

Assessment of cost as a function of abatement options in maritime emission control areas

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ABSTRACT

This paper assesses cost as a function of abatement options in maritime emission control areas (ECA). The first regulation of air pollutions from ships which came into effect in the late 1990's was not strict and could easily be met. However the present requirement (2015) for reduction of Sulphur content for all vessels, in combination with the required reduction of nitrogen and carbon emissions for new-built vessels, is an economic and technical challenge for the shipping industry. Additional complexity is added by the fact that the strictest nitrogen regulations are applicable only for new-built vessels from 2016 onwards which shall enter US or Canadian waters. This study indicates that there is no single answer to what is the best abatement option, but rather that the best option will be a function of engine size, annual fuel consumption in the ECA and the foreseen future fuel prices. However a low oil price, favors the options with the lowest capex, i.e. Marine Gas Oil (MGO) or Light Fuel Oil (LFO), while a high oil price makes the solutions which requires higher capex (investments) more attractive.

KEY WORDS: Shipping and environment, Emission reduction, Abatement options and cost, ECA, IMO.

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1. Introduction

With stricter emission rules and more public focus on maritime transport, reducing emissions in a cost efficient way has become a necessity for shipping lines. Historically, shipping emissions were not perceived as a problem since vessels operated at sea far from humans. In the 1970's several studies confirmed the hypothesis that air pollutants could travel several thousands of kilometer before deposition and damage occurred. In the late 1980s, the International maritime organization (IMO) started its work on prevention of air pollution from ships, and in 1997 the air pollution Annex (VI) was added to the International Convention for the Prevention of Pollution from Ships ([MARPOL Convention](#)). The Annex (VI) sets rules for nitrogen oxides (NO_x) and Sulphur oxides (SO_x) emissions in the exhaust gas. Developments in regulating maritime carbon dioxide (CO₂) emissions started in the same year (1997).

According to the Third IMO 2014 Greenhouse gas study, Sulphur and Nitrogen oxide emissions from maritime transport in 2012, accounted for 10 % - 15 % of global anthropogenic SO_x and NO_x emissions compared to around 3 % of global CO₂ emissions ([Smith et al., 2014](#)). In response to the impact of these emissions, IMO is tightening the emission limits for NO_x, SO_x and CO₂ ([Lindstad and Sandaas, 2014](#)). First, IMO has defined the coast around North America and the North Sea and the Baltic as Emission Control Areas (ECA) with stricter SO_x rules beginning in 2015, i.e. the Sulphur emissions has to be less than 0.1 % of the emissions content by weight. Globally the Sulphur rule becomes stricter from 2020, i.e. 0.5 % compared to the present cap of 3.5 %; Second, IMO requires that new-built vessels from 2016 onwards which operates fully or parts of their time in the North American ECA shall reduce their NO_x emissions by 75 %, i.e. less than 3.4 gram (IMO tier III) compared to less than 14 gram globally (IMO tier

II); Third, the EEDI uses a formula to evaluate the CO₂ emitted by a vessel per unit of transport based on a fully loaded vessel as a function of vessel type and size. The EEDI thresholds have been agreed upon for major vessel types and it is expected that the EEDI thresholds stepwise will become up to 30 – 35 % stricter within the next 20 years ([Lindstad et al., 2014](#)).

Ships emissions, their impact and solutions to reduce their emissions have been part of major studies such as: the *Second IMO GHG study 2009* ([Buhaug et al., 2009](#)); the *Technical support for European action to reducing GHG emissions from International Transport* ([Faber et al., 2009](#)); and the *Quantify project* which assessed the climate impact of global and European transport systems ([Eyring et al., 2007, 2007a, 2009](#)). [Hennie et al. \(2012\)](#) addresses the complexity of reducing NO_x and that some of the technical options for reducing NO_x emissions increases fuel consumption and hence CO₂ emissions. [Brynjolf et al. \(2014\)](#) has studied the environmental impact as a function of technical abatement option and available fuels, and their results indicates that gas based fuels has better environmental performance than diesel based abatement options. [Jiang et al. \(2014\)](#) has compared sulphur scrubbers versus marine gas oil (MGO) and their results indicate that scrubber technology is efficient in reducing Sulphur and particle emissions, and that scrubber's gives best profitability at high price spread between heavy fuel oil (HFO) and MGO. [Acciaro \(2014\)](#) has used real option analysis for financial assessment of retrofitting existing vessels to run on Liquid Natural Gas (LNG) instead of HFO or MGO. The findings indicates that increased use of LNG as a marine fuel depend on reduction in retrofitting cost and the price ratio between LNG and the traditional fuels (HFO, MGO).

Taking the perspective of the ship-owner, there is a need for more focus on cost assessments as a function of annual fuel consumption in the ECA's. This is also relevant for the

policy makers since the Ship Owners, their Associations and the sea based Intermodal providers all communicates the message that the stricter rules will make short sea shipping less competitive versus road only solutions.

