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Agenda item 7

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CONSIDERATION OF THE IMPACT ON THE ARCTIC OF EMISSIONS OF BLACK CARBON FROM INTERNATIONAL SHIPPING

An update to the investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping

Submitted by Canada

SUMMARY

Executive summary:	This document provides an update of a report submitted to BLG 17 on investigating appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping
Strategic direction:	Number to be assigned after A 30
High-level action:	Number to be assigned after A 30
Output:	Number to be assigned after A 30
Action to be taken:	Paragraph 4
Related documents:	BLG 16/16 and BLG 17/INF.7

Background

1 BLG 16 established a Correspondence Group and instructed it, inter alia, to identify and collate possible control measures to reduce the impact of Black Carbon emissions from international shipping (BLG 16/16, paragraph 8.59.6).

2 With a view to facilitating the ongoing work of the Sub-Committee on consideration of the impact on the Arctic of emissions of Black Carbon from international shipping, a study sponsored by Transport Canada was undertaken to investigate appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping. The report of the investigation was submitted to BLG 17 (BLG 17/INF.7).

3 With further consideration of appropriate control measures to reduce Black Carbon emissions from international shipping anticipated in advance of PPR 6 in 2019, an update to the previously submitted report on control measures has been prepared based on a review of

scientific literature published since the first report submission. The updated reported is set out in the annex to this document.

Action requested of the Sub-Committee

4 The Sub-Committee is invited to note the information provided.

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ANNEX

Investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping -

Study Report

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20th of November 2012

Foreword

This study was carried out using funds provided to IMO by Transport Canada for analytical studies and other activities pertaining to the control of air related emissions from ships. The study was tendered under the title 'Investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping' and was won by a consortium lead by LITEHAUZ (Denmark). The participitants responsible for the study were Dr. Daniel A. Lack currently at the University of Colorado, Boulder, USA; mr. Jørgen Thuesen and mr Robert Elliot, ERRIA, Denmark; and Dr. Frank Stuer-Lauridsen, mr. Svend B. Overgaard and ms. Ditte Kristensen, LITEHAUZ, Denmark.

List of Abbreviations

AHTS	Anchor Handling Tug Supply
AMSA	Arctic Marine Shipping Assessment
BC	Black carbon
CA	Commercially available
CAPEX	Capital expenditure
CO_2	Carbon dioxide
DE	Demonstration
DME	Dimethyl ether
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filters
ECA	Emission control area
EEDI	Energy efficiency design index
ESP	Electrostatic precipitators
FW	Fresh water scrubbers
HFO	Heavy fuel oil
IM	Immediate
IMO	International Maritime Organization
IN	Intermediate
LNG	Liquefied Natural Gas
LT	Long-term
MARPOL	International Convention for the Prevention of Pollution From Ships
MDO	Marine distillate oil
MEPC	Marine Environment Protection Committee
MCR	Maximum Capacity Rating
MT	Medium Term
NA	Not available
NR	Not reported
NO_X	Mono-nitrogen oxides
OPEX	Operating expense
OS	Other sectors
OSV	Off-shore Supply Vessel
PM	Particulate matter
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific fuel oil consumption
SO_X	Mono-sulphur oxides
SSDR	Slow-steaming de-rating
SWS	Sea water scrubbers
UI	Unlikely Implementation
ULSD	Ultra-low sulphur diesel
VOC	Volatile organic compound
WiFE	Water-in-fuel emulsion

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1 Introduction

1.1 Black Carbon

Black Carbon (BC) is the product of incomplete combustion of organic fuels. Specifically, it is strongly light absorbing across the visible wavelength spectrum. The largest sources of BC are fossil fuel, biomass and biofuel combustion [1]. BC has distinct human health impacts [2, 3] and is a potent climate forcer creating significant atmospheric warming [4]. Recent national and international reports provide comprehensive details on the definition, sources and impacts of BC [5-7], and the following detailed definition for BC has been proposed to the International Maritime Organization (IMO) by the Institute of Marine Engineering, Science and Technology [8]:

> *Black Carbon (BC) is strongly light-absorbing carbonaceous material emitted as solid particulate matter created through incomplete combustion of carbon-based fuels. BC contains more than 80% carbon by mass, a high fraction of which is sp^2-bonded carbon, and when emitted forms aggregates of primary spherules between 20 and 50 nm in aerodynamic diameter. BC absorbs solar radiation across all visible wavelengths and freshly emitted BC has a mass absorption efficiency of $5m^2g^{-1}$ at the mid-visible wavelength of 550 nm. The strength of this light absorption varies with the composition, shape, size distribution, and mixing state of the particle.*

1.2 Black Carbon from Ships

BC emissions from the international commercial shipping industry are thought to contribute about 1-2% of global BC [9]. Ships emit more particulate matter (PM) and BC per unit of fuel consumed than other fossil fuel combustion sources due to the quality of fuel used [10]. BC emissions from ships contribute (as a component of PM) to increased human morbidity and mortality [11]. Several other studies have also been undertaken into the impact of shipping emissions [12, 13, 14].

1.3 The Impact of Black Carbon from Ships on the Arctic

With the dramatic decline of Arctic sea ice over the past few decades, culminating in a minimum sea ice extent of 4.28 million km^2 in 2007 (compared to ~10 million in 1970) [15], comes the possibility of regular transits of the Arctic by commercial shipping traffic. New data from mid September 2012 shows even lower minimum ice coverage of 3.41 million km^2. The ice loss rate was in the 2012 season 91,700 square kilometres per day, as opposed to 66,000 square kilometres per day in 2007 [15]. Journeys between Asia and Europe and Eastern US and Asia through the Arctic could cut travel distances by 25% and 50% respectively, with coincident time and fuel savings also resulting. The exploration for, and development of resource reserves (e.g. oil, natural gas, forestry), and increased access to fisheries will also drive an increase in localized shipping traffic [16-18]. Exploitation of opening Arctic-shipping routes may be restricted or delayed by several factors. Reductions in multi-year sea ice in some areas of the Northwest Passage (NWP) and Northeast Passage (NEP) will be required to improve Arctic transit viability. Vessel redesign and construction may be needed, appropriate weather conditions in an ice-reduced regime are not assured and new regulations are likely to arise for emergency response, ice charting, ice breaking, and national sovereignty issues [16-19].

The climate of the Arctic region is known to be warming at almost twice the rate of the rest of the world [4, 16]. The mechanisms of this warming, and in consequence Arctic sea ice and snow loss, are closely linked to surface air temperatures, ocean circulation and radiative fluxes [20]. The majority of influence on the radiative forcing in the Arctic is from external (i.e. outside of the Arctic) emissions of greenhouse gases and particulate matter [16, 21], with possibly half of Arctic temperature rise linked to BC [21]. Most Arctic BC pollution is sourced from anthropogenic and biomass burning activity within Eurasia [22], and outside of strong biomass burning years BC levels may be stabilizing or decreasing in the Arctic [21, 23-25]. Recent work shows that also ship BC emissions from outside of the Arctic can contribute to Arctic warming [32].

Increases in Arctic shipping will introduce direct near-surface emissions of pollution, including BC. These direct emissions are significant contributors as Arctic warming is most sensitive to emissions within the region compared to the current emissions where most must survive long-range transport from its source before directly impacting the region [21, 26]. The warming efficacy of BC in the Arctic is at least double that of CO_2, as it absorbs incoming and snow-reflected radiation [22] and accelerates snow and ice melting when deposited to those surfaces [27]. It is therefore likely that any climate benefits of BC reductions within traditional shipping routes will be met with increases in the warming effect of BC emissions across the new Arctic routes. Current and future inventories of Arctic BC from shipping activities have been developed predicting significant increases of BC emissions in future years [28, 29]. The use of these inventories to model the climate impacts of ship-emitted BC show that regional scale effects are difficult to distinguish from the impacts of other BC sources. However shipping BC potentially contributes up to 50% of BC in some regions of the Arctic [31] and localized increases in snow and ice melt do occur near the projected shipping lanes [30, 31] [32].

1.4 The International Maritime Organization and Black Carbon from Ships

In recent years the IMO has introduced international regulation to reduce emissions of nitrogen oxides [33] and the sulphur content of fuel [34], which are linked to ground level ozone and particulate matter, and both of which have an impact on human health. In addition, the IMO has also commissioned studies in the impacts of greenhouse gases from ships [35] and subsequently introduced carbon dioxide reduction measures in the form of a ship energy efficiency design index (EEDI) requiring continual improvements in ship efficiency [36]. Efforts to investigate the definition, measurement and impact of BC emissions from shipping have been initiated [37].

