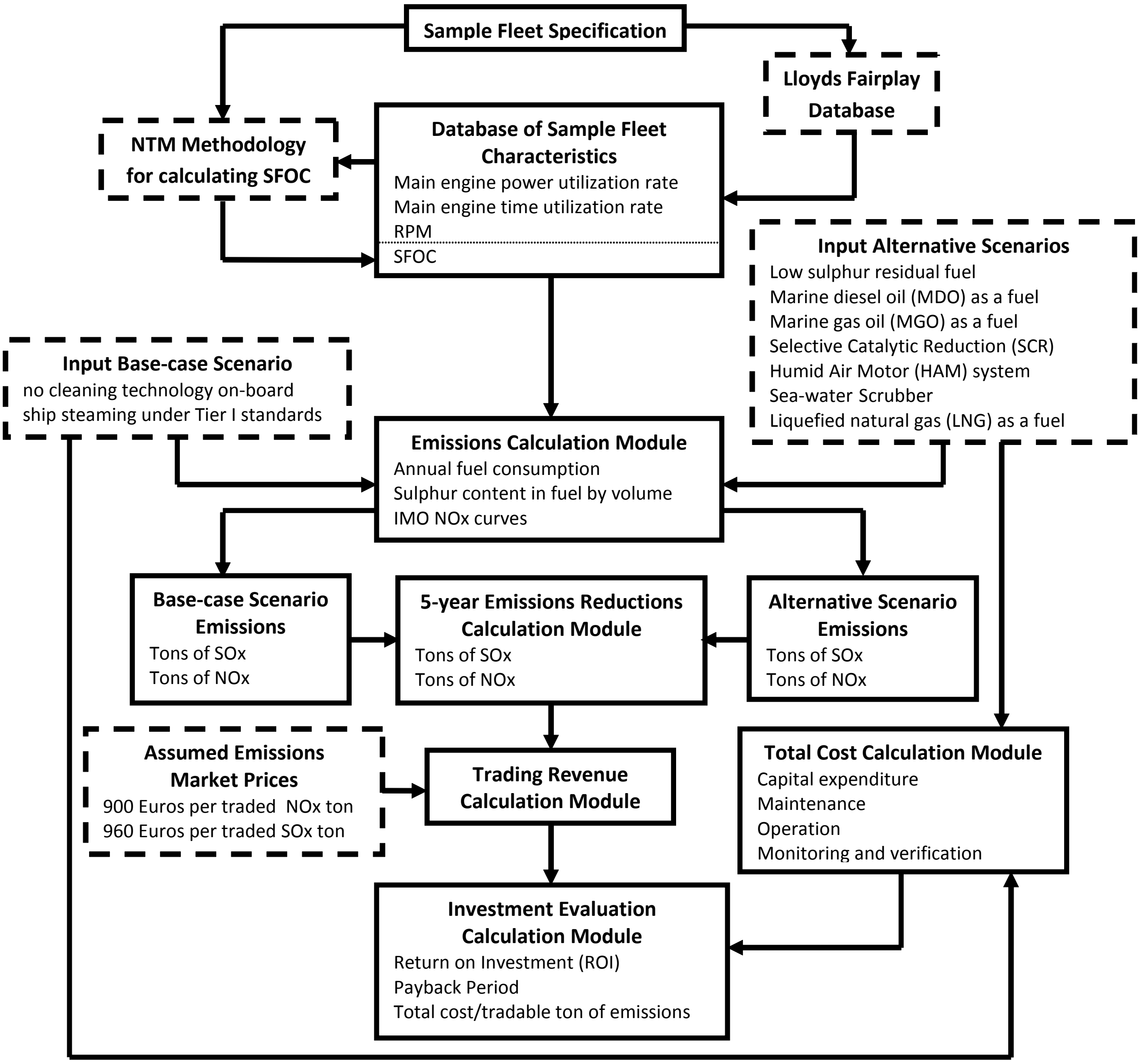
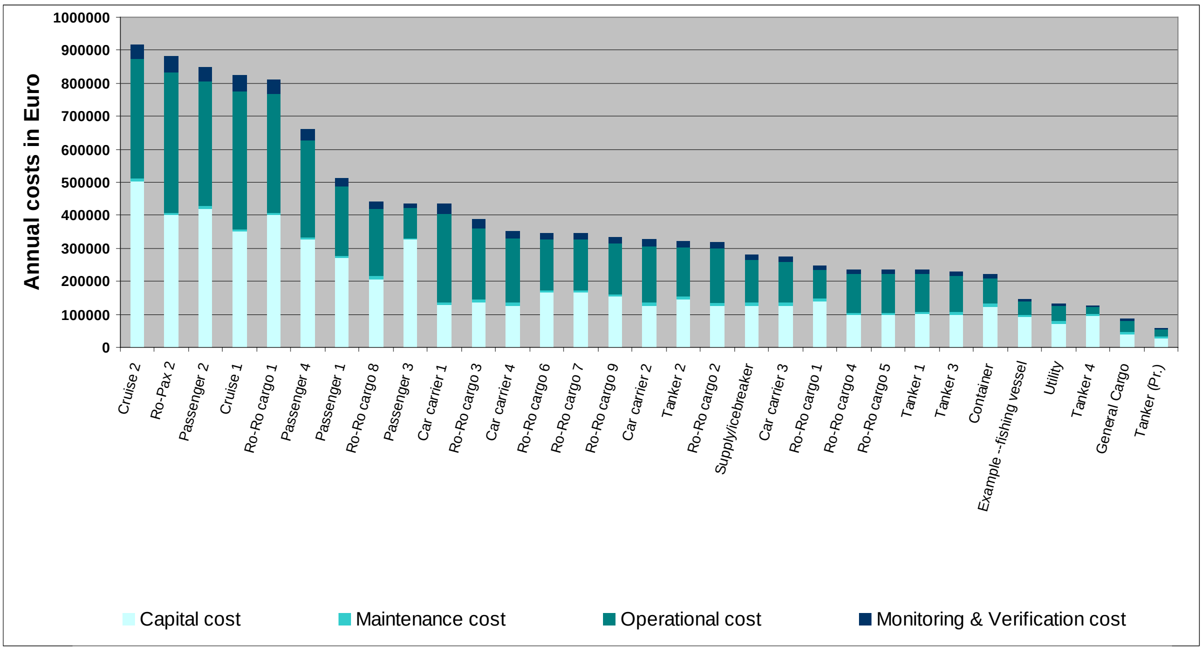