2. Methods

We need assessment of costs and fuel consumption, see [Lindstad et al. \(2011\)](#) and [Lindstad et al. \(2014\)](#) limiting our attention to the vessels and their use, not including port side consequences. The annual fuel consumption can be divided into three (3) parts: fuel consumption for sailing outside an ECA, for sailing inside ECA and during port stays. The power required for sailing (1) can be split into four parts: the propulsion power required for calm water conditions (P_s), the power for countering added resistance by waves (P_w) and wind (P_a), and the auxiliary power (P_{aux}) for equipment and hotel load. The required engine power with respect to required propulsion power is a function of the propulsion efficiency η , which typically is around 65 - 75 % at calm water conditions and designs speed and which drops in rough seas and at low speeds ([Lindstad et al., 2013](#)).

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{aux} \quad (1)$$

This setup is established practice ([Lewis, 1988](#); [Lloyd, 1988](#); [Lindstad et al. 2013](#) and [Lindstad et al., 2014](#)).

During a voyage, the sea conditions will vary and this is handled by dividing each voyage into sailing sections, with a distance D_i for each sea condition influencing the vessels speed v_i and the required power P_i . In general this amounts to

$$\sum_{i=1}^n \frac{D_i}{v_i} \cdot P_i, \quad (2)$$

where the quotient denotes the time spent on each leg. The annual fuel consumption consists of the fuel consumption in the ECA and non-ECA sailing. Adding the port stay we get

$$F^O = K_f^O \cdot \left(\sum_{\substack{i=1 \\ i \notin ECA}}^n \frac{D_i}{v_i} \cdot P_i \right), F^{ECA} = K_f^{ECA} \cdot \left(\sum_{i \in ECA}^n \frac{D_i}{v_i} \cdot P_i + T_{lwd} \cdot P_{aux} \right) \quad (3)$$

where F^O denotes the fuel consumption outside an ECA, while F^{ECA} denotes the consumption for sailing inside ECA and for staying in port. These are the two terms for each voyage. The formula (3) assumes a linear relation between fuel consumption and produced power.

The annual cost including voyage fuel costs and abatement costs is given by (4)

$$C_a = C^{ECA} \cdot F^{ECA} + C^O \cdot F^O + C_v^{capex}. \quad (4)$$

Hence, the annual costs increase as a function of abatement technology and fuel is given by (5)

$$\Delta C_a = C^{ECA} \cdot F^{ECA} + C^O \cdot F^O + C_v^{capex} - C^{HFO} \cdot F^{HFO}. \quad (5)$$

Here C_v^{capex} denotes the annual costs of the abatement technology used. This comprises the annual share of the capital costs and the operating costs.

3. Data set and Abatement options

When fuel is burnt in combustion engines, it gives exhaust gas containing: Carbon dioxide (CO₂), Carbon monoxide (CO), Sulphur oxides (SO_x), nitrogen oxides (NO_x), methane (CH₄), black carbon (BC) and organic carbon (OC). The emitted CO₂ and CO is a function of the carbon content in the fuel and the engine load relative to its rated power. The emitted SO_x are a

function of the Sulphur content in the fuel. The emitted NO_x is a function of fuel type, engine technology and the engine load relative to its rated power. The emitted BC, formed by incomplete combustion of fossil fuels, is a function of the engine load relative to its rated power. Scrubber technology or other after treatment of the exhaust gas is an effective means to reduce the emissions of SO_x, NO_x and BC. For vessels that use liquid natural gas (LNG), leakage of unburnt methane CH₄ is a challenge, since methane is a greenhouse gas (GHG) with a global warming impact (GWP₁₀₀) 30 times stronger than CO₂ per gram emitted ([IPCC, 2013](#)).

All these emissions can be reduced proportionally if shipping's fuel consumption is reduced through lower global transport volumes and tonnages, lower fuel consumption per freight unit transported or by replacing fossil fuel with renewable energy such as wind or solar. The scope of this paper is not to assess any of these options but instead to focus on cost as a function of abatement options in maritime emission control areas (ECA).

In this study we have focused on abatement options for ships with two different engine sizes. The smallest of these, the 4 000 kW engine represents an average engine in coastal vessels, i.e. vessels with a dead weight (dwt) in the 5 000 to 15 000 ton range. The largest, the 12 000 kW engine represents a typical engine size installed in larger container feeders, Ro-Ro vessels and large bulkers and tankers. We calculate typically annual fuel consumption based on equation one (1) to three (3) in the methods section. This gives annual fuel consumption of around 3 000 tons for the vessels in the 4 000 kW range and around 7 500 ton for the vessels in the 12 000 kW range. These figures are of the same magnitude as previously published by [Lindstad et al. \(2012\)](#) and [Smith et al. \(2014\)](#). All the proposed options can be used both on new-ships and as retrofit, however Liquid Natural Gas (LNG) is not a realistic option for retrofits due to its high investment

cost, and the fact that storage of the LNG fuel on board the vessels are space demanding. The annual capital cost for the abatement options on a new-built vessel is based on the same cost structure as for the vessels itself, i.e. typically 8 % of the capex for financial cost and 4 % of the capex for the direct operational cost (crew, supplies, maintenance, insurance, management). In comparison, typical payback of retrofits is based on 5 years, which implies that the annual additional capex cost for the abatement options will be 80-120% higher.