Discussion on reduction of PM from ships at the IMO, with specific or implied reference to BC arose from the establishment of a correspondence group during the 10th session of the Bulk Liquids and Gases subcommittee [38]. This correspondence group was established, “with a view to controlling emissions of particulate matter (PM), study current emission levels of PM from marine engines, including their size distribution, quantity, and recommend actions to be taken for the reduction of PM from ships” [38]. The group reported to BLG 11 (2007) [39] on multiple options for reductions in all PM, some of which specifically suggested PM (rather than just fuel sulphur or particulate sulphate) limits. During BLG 12 (2008) [40], Norway submitted a paper recommending a standard for PM measurement (ISO 9096) that was compatible with the high sulphur fuel used in many ships [41], thereby establishing an important benchmark for the following discussions of reliable measurement protocols. At MEPC 59 (2009) [42] the United States and Canada submitted a proposal to the IMO to establish an emission control area (ECA), for control of SO_X, PM and NO_X emissions [42]. This North American ECA was approved at MEPC 60 in 2010 [43]. Also during MEPC 60, Norway, Sweden and United States provided an outlined of the effects of BC on the Arctic and suggested possible actions for mitigation of BC from ships [44]. During MEPC 61 (2010) [43] the IMO agreed in relation to BC from ships "to invite interested Member Governments and international organizations to submit concrete proposals with specific measures to BLG 15". Information papers were submitted to BLG 15 (2011) [45] relating to an international report on the science of BC and climate [46] and the impacts of ship BC on the Arctic [32]. Further discussions on BC at BLG 15 and MEPC 62 (2011) [37] led to the following tasks to be identified for the BLG subcommittee:

1. *develop a definition for Black Carbon emissions from international shipping;*
2. *consider measurement methods for Black Carbon and identify the most appropriate method for measuring Black Carbon emissions from international shipping;*
3. *investigate appropriate control measures to reduce the impact of Black Carbon emissions from international shipping; and*
4. *submit a final report to BLG 17*

BLG 16 (2012) saw six informational submissions on ship BC issues [8, 47-51] related to these four points. The submissions include suggestions for definitions, appropriate measurement techniques (i.e. techniques, not measurement protocols) as well as two presentations, and in addition to establish a working group on *Consideration of the Impact on the Arctic of Emissions of Black Carbon from International Shipping* to address in more details the four points above. This document is expected to contribute to point 3 of the BLG correspondence group. The relevant IMO information papers have been assessed and used, where appropriate in this report.

2 Measurement and Data Availability

2.1 Black Carbon Measurement and Data Availability

The availability of BC mass emission data from ship engines and relative measurements of BC mass before and after treatment of fuels or exhaust is limited. Particularly relative to other BC sources such as on-road diesel engines. It is recognized that there are strengths and weaknesses to various measurement techniques [2], however, Lack and Corbett [10] reviewed the measurement of BC and related species such as elemental carbon (EC) from ship engines. The findings show that, within an uncertainty of approximately ±20%, most analytical methods for measuring the mass of the strongly light absorbing material defined as BC, are the same. Since there is a strong lack of data availability for shipping BC abatement technologies, this review paper will consider all the available BC and PM data with emphasis on peer-reviewed data, with appropriate caution placed on indirect measures of BC (discussed below).

The majority of research into the emissions of BC from diesel engines is sourced from the on-road diesel fleet (trucks and busses) where significant fuel-quality, fuel treatment, and exhaust treatment regulations have been mandated [52-54]. Some of these regulations have only just emerged for the commercial shipping industry [34] and measurement campaigns for ship emissions have not been prioritized due to former lack of regulation and difficulty in accessing or instrumenting large commercial ships and engines.

Where available, measurements of BC from ship engines are used in the assessment of abatement technologies. However, to make the full assessment of technologies measurements of species similar to BC (see Lack and Corbett [10]) and alternative proxies for BC and BC emissions reductions were in some cases considered.

2.2 Particulate Matter as a Proxy for Black Carbon

BC is a component of PM mass, the contribution of which is dependent on the combustion source. For example, BC from biomass burning comprises 2 - 5% of total PM mass [55] where BC from engines burning ultra-low sulphur diesel can range from 65% - 75% of PM mass [56, 57]. BC is also formed within a diameter range of 20 – 250nm [e.g. 58, 59, 60], unlike PM which can range up to many 1000's of nm [61] and commonly measured and reported as PM10 (<10 μm diameter) or PM2.5 (<2.5 μm diameter).

Where BC mass measurements were not available, PM mass measurements were used as a proxy if one of the following criteria were met[1]:

[1] Information regarding whether bulk PM, or size selected PM was used as a proxy for BC in this review is summarised-for each abatement technology in Table 9.

- Where BC and PM removal were not expected to differ based on the abatement technology. For example, BC is known to be hydrophobic upon emission from many sources. Scrubbing technology that relies on particle wetting may have different removal rates. In contrast a filter will remove particles of the same size regardless of composition.

- Where PM removal rates were provided as a function of PM size, extrapolation to a BC removal rate is possible.

For one study particle number was the only particle measurement available. We view this as a semi-quantitative proxy for BC.

2.3 Fuel Efficiency Improvements as a Proxy for Black Carbon Reduction

BC emission is directly proportional to fuel consumption (at full engine load) [10]. At reduced engine load, or inefficient operation of the engine, this direct proportionality is not likely to hold [10]. In the assessment of fuel efficiency measures for BC reductions, it is assumed that when a measure reports a fractional change in fuel consumption that BC mass emissions will also reduce by this amount[2].

2.4 Primary Abatement Metrics

All PM or BC reductions are given as a percentage reduction from the units presented in the literature. This could be PM or BC mass per unit fuel consumed, per distance travelled or per unit of work. The use of relative PM, or BC reductions eliminates the need to convert data into a single unit. In each table up to three numbers are given for BC abatement potential for each technology: LOW|MID|HIGH; which represents the lower, middle and upper bound of abatement potential identified from literature. A negative number indicates an increase in BC emissions. Where a middle abatement potential is not discernable from literature an average between the lower and upper bounds is used. This method of presenting abatement potential is also used for CO_2 reduction assessment.

2.5 Secondary Abatement Considerations

While BC is the primary abatement focus, the IMO has also spent significant effort in the abatement of CO_2, NO_X and SO_X. In this review the BC abatement option is also assessed with regards to the technology's reduction of CO_2 and the qualitative abatement potential for NO_X and SO_X. These assessments are considered as co-benefits to the BC abatement technology.

2.6 Technology Maturity

The overall purpose of this review is to provide input to IMO's assessment of available instruments for regulating this area. In order to fully address the availability of the abatement technologies the Long List assessment of abatement options given in this review therefore includes an estimate of the maturity of the technology. These include:

[2] Details of when this BC proxy is used when assesseing the abatement technologies are given in Table 9.

CM: *Commercially Available* – **M**ultiple units operational in the shipping sector.

CF: *Commercially Available* – **F**ew units operational in the shipping sector.

DE: ***De**monstration* – Feasibility demonstrated in the shipping sector, but it is not commercially available yet.

OS: ***O**ther **S**ectors* - Technology is commercially available in other sectors and potentially applicable in shipping.

NA: ***N**ot **A**vailable* - Technology may not be available in the long term.

2.7 Technology Uptake Time

The long list assessment of abatement options includes an estimate of implementation time based on the maturity of the technology, requirements for retro-fit, ship newbuilds, research or design.

IM: **Im**mediate - <12 months. Commercially available.

IN: **In**termediate - 1 - 5 years. Commercially available, but major retro-fit or newbuild required.

MT: **M**edium **T**erm - 5 – 10 years. Not commercially available. Design/experimental stage and will require further development, research and commercialization.

LT: **L**ong-**T**erm - > 10 years. Major design, safety and commercialization effort necessary.

UI: **U**nlikely **I**mplementation - Technology unlikely to be implemented.

3 Black Carbon Abatement Options

BC abatement technologies are assessed within the following categories:

- Fuel Efficiency – Vessel Design
- Fuel Efficiency – Engine Options
- Fuel Efficiency – Monitoring Options
- Slow Steaming
- Fuel Treatments
- Fuel Quality (Traditional Fuels)
- Alternative Fuels
- Exhaust Treatment

The fuel efficiency measures presented are mostly summaries of a number of the high-return options from the guide to ship eco-efficiency technologies and measures [62]. A full lifecycle assessment of fuel production, waste disposal and new ship builds with inclusion of externalized cost should be considered for each new abatement technology, but it is beyond the scope of the current study. Currently, the data availability and data quality of the majority of the technology options regarding life cycle assessment do not render such an exercise feasible.

3.1 Fuel Efficiency - Vessel Design (excludes engine, fuel options)

Improved fuel efficiency through vessel redesign will save fuel costs and reduce emissions. Many fuel-efficient vessel design options are currently available. An energy efficiency design index (EEDI) has been adopted by the IMO [36] and requires step-wise improvements to the energy efficiency of new build ships, starting at 10% reduction in CO_2 per tonne-mile from 2015, increasing to 20% and 30% from 2020 and 2025, respectively. The options for improved efficiency are left to the designers, builders and owners of the new ships [63], and presumably will allow the most cost-effective options to be developed and integrated into new ship builds. The EEDI will reduce fuel consumption (and thus fuel costs) and these reductions in CO_2 emissions will simultaneously reduce the emissions of co-emitted species such as BC. Where fuel efficiency measures are implemented that move the engine away from efficient combustion e.g. reduced engine load during slow steaming [10], this linear co-reduction of BC will likely not occur. Future vessels designed for slow steaming will likely incorporate lower power engines so they can operate near the maximum engine load, or will use engines that can be de-rated or re-tuned for the lower load. For all measures where maximum engine efficiency is maintained it is assumed that those measures implemented by industry will provide co-benefit reductions in BC emissions. The options, and estimated efficiency improvements, for such efficiency measures are presented in Table 1.