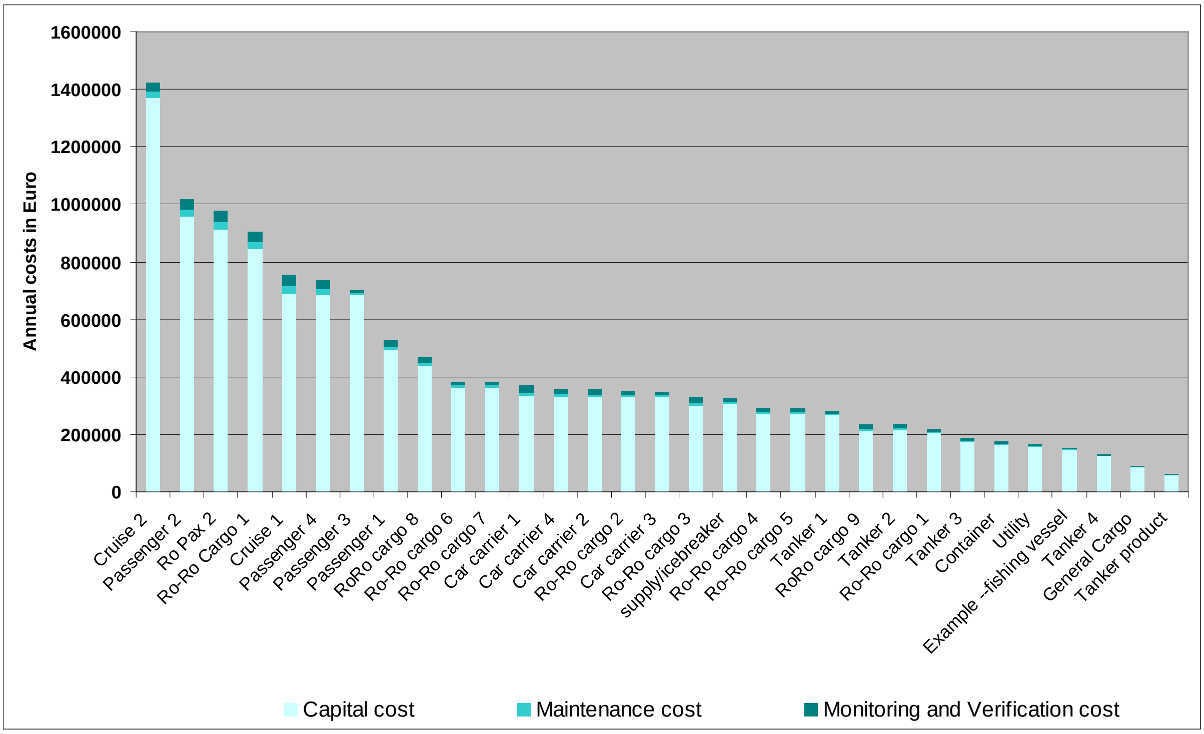