The fuel costs used in this assessment is the cost differential between using Heavy Fuel Oil (HFO) and the alternative fuels. Heavy fuel oil is the low quality heavy fractions of the crude after the light fractions such as Naphtha, Petrol, Diesel, Jet fuel, and light fuel oil has been extracted out at the refineries. This means that variation in the HFO price does not influence the assessment. However some comments are required; First all comparisons are based on comparing fuel prices based on equal energy content, i.e. ton of oil equivalent (TOE); Second, for Marine Gas Oil (MGO) two price differentials are used, a high based on the average differential with a high oil price (600 USD/ton), i.e. + 300 USD/ton as in 2012- 2014, and with a low oil price (300 USD/ton), i.e. + 150 USD/ton as at the end of 2014 and early 2015. It could be argued that the plus 150 USD/ton is in the low end. In this analysis, this option also covers the Light Fuel Oil (LFO) which is a heavy fuel oil where the Sulphur has been extracted to meet the 0.1% Sulphur requirement and which is available in the market at a rebate compared to MGO ; Third for LNG, which apart from Norway and ships carrying LNG is a new fuel for maritime application, we use three different LNG prices for the comparison, a price equal to HFO for the basic comparison, a high LNG price which is 100 USD per ton higher and a low price which is 100 USD per ton lower. Presently the price variations between the LNG prices in US Gulf, Zebbrugge in Europe, or small scale distribution in Norway is larger. However as can be seen from the analysis, plus

minus 100 USD per ton makes a large impact on the results and conclusions; Fourth the total feedstock of methanol is small compared to the traditional fuels and there are large price variations; Fifth, Dimethyl Ether (DME) is here converted from Methanol onboard the vessels and has the same price uncertainty as Methanol. The main exogenous figures for each of the assessed abatement options and the respective fuels are as shown in Table 1.

Table: 1 Cost of abatement options

	Capex cost in million USD (*)		Fuel price per ton	Fuel cost differential	Other Additional cost per ton of fuel
	12 000 kW power	4 000 kW power		$C^{ECA} - C^{HFO}$	
HFO (high)			600		
HFO (low -(1))			300		
MGO high HFO			900	300	
MGO low HFO (1)			450	150	
EGR	1.0	1.0			
Scrubber open loop	3.0	2.5	0	0	25
Scrubber closed loop	5.0	4.5	0	0	50
LNG (HFO + 100)			700	100	
LNG (HFO - 0)	9.0	5.0	600	0	
LNG (HFO - 100)			500	-100	
Methanol	2.0	1.0	800	200	
Methanol conversion to DME	3.0	2.0	800	200	

(*) Cost figures based on: DNV 2013; Einang et al. 2011; Hennie et al. 2012; MAN Diesel 2013; Norwegian NOx Fond 2014; Ramne 2011; World maritime news 2013; Dialogue with Industry and ongoing building projects.

Here marine gas oil (MGO) satisfies the Sulphur requirement and in combination with Exhaust Gas Recirculation (EGR) it satisfies the NOx requirements for new built vessels from 2016

onwards. The EGR row gives the cost for using EGR to fulfill the NO_x thresholds. The Scrubber system satisfies the Sulphur requirements and in combination with EGR they also fulfill the NO_x thresholds. The benefit of the scrubbers is that they enables continuous use of Heavy fuel oil (HFO), which is the most common fuel at sea today due to the fact that it is the cheapest available fuel. Comparing scrubbers the closed loop systems can be used in all sea areas and ports while there will be areas where open loop systems cannot be used due to environmental reasons. The liquefied natural gas (LNG) satisfies the Sulphur requirements for all available engine technologies and the NO_x requirements, either directly for pure gas engines or dual fuel low pressure engines, or in combination with EGR for the dual fuel high pressure engines. Dual fuel means that the engine can run on traditional fuel such as HFO, LFO or MGO in addition to LNG, where the LNG is injected either at high or low pressure and ignited by a small amount of diesel. The disadvantage with the low pressure dual fuel engine is that fugitive methane emissions are higher than for the high pressure dual fuel engine ([Stenersen and Nilsen 2010](#)). However all these LNG engine technologies satisfy the ECA regulation and comes at a similar cost level since the LNG storage tanks and handling system is independent of the engine technology. Methanol satisfies the Sulphur requirement and in combination with EGR it satisfies also the NO_x requirements for new built vessels from 2016 onwards. Apart from a few test cases ([Ramne, 2011](#)), methanol is not used as a marine fuel today. However in Sweden which has a large forest industry there are a strong drive to develop solutions which will make forest based Methanol a maritime fuel on its own, or by converting it to Dimethyl Ethers (DME) onboard the vessels before it is used in the engine with cost figures as shown by the last row.