Table 1 Fuel Efficiency Options (excludes engine and fuel options)[a] (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Tech-nology Maturity	Uptake Time	Remarks	Ref.
EEDI	10|20|30	10|20|30	CA1| CA2| D	2015/ 2020/ 2030	Required due to regulation. New-builds, >400 tonnes	[36]
Ballast Water & Trim	1|4|5	1|4|5	CM	IM		[62]
Propeller Optimization[b]	3|nr|20	3|nr|20	CM	IM		[62]
Construction Weight	nr|5|nr	nr|5|nr	CF	IN	Newbuild required	[62]
Air Lubrication	3.5|10|15	3.5|10|15	CF	IM	Retro-fit or new-build required	[62]
Aerodynamics	3|nr|4	3|nr|4	DE	IN	Retro-fit or new-build required	[62]
Hull Coatings	2|5|9	2|5|9	CM	IM	Material and dry dock costs	[62]
Hull Cleaning	3|5|10	3|5|10	CM	IM	Labor and dry dock costs	[62]
Wind - Fletner Rotors	3.6|nr|12.4	3.6|nr|12.4	DE	MT	Design, commercialization	[62]
Wind - Sail/Kites	2|nr|26	2|nr|26	CF	IM	Capital cost	
Solar	5|nr|17	5|nr|17	DE	IN	Retro-fit or new-build required	[62]

[a]All efficiency measures in this section are assumed to produce reductions in NO_X and SO_X

[b]Combination of multiple technologies from [62]

3.2 Fuel Efficiency – Monitoring Options

Fuel efficiency improvements due to sophisticated monitoring of ship systems and weather may also contribute to the overall efforts to reduce fuel consumption from ships. There are currently monitoring options available for efficient routing of ships around weather systems and for efficient autopilot operations. Any fuel efficiency gains from these systems will also reduce BC emissions.

Table 2 Fuel Efficiency Options (Monitoring Options) [a] (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks	Ref
Weather Routing	2|nr|10	2|nr|10	CM	IM		[62]
Auto-Pilot Upgrades	0.5|nr| 4	0.5|nr| 4	CM	IM		[62]

[a]All efficiency measures in this section are assumed to produce reductions in NO_X and SO_X

3.3 Fuel Efficiency – Engine Options

3.3.1 Slide Valves

Slide valves are commercially available technology used as a retro-fit options for traditional marine diesel engine valves that optimise fuel injection spray patterns [64]. Available data would suggest that there are neutral or improved (1% at best) fuel efficiency responses from the use of slide valves [65-67]. This technology has been successfully applied to reduce NO_X emissions while also showing reductions in emitted PM and VOC. MAN Diesel and Turbo [68] suggest, that slide valves are an essential retro-fit for slow-steaming where de-rating is not possible (see section 3.3.2). There is one report of a 2% fuel consumption increase with the use of slide valves [69]. Corbett et al. [65] assessed the potential for BC reductions for slide valves, concluding that reported PM reductions were equivalent to BC reductions (at 25%). This technology will have the largest impact on older engines [70] and it is becoming standard on new engines [e.g. 71]. Since slide valves reduce NO_X emissions the uptake of this technology is partially motivated by IMO NO_X regulations.

3.3.2 Tuning of Fuel Injection, Timing and Pressure, and De-Rating.

Real time electronic monitoring and tuning of diesel engine parameters, such as fuel injection pressure and timing and fuel atomization quality, allow for optimum combustion characteristics as engine loads change [71, 72]. Sub-optimal combustion leads to increased fuel consumption between 1 and 3% [62, 72], and cause BC formation. The optimisation of combustion conditions with engine load (or power demand) can also be achieved through the use of engines with cylinders that can be brought on and off line [i.e. traditional de-rating, 72]. This technology is available on new marine diesel engines and would require new engine installation.

Engines that use real time tuning of fuel injection parameters and common rail fuel injection [73] will have substantially reduced BC emissions at loads below that originally rated for the engine. The extent of reduction of BC emissions depends on the load of the engine as discussed in the Slow-Steaming section (3.4).

Table 3 Fuel Efficiency Options (Engine Options)[a]

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks	Ref.
Slide Valves	1|0|-1	10|25|50	CM	IM	Motivated by IMO NO_X regulations. Hardware Cost	[65]
Real Time Tuning, De-Rating	1|2.5|4	1|2.5|4[b]	CM	IN	New engine needed	[62, 72]

[a]All efficiency measures in this section are assumed to produce reductions in NO_X and SO_X

[b]BC reduction from reduced fuel consumption only. BC reductions from improved combustion conditions discussed in *Slow Steaming* section (3.4)

3.4 Slow Steaming

Slow steaming is a reduction from full ship speed to a lower speed. This option is attractive for reductions in emissions from ships, as fuel consumption increases as a cubic function of vessel speed [74]. This means a 10% decrease in speed will lead to a ~27% decrease in fuel consumption [75]. An increase in the transit time of a ship will lead to a reduced capacity to move goods and maintain delivery schedules. If this lost capacity is replaced in the form of additional ships the added cost reduces the benefits of slow steaming. A 10% reduction in speed therefore results in a net 20% reduction in fuel consumption overall [75, 76]. Since 2008 (global financial crisis) many ship companies have reduced ship speeds to reduce fuel consumption (thus cutting costs). One report suggest that since 2008 the average speed of the global shipping fleet has reduced speed by 15% [77] which would suggest a 30 - 40% reduction in fuel consumption. MAN Diesel and Turbo [68] conducted a survey that revealed that 75% of the global bulk and container shipping fleet was conducting some form of slow steaming during 2011, with many operating in this manner since 2007. The majority of survey respondents operated at between 30 and 50% engine load. AP Moller Maersk have reported a 22% reduction in fuel costs resulting from reducing engine load from 100% to 40% for 73% of their fleet [78]. With reduced fuel consumption comes a corresponding reduction in CO_2 and some other emissions. Based on this literature review, further discussion on slow steaming is done assuming an engine load reductions from 100% to 40% (in speed, from 25 knots to 18 knots).

3.4.1 Slow Steaming without Re-Tuning / De-Rating

If a ship reduces speed without any adjustment to the engine combustion process, BC emissions can increase due to inefficiencies in combustion [10, 79, 80]. MAN Diesel and Turbo note that it is common for soot build-up to occur within the engine when running at loads less that 100% [68]. Lack and Corbett [10] reviewed 40 different measurement of BC emissions under varying engine loads and showed that absolute BC emissions (mass per distance travelled) can increase by an average of 30% if the engine load is reduced to 40% when the engine is not re-tuned to the new load (see Figure 1). Load reductions from 100% to 20% and 10% can increase BC emissions by 60% and 90% respectively. In another example entailing AP Moller Maersk vessels, it was found that engine load reductions from 60% - 35% could have led to a 7% increase in absolute emissions of BC if the engines were not re-tuned [10]. Based on the review of available data, BC emissions appear to remain constant over the load range of 80 – 100% [10] and BC emissions are therefore likely to increase when speed reductions are obtained from engine load <80%.

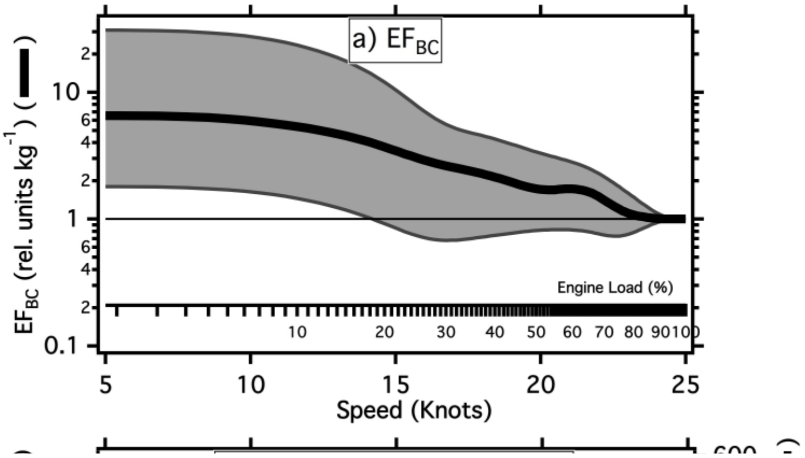


Figure 1 BC mass changes per distance travelled as a function of vessel speed. Reproduced from Lack and Corbett [10]

3.4.2 Slow Steaming with De-Rating / Re-Tuning / Slide Valves

Fuel efficiency gains and emission reduction potential of real-time tuning, slide valves and de-rating of engines were discussed in section 3.3. These processes have the potential to reduce fuel consumption by 1 – 4%. The use of this technology can counteract the significant increase in BC emissions caused by operation of engines at lower loads (section 3.4.1). Theoretically, re-tuning/de-rating of engines to provide ideal combustion at all loads would reduce BC emissions in line with the reductions in fuel consumption. For example, the 7% reduction in CO_2 emissions per container moved (2008 – 2010) presented by AP Moller Maersk [76] would result in a 7% reduction in BC emissions per container moved. Likewise, the load reductions shown in the example by Lack and Corbett [10] would provide 20% reductions in BC emissions. Whether ideal re-tuning and de-rating can be achieved is a question with little data to provide guidance. Slide valves are also suggested as an essential technology for significant reductions in BC emissions during slow steaming when re-tuning or de-rating is unavailable [68].