Figure 5: Cost composition for implementing the SCR system in the sample ships



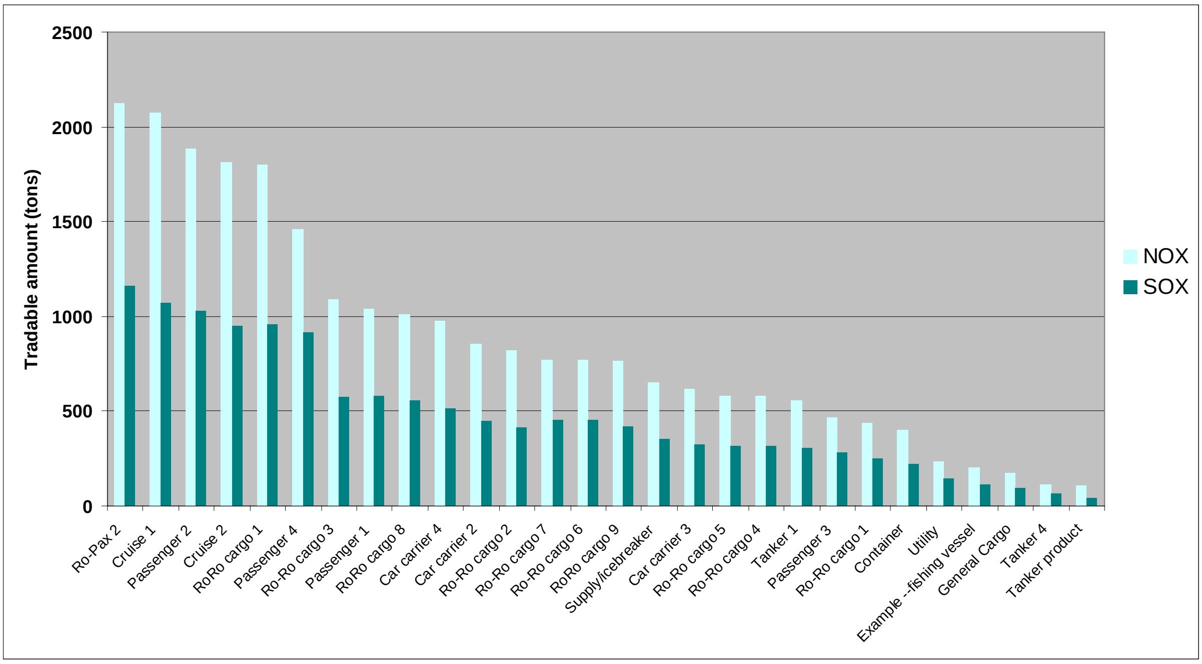
Source: Calculated and drawn by the authors.

Figure 6: Cost composition for implementing the HAM system in the sample ships



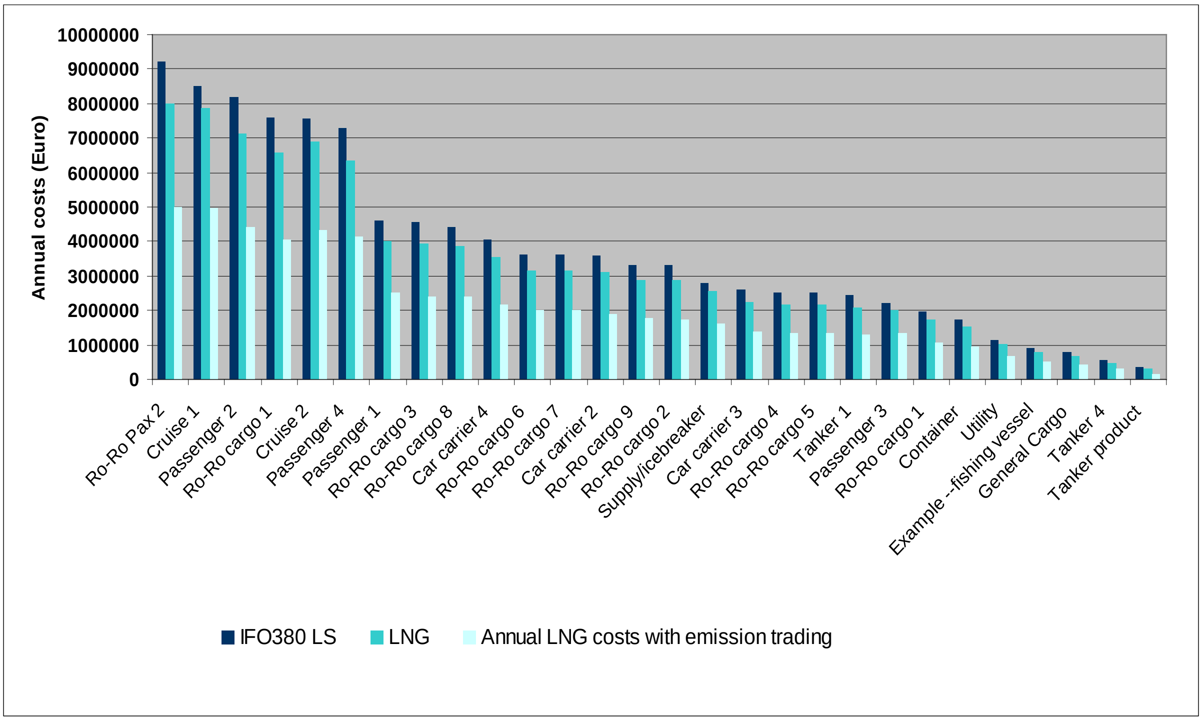
Source: Calculated and drawn by the authors.

Figure 7: Reductions in NOx and SOx emissions (tradable amounts) for the sample ships when utilising natural gas



Source: Calculated and drawn by the authors.

Figure 8: Annual fuel costs of the sample ships - IFO380 LS and LNG (with and without trading)



Source: Calculated and drawn by the authors.