4. Analysis

The aims of this analysis is to assess and rank the abatement options with focus on cost as function of annual fuel consumption in ECA areas, for the existing fleet and new built vessels from 2016 onwards. Some vessels will operate the whole year in ECA areas; some parts of the year; some will operate part of the year in the European ECA and parts of the year in the North American ECA; and some vessels hardly ever. To keep the assessment simple we have chosen to assess the abatement options as a function of annual fuel consumption in the ECA's. This is first done for vessel types with engine sizes in the 4 000 kW range followed by vessels with engines in the 12 000 kW range. In this comparison the payback model for the capex is based on five year payback for retrofit on existing vessels and 15 years payback for new-built vessels. The first figure shows existing vessels with 4000 kW engines (Fig 1), the second shows new-built vessels with 4000 kW engines operating in the North Sea and Baltic (Fig 2), the third shows new-built vessels with 4000 kW vessels operating in the US and Canadian waters (Fig 3). In each of the figures, the graphs show annual fuel consumption in ton in the ECA on the horizontal axis and the annual costs increase as a function of abatement technology and fuel, i.e. calculated by equation (5) on the vertical axis.

Two vertical dotted lines have been plotted, where the first shows the ranking of options for vessels which operates 50% of the year in Emission control areas (ECA) and the second for vessels which operates 100% in ECA. It should here be noted some vessels will consume more and some less, and that the 50% and 100% plot represent the typical average consumption.