Table 4 Summary of Slow Steaming as an Abatement Option (100% load -> 40% load). (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	⇓NO_X	⇓SO_X	Technology Maturity	Uptake Time	Remarks	Ref.
Slow Steaming: No De-Rating	7|nr|25	0|nr|-30[a]	N[b]	Y	CM	IM	Fuel Savings, increased travel time	[10, 75, 76, 78]
Slow Steaming: With De-Rating/ Re-Tuning/slide valves	8|nr|29	0|nr|30[a]	Y	Y	CM	IN	New engine needed	[10, 62, 72, 76, 78]

[a]BC reductions based on the load changes presented in the references provided

[b]NOx emissions remain the same until low engine loads (<20%) where they increase

3.5 Fuel Treatments

3.5.1 Colloidal Catalysts

Heavy metals such as cerium and vanadium are known to catalyze the combustion of BC [81]. When introduced into liquid fuels as a colloid, the fuel atomization process is improved leading to improved fuel consumption and heavy metal particles at the point of BC formation, thus reducing the extent of BC formation [62, 82]. On land transportation vehicles these colloidal catalysts are often combined with particulate filters to reduce overall PM emissions [83]. It has been suggested that HFO, having relatively high concentrations of vanadium, will produce less BC emissions than cleaner fuels, due to this catalytic effect [84]. Quantitative data on the effectiveness of colloidal heavy metal catalysts independent of other technologies is scarce, particularly for HFO.

3.5.2 Water-in-Fuel Emulsion (WiFE)

Water-in-fuel emulsions lead to improvements in combustion by improving the atomisation of the fuel and have shown emissions reductions within the marine and on-road sectors. In the review of Corbett et al. [65] WiFEs were shown to reduce PM emissions by 42 - 63%, with one study reporting that BC emissions were reduced preferentially over PM (70 - 85% BC reduction compared to 44 – 57% PM reduction) [65]. Corbett et al. concluded that reductions in BC emission were at least equivalent to PM reductions, assuming 50% BC reductions. This review also suggested that there was an increase in fuel consumption of 1.5%. Recent reports from NoNOx LTD. [85] on a variety of combustion engines using diesel suggest that WiFE leads to reductions in fuel consumption of 7 – 15% when 10% - 17% water is added to the fuel (by volume). PM reductions of 60 – 90% were also suggested [86]. Alternative WiFE systems show that emulsions of water (20%) and HFO can reduce PM emissions by 83%, BC emissions (a crude estimate) by 86%, and CO_2 reductions by 17% [87]. This CO_2 reductions is consistent with the reductions in fuel consumption of 12 – 18% seen for a WiFE trial with a lighter diesel fuel [87]. However, only preliminary communications of proprietary studies are currently available with little information on other engines conditions such as the existence of injectors, electronic timing or slide valves[3].

Table 5 Summary Fuel Treatments as an Abatement Option (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	⇓NO_X	⇓SO_X	Technology Maturity	Uptake Time	Remarks	Ref.
Colloidal Catalyst	2|nr|10	nr	Y	Y	OS	IM		[62, 83]
Water-in-Fuel Emulsion	-1.5|nr|18	50|nr|90	Y	Y	CF	IM		[62, 65, 85, 87]

[3] These studies were obtained directly from the individuals/companies involved and it is our impression that they would be made available to anyone requesting them.

3.6 Fuel Quality – Traditional Fuels

3.6.1 HFO – Distillate

HFO is a fuel used almost exclusively in the marine shipping sector, which contains significantly higher concentrations of sulphur, aromatic hydrocarbon, and inorganic ash. All of which are know to reduce fuel combustion efficiency [88] and produce, amongst other emissions, BC. As discussed in section 3.5.1 there is some suggestion that the high levels of vanadium in HFO can catalyze the combustion of BC as it forms, thus reducing overall BC emissions. However, as mentioned in section 3.5.1 there is no data enabling an assessment of this potential for HFO.

Lack and Corbett [10] reviewed 19 separate comparisons between HFO and higher quality fuels and concluded that this shift would result in BC reductions between 30 and 80%. This assessment is consistent with a well-established link between fuel quality and BC emissions for on-road diesel engines. The large range of reported BC reduction introduces added difficulty is assessing this abatement option. In addition, some of the trials reviewed by Lack and Corbett [10] showed increases in BC emissions when moving to cleaner fuels, which has been suggested as evidence for the catalytic effect of vanadium [84]. However, inconsistencies in measurement results cast uncertainty on this conclusion. Recent data on fuel switching trials on a single vessel show variable results with increased BC emissions (30% - 50%) at low loads for a switch to cleaner fuel, and inconclusive data or decreased BC emissions (35 – 45%) at high loads for the switch to cleaner fuel (results were reported for both auxiliary and main engines) [80]. The conclusions of the review of Lack and Corbett [10] and data from other-sector literature do, however, provide a balance of evidence that a switch from high sulphur residual fuels to low sulphur distillates, at high loads in particular, will lead to BC reductions. Certainly more research is required using reliable measurement tools to increase the statistoics on such a conclusion, however, this report utilises the current evidence to provide its recommendations.

A switch to cleaner distillate fuels also comes with an increase in energy content of 6 – 8% [80, 89], which will reduce required fuel consumption by the same amount.

Table 6 Fuel Switch as an abatement option (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	⇓NO_X	⇓SO_X	Technology Maturity	Uptake Time	Remarks	Ref.
HFO - Distillate - energy content	6|nr|8	6|nr|8	N[a]	Y	CM	IM	Fuel cost/ availability	[80, 89]
HFO - Distillate	0	0|45|80	N[a]	Y	CM	IM	Fuel cost/ availability	[10]

[a]Studies show slight positive and negative changes of NO_X emissions when cleaner fuel is used [e.g. 90, 91]

3.7 Alternative Fuels

3.7.1 Biodiesel

An extensive review across many transportation sectors of the emissions of biodiesel compared to conventional low sulphur diesel, shows overwhelming evidence for a 50-90% reduction in PM emissions. This is due to the lower concentrations of aromatic hydrocarbons, higher cetane numbers (combustion quality) and higher oxygen content in biodiesel [92]. Mixtures of biodiesel and conventional diesel show progressively decreasing PM emissions as biodiesel content increases [92, 93]. For example, 20% biodiesel mixtures reduced PM emissions by ~20 -30%, while 100% biodiesel reduced PM emissions by 50-70%. That review focussed on the emission reductions using low sulphur diesel as a baseline. As emissions from the combustion of low sulphur diesel predominantly is comprised of BC and organic matter, the quoted PM reductions are highly probably proxies for BC. Biodiesel contains 8 – 11% less energy than conventional diesel [90, 92-94] and fuel consumption will therefor increase by this amount. A main driver for biofuels is the reduction in life cycle carbon (CO2) and it has been suggested that the increased fuel consumption (and CO2 emissions) from biodiesel are significantly offset by the closed carbon cycle of biodiesel feedstock..

Within the shipping industry a number of biofuel experiments have taken place [90, 94, 95]. Jayaram et al. [94] showed a 38% reduction in BC using 50% biodiesel/ultra low sulphur diesel mixture, while Petzold et al. [90] showed BC reductions in the range of 60 – 75% for four different biodiesels compared to HFO.

The biodiesels used in all of the studies referenced were sourced from vegetable oil (soya, palm, sunflower) or animal fats. Biofuels such as methanol, ethanol or dimethyl ether is not considered in this section, although do form part of the discussion in section 3.7.3.

3.7.2 LNG

Extensive reviews of the effect of LNG on PM emissions within light-duty (passenger cars) and heavy-duty diesel engines (buses, trucks) suggest that PM emissions are cut by 88 – 99% [96-98]. Because the majority of PM emissions from ultra-low sulphur diesel (ULSD) fuel are BC, these PM reductions are likely an effective proxy for BC (see section 2.2). US EPA data suggest that BC emissions are eliminated when using LNG [57]. No data has been identified on PM or BC emissions from LNG engines used in ships. In terms of the reduction of the global warming (GW) potential, possible fugitive emissions of methane during LNG production may counteract an otherwise positive BC effect from LNG.

3.7.3 Methanol - Dimethyl Ether (DME) (Ethanol - Diethyl Ether)

DME is the product of the dehydration of methanol, which has a higher cetane number than methanol itself. It can be produced from many sources, i.e. coal, biomass and CO_2. The use of DME directly as a fuel in diesel engines, or the onboard dehydration of methanol to form DME, is the subject of significant research in the assessment of the 'well to wheels' potential as an alternative to HFO. The SPIRETH program [99] is investigating the onboard catalyzed dehydration of methanol or ethanol. Limited data on this fuel source suggests that a 97% drop in particle number results from the use of dehydrated ethanol compared to a diesel engine (presumably running ultra-low sulphur diesel) [100]. Particle number reductions by themselves cannot be confidently applied to BC reductions. The SPIRETH report and a report from Wartsilla [101] suggests that the use of DME produces “no particulate emissions” or “low or no soot”. On other parameters there appeared to be a 9% reduction in fuel efficiency and a 35% reduction in NO_X emissions, although these were based on one series of measurements [100]. Methanol storage is reported to have similar storage requirements as LNG [102] while DME can be integrated into LNG fuel and engine systems [103]. Production of DME from renewable sources or as by-product from other productions is also showing promise with net CO_2 reductions of 95% when produced from biomass [104].

3.7.4 Nuclear

The use of nuclear ships has occurred in military applications, ice breakers, and coast guard operations in the Arctic. Nuclear vessels will only have an impact on global emissions when reactor design, ship design, fuel security and waste disposal issues are considered in addition to the substantial delay in fleet replacement. BC emissions from this fuel source could be virtually eliminated. This type of alternative fuel is not considered in any further detail.

Table 7 Summary of Alternative Fuels as an Abatement Option (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	⇓NO_X	⇓SO_X	Technology Maturity	Uptake Time	Remarks	Ref.
Biodiesel - 100%	-5|nr|-11	50|nr|75	N	Y	DE	IM	Fuel Availability	[90, 92, 94, 105]
Biodiesel - 20%	-1|nr|-3	10|nr|30	N	Y	DE	IM	Fuel Availability	[92-94]
LNG	15|nr|30	88|nr|99	Y	Y	CF	IN	Engine/fuel storage retrofit. Port supply of LNG. Fugitive emissions.	[62, 96-98]
Methanol/DME	nr|-9|nr	nr|97|100	Y	Y	DE	MT	Fuel storage retrofit and onboard catalysis units required	[99, 100]
Nuclear	nr|nr|95	nr|nr|95	Y	Y	NA	LT -> UN	Design, security and waste issues. CO_2 and BC emissions from fuel production/disposal	

3.8 Exhaust Treatment

3.8.1 Electrostatic Precipitators (ESP)

PM is often naturally charged due to rapid airflow around the particle creating static electricity. Electrostatic precipitators (ESP) take advantage of this charge by flowing the exhaust between charged plates, leading to particle precipitation from the exhaust flow. This technology is commonly used in large stationary sources such as mines and factories. The method is an attractive option due to high collection efficiencies and low added energy use, as there only is a minimal pressure drop in the exhaust system. Collection efficiencies for PM sized 40 – 700nm can range from 60 – 100% by mass [106-110]. Trials on small engines, where the volume of exhaust is minimal compared to large ship engines, show PM reductions of 80 – 90% between 40 and 700nm [110]. Trials on a 4 stroke engine running marine distillate oil (MDO) show PM reductions of 75 – 85% and BC reductions of 50 – 80% across all engine loads [106]. Some trials report 100% PM removal at larger sizes (~500nm) and 95% efficiency at smaller sizes (70nm – the diameters close to atmospheric BC [108]). One trial performed on a 140 kW engine running on HFO show PM and BC reductions of 60 – 80% across the 40 – 700nm size range [109]. ESPs so far have had very limited application to large diesel engines.

3.8.2 Diesel Particulate Filter (DPF)

Diesel particulate filtration (DPF) is a technology that has been used extensively for reductions in PM emissions within the on-road vehicle sector. DPFs use ceramic or metal filters to trap the PM prior to exhaust emission and periodic cleaning is required. The PM is concentrated in the filter and then combusted via active or passive processes and increase. A DPF results in an added fuel consumption of about 4% [65, 111] due to exhaust flow pressure drops [70]. The combination of ULSD and DPFs are the basis for “clean diesel” and most DPFs are only effective when combined with clean fuels (e.g. < 500ppm sulphur). At high sulphur levels the filters become ineffective or may actually produce PM [65].

PM reductions from diesel cars, trucks and buses fitted with DPFs range from 70% - 98% [65, 97, 112-115] and the option can be used on diesel containing biodiesel and water emulsions up to 5% and 10% respectively [112]. The use of DPFs on ship engines has been limited, however one manufacturer claims 99.9% PM reductions for engines up to 600 kW [116]; the Mitsui O.S.K. Lines have performed a DFP demonstration on the power generation engine of an ocean going ship using C Heavy Oil (1% S max.) reporting 80% PM reductions [117]; and engines up to 6000 kW have been tested with DPFs [65]. Specific BC controls on ship engines have been reported at 95 – 99.7% [65, 111, 115]. Many reports suggest that the effectiveness of DPFs is severely reduced as fuel impurities increase, thus making DPF application to HFO combustion a significant challenge [112, 114].

3.8.3 Diesel Oxidation Catalysts (DOCs)

Diesel oxidation catalysts (DOCs) are commonly used in the on-road transportation sector. The technology utilises precious metals on a honeycomb structure, through which the exhaust is passed to oxidize the exhaust components to less harmful species [118]. PM reductions of 20% - 40% have been reported, however, this reduction is specific to particulate organic matter and has little effect on BC [118].

3.8.4 Selective Catalytic Reduction (SCR)

Selective catalytic reduction (SCR) is an exhaust treatment that reduces NO_X concentrations significantly. The technology is applied in the marine sector. There is sparse evidence that BC reductions can occur with SCR (up to 35%) [138] while other studies show no evidence of PM reductions [119, 120].

3.8.5 Exhaust Gas Recirculation (EGR)

Exaust gas recirculation (EGR) is an exhaust treatment that reduces NO_X emissions that, in combination with an internal scrubber, have an effect on removal of particles (this is assessed section 3.8.6). The recirculation in itself does not reduce BC and it may in fact increase the build up of soot [121].

3.8.6 Exhaust Gas Scrubbers (EGS)

Exhaust gas scrubbers have been developed for marine engines as an option to reduce exhaust SO_2 emissions to IMO limits in emission control areas (ECAs) while still using HFO. Scrubbers can use seawater or freshwater to scrub the exhaust to remove gas and particle pollutants. Freshwater scrubbers require an alkaline reactant to effectively remove the acidic sulphur compounds of the exhaust while seawater is sufficiently alkaline to achieve this removal. Dry exhaust gas scrubbers are also in commercial production, and remove SO_2 via chemical absorption to calcium hydroxide. Lack and Corbett [10] and Corbett et al. [65] have reviewed the efficacy of marine exhaust sea water scrubber (SWS) for removal effectiveness of PM and BC. While PM removal rates often exceed 75% it is apparent that PM removal rates are dependent on particle size and water uptake ability. High sulphur fuels (e.g. HFO) produce hygroscopic PM that can associate with BC, and increase the removal of BC to 50 – 75%. Removal of BC in low sulphur fuel is found to be 20 – 55%. Figure 8 in Lack and Corbett [10] show the BC removal efficiency for SWS's for both high and low sulphur fuels. Dry exhausts gas scrubbers also claim PM removal [122] with one manufacturer reporting PM removal efficiencies of 98% [123]. It is not known from these reports whether there is an effective removal of BC, although claims that the ultrafine particles are removed effectively have been reported [124]. The further discussion is limited to SWS systems, though it is assumed that PM removal for seawater and freshwater scrubbers are equivalent.

Table 8 Summary of Exhaust Treatments as an Abatement Option (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	⇓NO_X	⇓SO_X	Technology Maturity	Uptake Time	Remarks	Ref.
Electrostatic Precipitators	-5|nr|nr	60|nr|80	N	N	OS	IN	Size, Commercial availability for ships	[106-110]
Diesel Particulate Filters	-1|-4|-6	70|85|99	N	N	DE	IN	Commercial availability for ships. Requires low sulphur fuel.	[65, 97, 112-114]
Diesel Oxidation Catalysts	nr|nr|nr	nr|0|nr	N	N	CF	IN	Often combined with DPF	[111, 112, 118]
Selective Catalytic Reductions	nr|nr|nr	0|nr|35	Y	N	CM	IM		[119, 120]
Exhaust Gas Recirculation	nr|nr|nr	nr|0|nr	Y	N	CF	IN	May increase BC Soot build up reported	(39, Pers Com Man)
Scrubbers - High Sulphur	-1.5|-3|-5	50|nr|70	Y	Y	CM	IM	Unit cost. Fuel S regulation motivation.	[10, 65]
Scrubbers - Low Sulphur	-1.5|-3|-5	20|nr|55	Y	Y	CM	IM	Unit cost. Fuel S regulation motivation.	[10, 65]

3.9 Summary of Data Sources and Sampling Protocols for BC Abatement

As mentioned in sections 2.1, 2.2, and 2.3, there are a number of different sources of data used to identify or infer BC reductions. These included fuel efficiency improvements and/or CO_2 reductions, measurements of bulk and size resolved PM, and measurement of BC, or BC equivalents. Table 9 shows which data sources were used for each of the abatement technologies. Where bulk PM measurements were used, the detailed information suggests that BC reductions are at least as high as the PM reductions due to the PM reduction mechanism affecting all PM and BC.

Table 9 BC Abatement Option and BC Reduction Data Source

Abatement Measure	CO_2/Fuel Efficiency	Size Selected PM	Bulk PM	BC
EEDI 2020	✓	×	×	×
EEDI 2025	✓	×	×	×
EEDI 2030	✓	×	×	×
Slide Valves	✓	×	✓	×
De-Rating	✓	×	×	×

Abatement Measure	CO_2/Fuel Efficiency	Size Selected PM	Bulk PM	BC
Slow Steaming - No De-Rating	✓	×	×	✓
Slow Steaming - De-Rating	✓	×	×	×
Colloidal Catalyst	×	×	×	×
Water-in-Fuel Emulsion	✓	×	✓	✓
HFO - Distillate	✓	×	×	✓
Biodiesel - 100%	✓	×	✓	✓
Biodiesel - 20%	✓	×	✓	✓
LNG	✓	×	✓	×
MeOH/DME	×	×	✓	×
Nuclear	✓	×	×	×
Electrostatic Precipitator	×	✓	×	×
Diesel Particulate Filter	×	×	✓	✓
Diesel Oxidation Catalyst	×	×	✓	✓
Selective Catalytic Reduction	×	×	✓	✓
Exhaust Gas Recirculation	×	×	✓	×
Scrubbers - High Sulphur	×	✓	✓	✓
Scrubbers - Low Sulphur	×	✓	✓	✓

Although 100% biodiesel is superior compared to 20% biodiesel, the former option is not considered feasible given limitations in biodiesel supply. Slide valves are already standard on new vessels but is a retrofit option on existing ships.