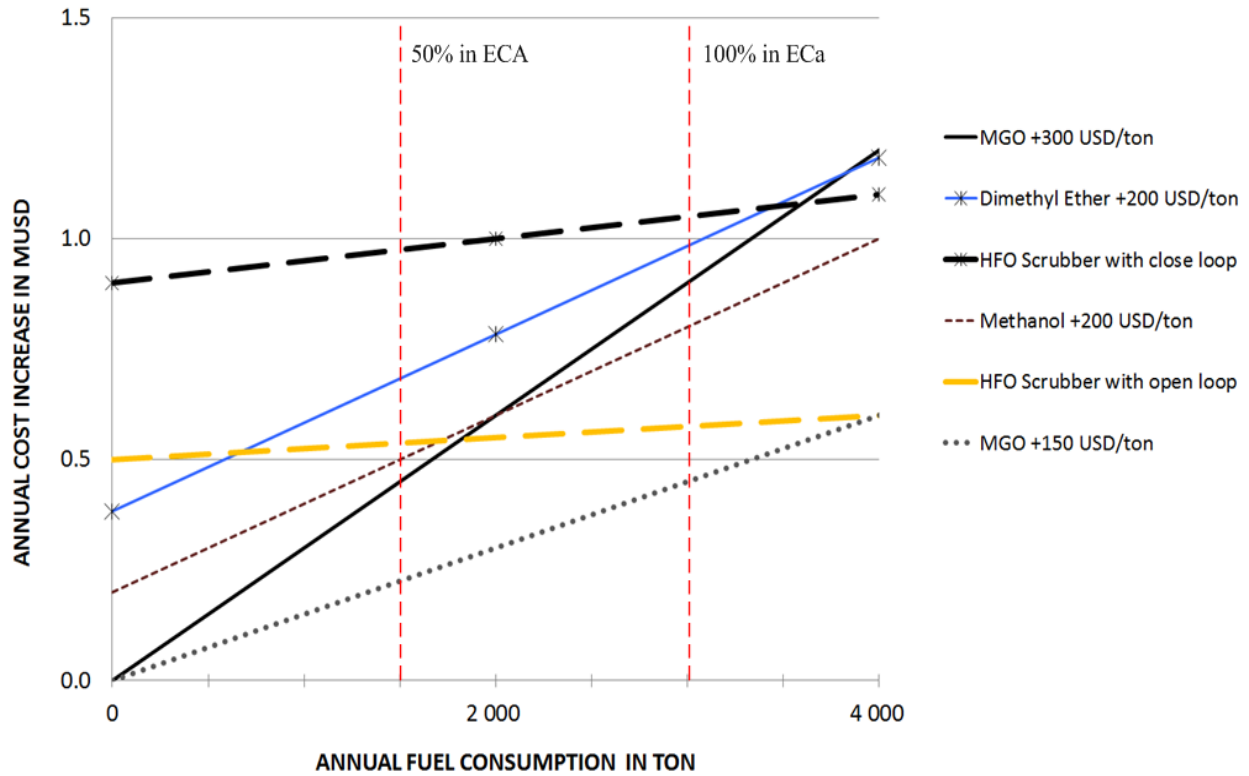


Fig 1 Existing vessels with 4 000 kW engine

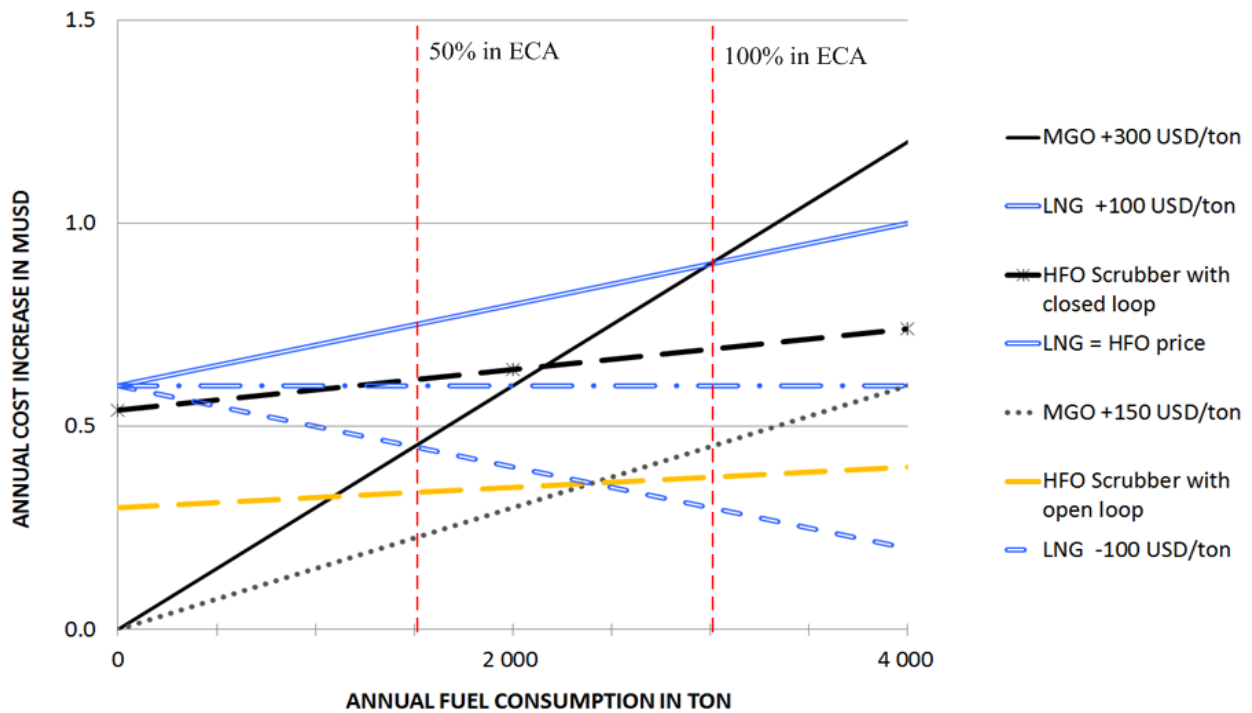


Fig 2 New-built vessels with 4 000 kW engine in Sulphur ECA

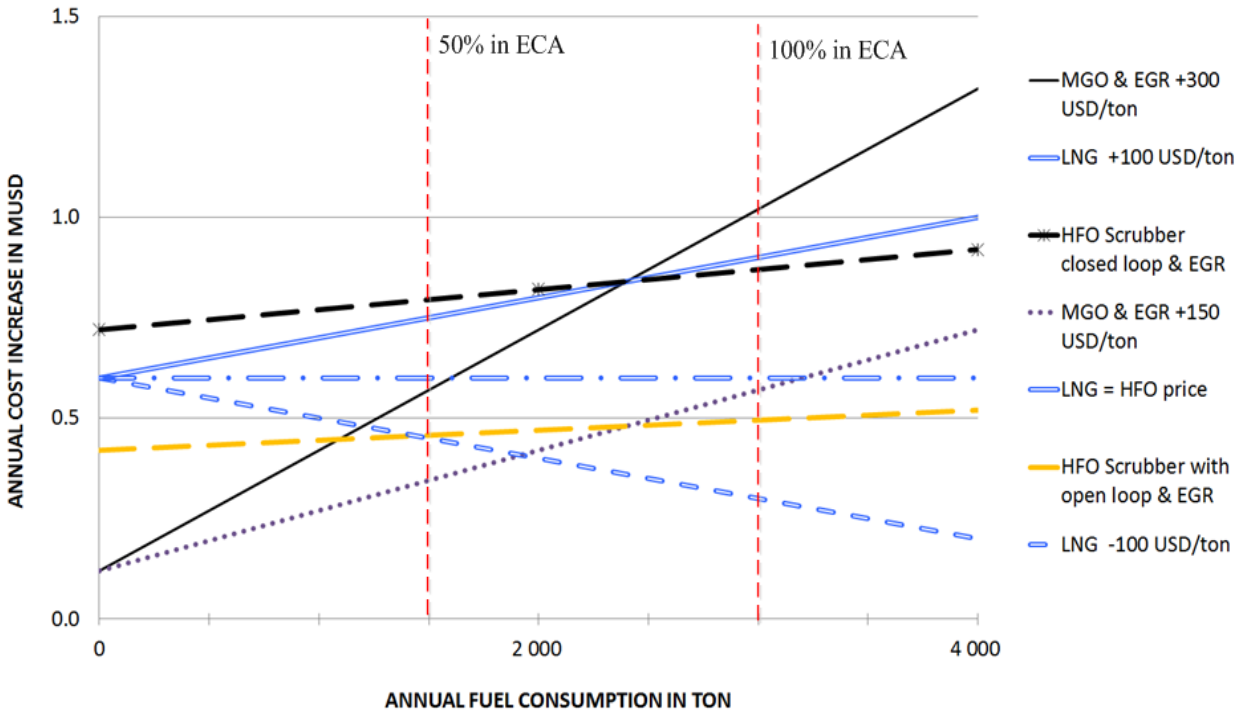


Fig 3 New-built vessels with 4 000 kW engine in Sulphur and Nitrogen ECA

The main observations from Fig 1, Fig 2 and Fig 3 are: First if annual fuel consumption in ECA's is less than 1000 ton, MGO gives the lowest additional cost both with a high and low MGO price; Second for existing vessels, MGO gives lower additional cost than any of the retrofit options with fuel prices at present level (early 2015), i.e. +150 USD/ton compared to HFO; Third, even for new-built vessels, MGO in combination with EGR is a cost efficient solution; Fourth open loop scrubbers give lower additional cost than LNG, unless the LNG becomes available at a rebated price compared to HFO; Fifth, a closed loop scrubbers, which is an option in sea areas where open loop scrubbers are banned from being used, is not competitive unless annual fuel consumption is high or LNG comes at a high price premium compared to HFO; Sixth if LNG shall become a competitive option at all, its price has to be lower than the price of the HFO. Fig 4 to Fig 6, focus on vessels with engine in the 12000 kW range.