Where abatement options were assessed via a particle sampling method (e.g. size selected, bulk PM, or BC measurement the used sampling protocols were noted, see Table 10. Some recent discussions at the IMO have seen recommendations for the use of a specific ISO protocol to measure ship emissions [41].

The summary presented in Table 10 reveals that the majority of data presented here, whether from industry reports, peer reviewed literature or elsewhere, contain un-reported information on the instrumentation and sampling protocols used. Peer reviewed research often utilized the ISO 8178 protocol [125], which was not recommended by Norway within IMO correspondence [41]. A number of studies used atmospheric sampling where dilution is much higher than any sampling protocol used for emissions testing in a laboratory. Insufficient dilution has been shown to have an effect on emissions measurement [e.g. 84]. Some other standard engine test cycles were also used. Although a standard protocol such as ISO 8178 or ISO 9096 would be preferable, the current lack of data on particle emissions from ships necessitates the judicious use of data from as many sources as possible. The summary presented below provides context for further discussions on future sampling efforts (i.e. whether a common protocol, or equivalent alternatives, should be implemented).

Table 10 BC Abatement Option and Measurement Details

Reference	Abatement Technology	Measurement Type (PM, BC, Size)	Sample Protocol/Method
[66]	Slide Valves	Unknown (PM)	Unknown
[67]	Slide Valves	Unknown (PM)	Unknown
[126]	Slide Valves	Unknown (PM)	Unknown
[127]	Slide Valves	Unknown (PM, BC)	Unknown
[113]	DPF	Unknown (PM)	Unknown
[112]	DPF	Unknown (PM)	Unknown
[114]	DPF	Unknown (PM)	Unknown
[116]	DPF	Unknown (PM)	Unknown
[117]	DPF	Unknown (PM)	Unknown
[111]	DPF	Smoke Meter (BC)	Peer Reviewed
[115]	DPF	Filter Mass (PM) TOA* (BC)	Peer Reviewed, ISO 8178-4, Code of Federal Regulation, Title 40 -80, 86
[65]	DPF	Unknown (PM)	Unknown
[10]	Scrubbers	TOA (BC), Filter Mass (PM), Size (PM)	New EU Driving Cycles, Dilution Tunnel
[65]	Scrubbers	Size (PM), Mass (PM)	Unknown
[123]	Scrubber	Unknown (PM)	Unknown
[106]	ESP	Filter mass (PM)	Unknown
[107]	ESP	Mass, Number (PM)	Unknown
[108]	ESP	Mass, Size (PM)	Unknown, Peer Reviewed
[109]	ESP	Mass, Size (PM)	Unknown, Peer Reviewed
[125]	SCR	TOA* (BC)	ISO 8178
[57]	LNG	Unknown	Unknown
[98]	LNG	Mass (PM)	Unknown, Review Article
[96]	LNG	Mass (PM)	Unknown, CBD and Brawnschweig Test-ing Cycles
[100]	MeOH/DME	Number (PM)	Unknown
[92]	Biodiesel	Mass (PM)	Unknown, Peer Review Article
[57]	Biodiesel	Unknown	Unknown
[90]	Biodiesel	Filter Absorption (BC)	ISO - 8178
[94]	Biodiesel	Filter Mass (PM), Size (PM)	ISO - 8178-1
[10]	HFO	Filter, TOA, Filter Absorption, Photo-acoustic (BC)	ISO - 8178, Atmospheric Dilution, In-creased Dilution Tests, Unknown
[80]	HFO	TOA* (BC)	ISO-8178
[10, 79, 80]	Slow Steaming	Filter, TOA, Filter Absorption, Photo-acoustic (BC)	ISO - 8178, 9096, 10054, 11614, Atmos-pheric Dilution, Unknown
[85, 128]	WiFE	Unknown	Unknown
[86, 129]	WiFE	Unknown	Unknown
[87]	WiFE	Smoke Number (BC)	Unknown

*TOA: Thermal-Optical Analysis

4 Short-List Selection of BC Abatement Options

The long list of BC abatement options was reduced to a selection of the highest-probability technologies using a set of objective criteria. It is recognized that in addition to the BC abatement potential, there are other factors that will improve the acceptance of a technology as an abatement option. These include changes in CO_2, NO_X, and SO_X emissions due to the technology, current commercial availability, and time to implementation.

Ranking: Criteria for Abatement Potential

BC Abatement: Each 10% reduction (or increase) in BC emissions due to the abatement technology was assigned 1 (or -1) point. For example, a 30% reduction in BC was assigned 3 points.

CO_2 Abatement: Each 10% reduction (or increase) in CO_2 emissions due to the abatement technology was assigned 1 (or -1) point. For example, a 10% increase in CO_2 was assigned -1 point.

NO_X Abatement: NO_X abatement is not a primary consideration for this project. Whether the specific BC abatement technology changes NO_X concentrations will be of secondary importance. If a BC abatement technology reduces NO_X emissions, produces no change or increases NO_X emissions, the abatement technology was assigned 1, 0 or -1 point respectively. This assignment indicates that the NO_X abatement is an order of magnitude less important than BC reduction.

SO_X Abatement: SO_X abatement is not a primary consideration for this project. Whether the specific BC abatement technology changes SO_X concentrations will be of secondary importance. If a BC abatement technology reduces, produces no change or increases SO_X emissions, the abatement technology was assigned 1, 0, or -1 points respectively. This assignment indicates that the SO_X abatement is an order of magnitude less important than BC reduction.

Technology Maturity: The commercial availability of a particular BC abatement technology will have an impact on the ability for successful uptake. The five technology maturity criteria outlined in section 2.6 are assigned points of 0 through 4, with the most mature technology receiving 4. This indicates that technology maturity is only approximately 50% of the importance of BC abatement.

Technology Uptake Time: The time required for implementation of the technology will impact the ability for successful uptake. The uptake time includes the time required for retrofits of current technology, newbuilds of ships, or design and commercialization of immature technology. The five technology uptake criteria outlined in section 2.7 are assigned points of 0 through 4, with the fastest implementation time receiving 4 points. This indicates that technology maturity is only approximately 50% of the importance of BC abatement.

This process was carried out for the midranges of abatement potential for BC and other air emissions, which resulted in the short list of abatement technologies. The process was also carried out for the low and high ranges for BC abatement potential, i.e., utilizing the LOW|MID|HIGH abatement potentials for each technology shown in Table 1 - 8 (not shown).

A summary of the BC abatement options score chart is presented in Table 11.

Table 11 Ranking of BC abatement options as a weighted points summary including other air emission reductions or employing only BC reduction points, technology availablility and implementation

Abatement Measure	All air emissions	Black Carbon only
EEDI 2020	11	8
EEDI 2025	12	8
EEDI 2030	16	9
Slide Valves	12.5	10.5
De-Rating	9.5	7.3
Slow Steaming - No De-Rating	0	0
Slow Steaming - De-Rating	12.4	8.5
Colloidal Catalyst	0	0
WiFE	17	15
HFO - Distillate	14.9	13.2
Biodiesel - 100%	10.5	11.3
Biodiesel - 20%	6.8	7
LNG	20.6	16.4
Nuclear	0	0
Electrostatic Precipitator	9.8	10
Diesel Particulate Filter	13.1	13.5
Diesel Oxidation Catalyst	0	0
Selective Catalytic Reduction	0	0
Scrubbers - High Sulphur	15.7	14
Scrubbers - Low Sulphur	13.5	11.8

The rankings of abatement technologies when considering BC compared to all air emissions are only slightly different when omitting EEDI, as it is not feasible as a retrofit option. The result is mainly affected by how high 100% biodiesel and electrostatic precipitators are on the top 10 list (see ranking below). The objective was to identify six technologies for consideration for feasibility and costing, and the consolidated list does not include 100% biodiesel, electrostatic precipitators and scrubbers for low-sulphur applications. Since slow steaming is voluntarily employed in the industry, this technology was included whereas slide valves were not, although the latter forms part of the WiFE technology.

Table 12 The top 10 abatement technologies ranked by including all air emission parameters or only Black Carbon. Final column shows the consolidated list of six abatement technologies

All air emission parameters	Black Carbon only	Consolidated list
1. LNG	1. LNG	1. LNG
2. Water-in-Fuel Emulsion	2. Water-in-Fuel Emulsion	2. Water-in-Fuel Emulsion
3. Scrubbers - High Sulphur	3. Scrubbers - High Sulphur	3. Scrubbers
4. HFO - Distillate	4. Diesel Particulate Filter	4. Diesel Particulate Filter
5. Scrubbers - Low Sulphur	5. HFO - Distillate	5. HFO - Distillate
6. Diesel Particulate Filter	6. Scrubbers - Low Sulphur	6. Slow Steaming - De-Rating
7. Slide Valves	7. Biodiesel - 100%	
8. Slow Steaming - De-Rating	8. Slide Valves	
9. Biodiesel - 100%	9. Electrostatic Precipitator	
10. Electrostatic Precipitator	10. Slow Steaming - De-Rating	

The top six abatement technologies from the midrange abatement potential are presented in full in Table 13. These abatement technologies are evaluated for BC abatement costs in section 5.

Table 13 Summary of the six technologies for the short-list BC abatement option

Abatement Measure	⇓CO_2 %	⇓BC %	⇓NO_X	⇓SO_X	Technology Maturity	Uptake Time	Remarks	Ref.
EEDI*	30	30	Yes	Yes	n/a	LT	Required due to regulation; New-builds, >400 tonnes	[36]
Slow Steaming: With De-Rating	18.5	15	Yes	Yes	CM	IN	New engine needed	[10, 62, 72, 76, 78]
Water-in-Fuel Emulsion	0	70	Yes	Yes	CF	IM		[62, 65, 85, 87]
HFO - Distillate	7	52	No	Yes	CM	IM	Fuel cost/ availability	[10]
LNG	22.5	93.5	Yes	Yes	CF	IN	Engine/fuel storage retrofit; Port supply of LNG; Fugitive emissions.	[62, 96-98]
Diesel Particulate Filters	-3.5	85**	No	No	D	IN	Commercial availability for ships; Requires low sulphur fuel.	[65, 97, 112-114]
Scrubbers - High Sulphur	-3	60	Yes	Yes	CM	IM	Unit cost: Fuel S regulation motivation.	[10, 65]

* The EEDI is not included in the BC abatement cost assessment; ** The 85% is a mid-range between the minimum and maximum reductions reported for LSFO. It happens to also correspond to the reductions reported for the HFO trial, however this is coincidental.

5 Cost and Feasibility of BC Abatement Technologies

The full technical and cost-analysis report is included in Appendix E, which evaluates the cost effectiveness of the short list of identified market-available BC abatement measures. A detailed summary of the report is provided in this section. The base example is a tanker (Aframax), for which both retrofit and newbuilding installation are provided.

For comparison, the installation costs on a range of ship types - tanker, container, bulker carrier, gas carrier, passenger ship, offshore supply vessel (OSV)/anchor handling tug supply (AHTS) and tug- are provided for vessels with similar engine size (10 MW) and vessels of approximately the same physical size vessel, i.e. with comparable docking costs (tugs and OSV)/AHTS excluded). The data is given in detail in the Appendix E.

5.1 Abatement Technology Case by Case

The selected abatement measures are applied to the base case, Aframax Tanker, as listed in Appendix E, where the calculated capital investment cost and application to seven vessels are summarized. Of the selected vessels, five are of similar tonnage but with very different power requirements due to application and speed requirements. Two vessels are smaller. The procedure to estimate the cost for each abatement measure was to utilise quotes from manufacturers, where it was concluded that there is a linear relationship between the price of the equipment and the power of the main engine, except for the EEDI, which is dependent on other parameters as well. Estimated uncertainty in these estimates is 10-20%. The quotes were converted to a U.S. dollar cost per kilowatt hour (USD/kW) and used to scale to the relevant vessel.

The capital investment of the abatement measures is approximately 80-90% of the total retrofitting cost, which minimizes the costs associated with installation location (labour etc.). Some of the retrofitting cases were estimated to take up to 40 days, and so the charter rates of each vessel type for this lost time were also taken into consideration. Reduced costs are obviously associated with the installation of the abatement measures at the vessel newbuild stage, and the reduction potential in capital expenditure (CAPEX) is between 40-60% depending on off-hire rates and installation time. During the vessel design phase for a newbuild, many of the smaller modifications to the standard design can be absorbed into the contract price. The cost difference between newbuilding and retrofitting is illustrated in Appendix E. The CAPEX calculations are based on the installed shaft power of the vessel at 100% MCR.

Consideration for the additional operating costs per day has also been taken into account. The additional operating costs per day are chosen due to the fact that each abatement measure has a varying degree of energy requirement, which is dependent on the abatement measure (Appendix E). The abatement measures do not require additional crew competencies except for LNG installation, where an estimated 10% additional crewing cost is required, due to the complexity and safety requirements of the systems. The reason for not including the vessels' individual operating expenditure (OPEX) is simply that the different vessels, owners and managers use different nationalities of crew, which could influence the OPEX considerably. Crewing costs are often approximately 50% of the total OPEX of a vessel, depending on the complexity and flag of registration. The OPEX calculations are based on 90% MCR.

5.2 Slow Steaming – With De-Rating

Slow steaming became popular within the shipping industry at the end of 2007, mainly with container vessel owners and operators, as a consequence of drastically dropping charter rates at the beginning of the global financial downturn. Vessels were instructed by owners to reduce main engine load to approximately 40% MCR, which decreased the speed by approximately 20%. Summarized calculations of an average fuel oil cost (FOC) savings of approximately 42% without a de-rated engine and 45% with a de-rated motor are shown in Table *14* below.

Table 14 Slow steaming (40% MCR) without and with de-rated engine

	Shaft power (kW)	Speed (knots)	Distance (nautical miles)	Time (hours)	Total fuel consumption (ton)	Fuel oil savings (%)
90% MCR (kW)	14,256	15.0	10,000	667	1,730	0%
40% MCR (kW) without de-rating	6,336	11.4	10,000	877	1,012	42%
40% MCR (kW) with de-rating	6,336	11.4	10,000	877	951	45%

From January 2010, owners started to investigate super-slow steaming down to below 35% MCR and as low as 10% MCR. Engine makers were initially hesitant due to the lack of experience, but in June 2011 MAN Diesel issued a service letter (SL11-544 MTS) permitting owners to reduce engine load down to 10% MCR, though with certain recommendations. Several problems may arise from low load operation e.g. loss of main engine turbocharger and propeller efficiency, hull fouling, and economizer soot build up.

Electronic engines (ME, ME-B and RT-FLEX) are more flexible for slow steaming, therefore it is recommended to convert all mechanical injection main engines to electronically controlled engines.

In the 2012 Danish initiative Green Ship Of The Future in Copenhagen, MAN Diesel presented a vessel emissions study [130], in which the conversion cost of the MT Nord Butterfly from an MC engine (mechanical injection) to an ME-B engine (electro hydraulic, common rail injection) was estimated. The conversion was from a 6S50MC-C (9,480 kW) motor to a 6S50ME-B motor with the same effective power. With our experience from MAN Diesel retrofits it is possible to calculate a cost per kW to scale the CAPEX to the specific vessels (See Appendix E). If a vessel already has an electronic engine installed, the CAPEX will be reduced approximately 45-50%.

Table 15 Green Ship of the Future: Vessel Emission Study (Copenhagen 2012) [130]

	Amount	Unit
NORD Butterfly ME-B Conversion	9,480	kW
CAPEX	800,000	USD
Cost for ME-B conversion	84	USD/kW

5.3 Water-in-Fuel Emulsion (WiFE)

In water-in-fuel emulisions (WiFE), water is added continuously to the fuel supply and a homogeneous mixture is achieved by mechanical measures. When WiFE is used it can be observed that the specific fuel oil consumption (SFOC) generally increases for the larger additions of water. This is due to the energy required to heat up the injected water to its saturation temperature, subsequent evaporation at the saturation temperature, and further super-heating to the temperature in the combustion zone. In previous work, the SFOC penalty at 30% vol. added water is estimated to be approximately 2% when considering evaporation and super heating only. It should be noted that the water may contribute with work in the expansion process, thereby reducing the actual SFOC penalty, and that little is known about to the corrosive effects from the water on the fuel system and other machinery related to the fuel system [137].

To retrofit a WiFE system to a standard engine, the following components need to be installed or replaced:

- A homogenizer unit, which heats the water and mixes it with fuel to form an emulsion prior to injection, is to be installed. CAPEX is estimated to USD 400,000 excluding retrofitting costs on a 40,000 kW engine [131]. To this a 20% price increase from 2006 to 2012 is assumed based on 3.5% inflation per year, which gives an USD/kW estimate of approximately USD 13/kW. If retrofitting costs are included, but excluding off-hire, the average cost is USD 27/kW. On the Aframax Tanker base case a retrofit time of 20 days with an off-hire rate of USD 20,000/day is assumed, which increases the cost to USD 52/kW.

- A possible increase in freshwater (FW) storage capacity onboard, as a standard FW generator cannot keep up with the FW consumption of the WiFE system. Thus, additional FW is to be stored onboard. FW consumption is dependent on power requirement and not ship size. A large, slow-steaming Aframax tanker will consume considerably less FW compared to a container vessel of the same size sailing at full speed. Average FW generation onboard a commercial cargo vessel is 25MT/day. The cost of FW water depends on many variables - trading routes, FW generation onboard and FW consumption on board (apart from WiFE). As this cost also has little influence on the CAPEX or OPEX, it is therefore not included in the calcalculations.

- Replacement of the standard fuel valve (fuel injector) with slide fuel valves is needed due to the more efficient atomization of the fuel and to optimise the combustion. The cost of the new slide fuel valves is included in the total cost as per Table 16.

Table 16 MAN Diesel: WiFE cost overview [132]

	Amount	Unit
Engine power	40,000	kW
Total WiFE unit cost and slide fuel valves	500,000	USD
Cost per kW (excl. retrofit)	13	USD/kW
Cost per kW (incl. retrofit, excl. off-hire)	27	USD/kW
Cost per kW (incl. retrofit and off-hire)	52	USD/kW

5.4 Heavy Fuel Oil (HFO) – Distillate

A fuel switch to destilate fuel from heavy fuel oil is a simple alternative to achieve compliance with current and forthcoming IMO emissions regulations on maximum allowable sulphur content in the fuel oil. There are two main challenges when running on distillate fuels, e.g. MGO: fuel viscosity and main engine cylinder lubrication [133].