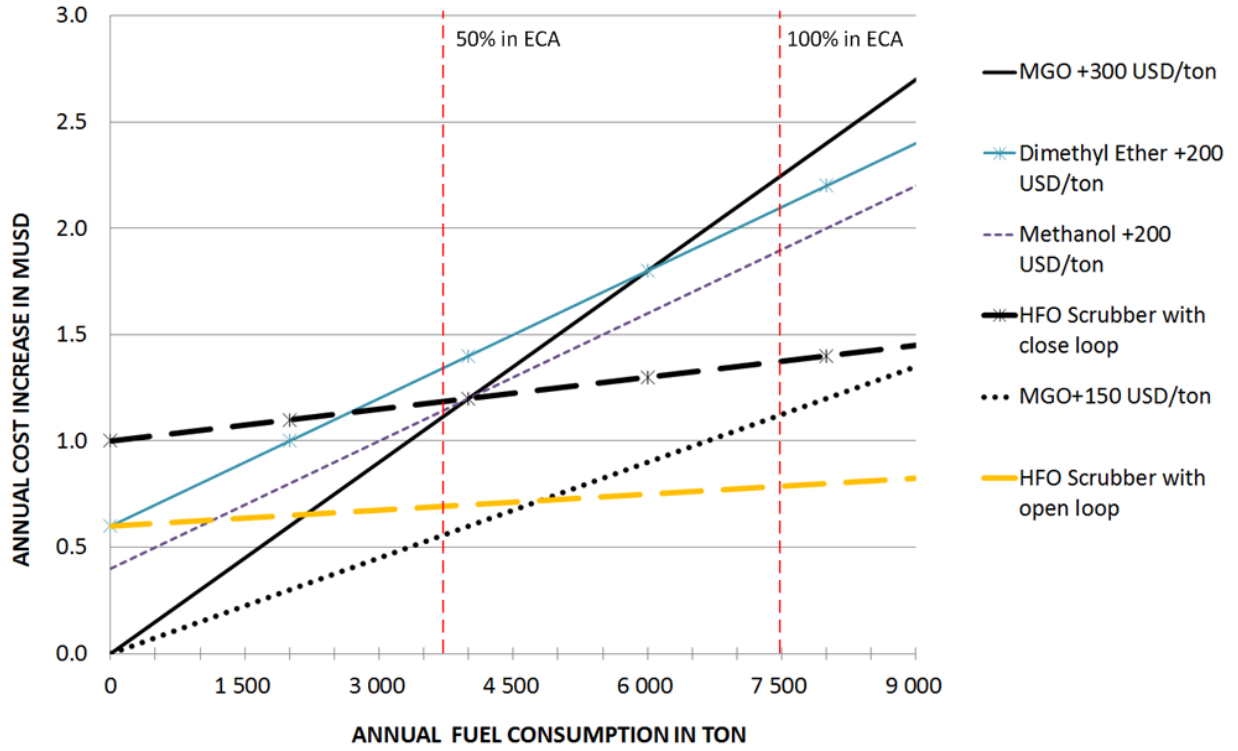


Fig 4 Existing vessels with 12 000 kW engine

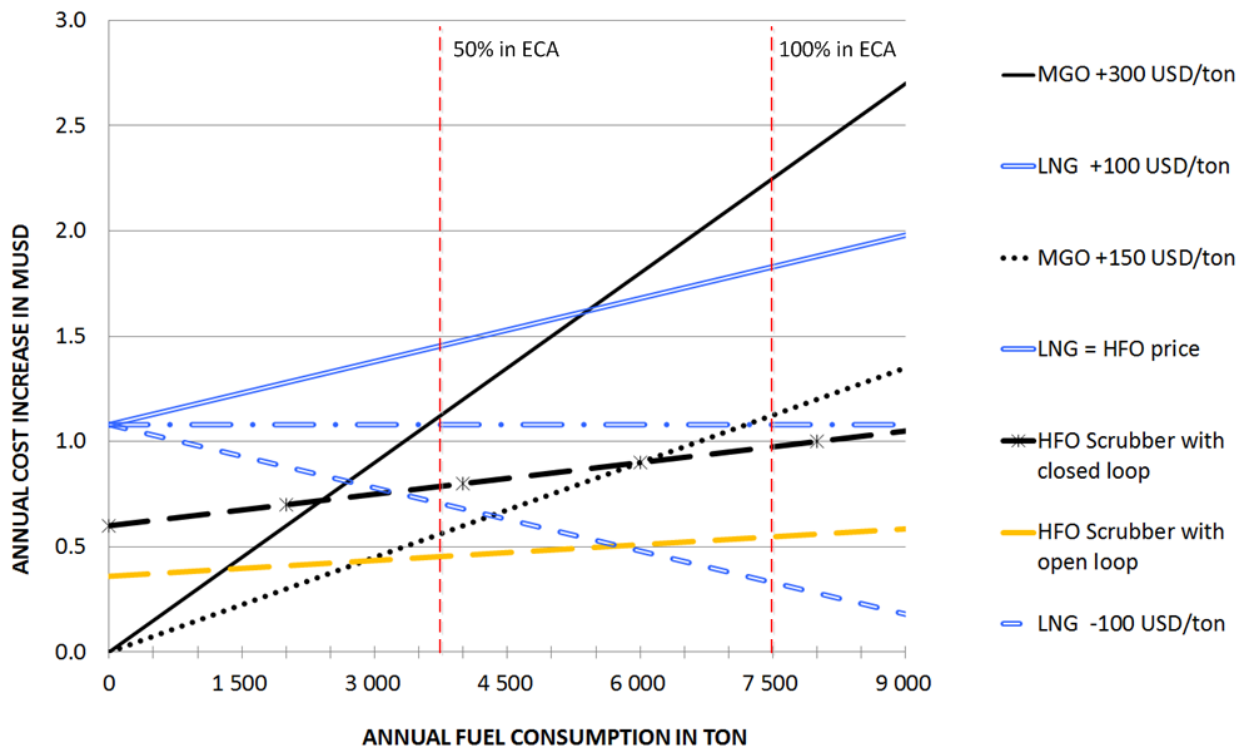


Fig 5 New-built vessels with 12 000 kW engine in Sulphur ECA

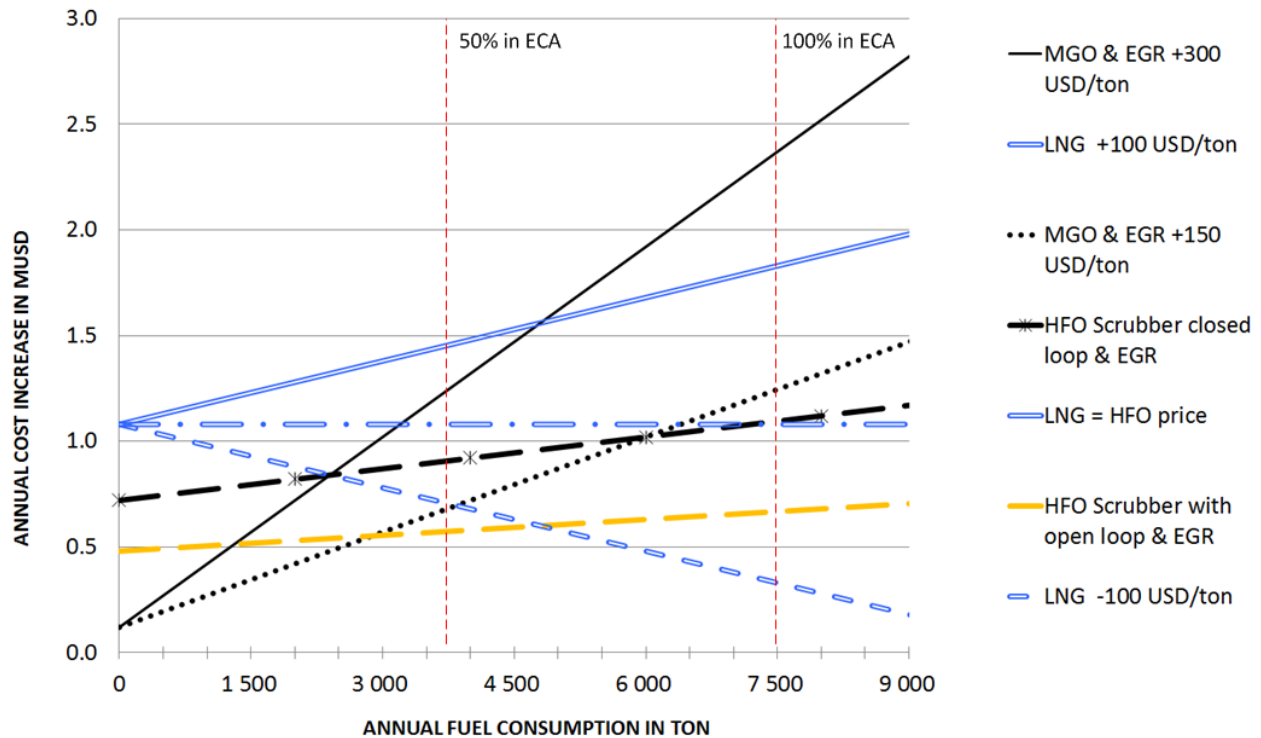


Fig 6 New-built vessels with 12 000 kW engine in Sulphur and Nitrogen ECA

The main observations from Fig 4, Fig 5 and Fig 6 are: First if annual fuel consumption in ECA's is less than 1500 ton, MGO gives the lowest cost both for existing vessels and new-buildings; Second, both open loop and closed loop scrubbers gives lower additional cost than LNG; Third, LNG needs a rebate of 100 to 150 USD per ton versus HFO to be competitive.

5. Cost Implications and Risk of Modal change

In Europe the risk of modal shift, i.e. more road transport and less transport by ships due to loss of competitiveness for seagoing vessels has been one of the major concerns regarding the stricter sulphur rules from 2015 onwards. Due to this it is relevant to look into the magnitude of these additional costs in comparison to the total annual cost of operating these vessels.

Typically a vessel with an engine size in the 4000 kW range will be a General Cargo vessel, a Container feeder, a product tanker or a chemical tanker, of which the chemical tanker is the most expensive to build and operate. In average 15 – 20 MUSD will be a typical average building cost for these vessels and 3000 ton of fuel are a typical yearly consumption. This gives 1.8 to 2.4 MUSD in annual capex and operational cost and 0.9 - 1.8 MUSD in fuel cost with HFO. Here 0.9 MUSD is based on 2015 prices and 1.8 on 2012 – 2014 HFO prices. With this consumption the additional cost per year for the best abatement options is approximately 0.3 - 0.5 MUSD. In percentage this increases the direct ship related transport cost of 10 – 15 %, while the percentage cost increase for the customers will be less since the fairway dues, port dues, cargo handling and hinterland transport all comes in addition to the ship specific cost as described above .

A vessel with an engine size in the 12000 kW range could be anything from a medium sized Ro/Ro or Vehicle carrier, a larger container feeder, a Panamax bulker or tanker or a large Chemical tanker. In average 30 – 50 MUSD will be a typical building cost and 7500 ton of fuel are a typical yearly consumption. In average this gives 4.8 MUSD in annual capex and operational cost and 2.2 – 4.5 MUSD in fuel cost with HFO. With this consumption the additional cost per year for the most cost efficient abatement options is approximately 0.5 – 1.0 MUSD. In percentage this increases cost for the direct ship related cost of 6 - 10 %, however the cost for the customers will be less since the fairway dues, port dues, cargo handling and hinterland transport all comes in addition to the ship specific cost as described above.

6. Discussions and Conclusions

We have assessed costs and emissions as a function of abatement options in maritime emission control areas. The results indicate that there is no single answer to what is the best abatement option, but rather that the best option will be a function of engine size, annual fuel consumption in the ECA and the foreseen future fuel prices. However a low oil price, favors the options with the lowest capex, i.e. MGO or LFO while a high oil price makes the solutions with higher capex more attractive. Another issue which adds complexity and might make the MGO or LFO more attractive is the debate about postponement of the 2020 global sulphur reduction to 2025. And even suggestion that the global reduction should be abolished due to the need for maintaining the cooling effect of shipping at high seas as a climate change mitigation measure ([Lindstad et al., 2015](#)). If that happens it means that the capex cost for the Sulphur abatement options fully has to be earned back on fuel cost savings within the ECA which also favours MGO or LFO compared to the scrubbers or LNG setups.

The results also indicate that the risk of modal shift, i.e. more road transport and less transport by ships due to increased cost is relevant, and that it is the smallest vessels which will get the largest cost increase, while for the larger vessels the cost increase is marginal and we cannot see that it will make much impact.

Regarding LNG, the results indicate that the price has to be equal or lower than the HFO price if LNG shall be an attractive abatement option. This should be feasible since the contractual prices for large scale deliveries in Zeebrugge or in the US Gulf is well below the present HFO price. On the other hand heavy fuel oil is the low quality heavy fractions of the crude after the light fractions such as Naphtha, Petrol, Diesel, Jet fuel, and light fuel oil has been extracted out at the

refineries. If LNG becomes more price competitive versus heavy fuel oil, the refineries options are: to sell HFO to land based power plants at a lower price than what they achieve in the shipping market; or to make large investments to transform the heavy fuel oil to lighter fractions such as diesel; or to reduce the price of the heavy fuel oil to match or outcompete the LNG.

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