- The fuel systems for engines, boilers and other machinery required to comply with IMO regulations are recommended to have a cooler or chiller arrangement fitted, to meet the fuel viscosity requirements for safe operation of the engine's fuel system. Vessels in the future will probably not experience problems running without a chiller due to the fact that engine and pump makers are designing their equipment to run on the lower viscosity fuels, but it is not recommended due to the increased wear on fuel systems. Cooling of the MGO is a not a straightforward solution, since several parameters should be considered before deciding the appropriate method of cooling, e.g., SFOC, duration of time using MGO, pumps and engine fuel system specification, and age.

- There is a correlation between low-sulphur fuels and BN or TBN (Base Number). Thus, when low-sulphur fuels with <1% sulphur are used, the cylinder lubrication rate is lowered to the minimum dosage recommended by engine makers (when using an oil for HFO (e.g., BN70)). In this configuration the cylinder liner would be overadditivated. Therefore, engine makers recommend changing to low BN cylinder lube oils of BN 40-50 when fuels below 1% sulphur are used for prolonged periods of time. Automatic cylinder feed rate regulating systems, e.g., the Alfa Lubricator, are recommended on newer engines in order to regulate the dosage automatically during different engine loads [133].

A chiller unit costs approximately USD 70,000 for the Aframax Tanker base case, which represents a USD 4/kW exclusive installation cost. The calculated cost inclusive installation is USD 13/kW; however, that does not include the expected 10 off-hire days. This chiller unit price could vary, depending on which system and maker are chosen.

Table 17 MGO chiller unit cost

	Amount	Unit
MGO chiller unit cost (excl. inst.)	70,000	USD
MGO chiller cost (excl. inst.)	4	USD/kW
MGO chiller cost (incl. inst.)	13	USD/kW

5.5 LNG/DME

Liquefied natural gas (LNG) is natural gas stored as liquid at -162°C. The predominant component is methane with some ethane and small amounts of heavy hydrocarbons. LNG as a fuel for marine propulsion and power generation has been common with 4-stroke engines as a dual fuel system for LNG tankers. In a dual fuel system, boil-off gas is used as fuel on loaded voyages and HFO on the ballasted voyage. Two-stroke LNG-powered engines have been in operation only as land-based, stationary engines for power generation running at a constant load. In contrast, marine engines have variable loads and restricted space for LNG fuel tanks. Both MAN Diesel and Wartsila have announced that they have LNG-powered two-stroke engines available for marine propulsion.

Vessel engine load depends on the vessel's operational characteristics. Generally, larger vessels such as bulkers, tankers and container vessels operate using two-stroke LNG engines with constant load and RPM for the majoroity of their journey. Variable loads on engines result from vessels with shorter journey times such as cruise liners, supply vessels and tugs. These vessels use four-stroke dual fuel engines with diesel electric propulsion units for better efficiency. Exhaust gas emissions (SO_X and PM) from the combustion of LNG are negligible, while CO_2 emissions are reduced (when the efficiencies from the tank to the propeller are considered) because LNG contains less carbon than do fuel oils.

There are two main disadvantages to LNG retrofits: LNG requires at least double the fuel tank volume of fuel oils, which is a challenge for vessels with limited or no deck space, e.g., container vessels, cruise liners and bulk carriers. Cost estimates for LNG fuel tanks range from USD 1,000/m^3 - USD 5,000/m^3. MAN Diesel advised that an LNG retrofit is not possible on a two-stroke mechanically controlled fuel system, thus a conversion to an electro-hydraulic common rail fuel system (ME-B) is required. There is a cost savings of approximately 20% if the vessel has an electrohydraulic common rail fuel system (ME-B, ME-C or RT-Flex) installed prior to LNG retrofit.

The following costs are involved with LNG installation on the Aframax Tanker base case:

Table 18 LNG conversion estimates

	Amount	Unit
Cryogenic plant	1,500,000	USD
LNG tank cost	1,000	USD/m^3
LNG tank capacity	2,000	m^3
LNG machinery conversion	42	USD/kW
NORD Butterfly ME-B conversion*	9,480	kW
CAPEX*	800,000	USD
ME-B conversion cost*	84	USD/kW
Total Engine LNF conversion cost (excl. inst.)	**126**	**USD/kW**
Total Engine LNF conversion cost (incl. inst.)	**455**	**USD/kW**

* Green Ship of the Future: Vessel Emission Study (ME-B conversion) [130]

Table 19 Fuel consumtion penalties

	Amount	Unit
Pilot fuel consumption penalty	2.0%	kg/kWh
Cryogenic pump fuel penalty	1.2%	kg/kWh
Total penalty	**3.2%**	**kg/kWh**

5.6 Diesel Particulate Filters (DPF)

The diesel particulate filter (DPF) system is comprised of silicon carbide ceramic fibers and a self-cleaning mechanism. The filter collects particulate matter (PM) as exhaust gas is forced through it and is very efficient at the removal of PM and BC. The self-cleaning element automatically combusts and eliminates PM buildup in the filter. This allows for continual operation without clogging the filter and requires no maintenance by seafarers. The use of particle filters in inland waterway vessels and highway trucks has been very successful.

The Japanese shipping line MOL started preliminary tests of a diesel particulate filter on a two-stroke engine in 2010. A demonstation test was initiated in November 2011 [134] and in February 2012 the DPF system had operated smoothly for more than 500 hours. With research support from the Japanese Classification Society (ClassNK), they have jointly developed a DPF system for marine diesel engines, which run on C heavy oil.

The MOL test is scheduled for about one year (operating time about 4,000 hours) to verify the system's PM collection performance. After that its durability will be assessed. The additional energy penalty due to exhaust back pressure is estimated to be approximately 0.4% of shaft power [135]. The space requirements of these filters (2-3 times engine volume) [135] introduce considerable cost.

A paper by Eelco den Boer, "Emissions from the Legacy Fleet" [135], estimates the installation cost of DPF on inland waterway vessels. The estimated CAPEX cost was reported to be EUR 50/kW ≈ USD 63/kW and the CAPEX including installation costs for a typical retrofit case to EUR be 110/kW ≈ USD 139/kW (EUR to USD exchange rate ≈ 1.26).

Table 20 Cost of DPF

	Amount	Unit
CAPEX DPF (excl. inst.)	63	USD/kW
CAPEX DPF (incl. inst.)	139	USD/kW

5.7 Scrubbers - High Sulphur

Trials of exhaust gas scrubbers have been conducted since 2006, and the system selected for this analysis has an open loop (seawater mode) system and a closed loop (internal freshwater mode) system. In a closed loop, freshwater is recycled, into which sodium hydroxide (NaOH) is continuously added in order to balance pH to a slightly alkaline value (required for optimal scrubbing operation). The closed loop is used for special areas or coastal waters where discharge water is restricted.

Scrubber consumables would result in FW mode. NaOH can be supplied as a 50% solution by tanker trucks at most major ports around the world as it is used in many industries to produce paper, soap, detergents etc. The vessel can also be supplied with large 5m^3 IBC containers with heat insulation due to volitaility from temperature change. NaOH flakes or pellets can also be supplied, in which case the crew will have to manually blend the dry product with water onboard.

The average costs of the equipment, Table 20, in USD/kW can be used to scale the price of the equipment linearly according to the power requirement for the specific vessel, as found in Appendix E. A typical newbuilding cost would be USD 330/kW, excluding off-hire and drydocking, and for a retrofit case USD 368/kW, including off-hire and drydocking.

Table 21 Scrubber cost

	Amount	Unit
Scrubber cost (excl. offhire and drydocking)	330	USD/kW
Scrubber cost (Incl. offhire and drydocking)	368	USD/kW

Table 22 RETROFIT: CAPEX in USD of retrofitting vessels of different type and engine size, but comparable physical dimensions to provide similar drydock costs. Shaft power is given in kW @100% MCR.

			EEDI (De-Rating)	De-Rating	Emulsion	LNG	HFO-distillate	DPF	Scrubber
1	Aframax	16,000	2,210,000	2,210,000	810,000	8,080,000	410,000	1,410,000	5,880,000
2	Container	85,000	9,730,000	9,730,000	2,970,000	45,630,000	1,500,000	6,160,000	29,240,000
3	Bulk Carrier	15,000	2,050,000	2,050,000	740,000	8,490,000	370,000	1,310,000	5,490,000
4	Gas	22,000	3,110,000	3,110,000	1,160,000	12,600,000	580,000	1,990,000	8,160,000
5	Passenger	75,000	9,330,000	9,330,000	3,120,000	41,250,000	1,570,000	5,930,000	26,540,000
6	OSV/AHTS	16,000	2,660,000	2,660,000	1,110,000	9,690,000	560,000	1,710,000	6,330,000
7	Tug	6,100	910,000	910,000	360,000	3,560,000	180,000	580,000	2,310,000

Table 23 NEWBUILD: CAPEX in USD of retrofitting vessels of different type and engine size, but comparable physical dimensions to provide similar drydock costs. Shaft power is given in kW @100% MCR

			EEDI (De-Rating)	De-Rating	Emulsion	LNG	HFO-distillate	DPF	Scrubber
1	Aframax	16,000	1,610,000	1,610,000	410,000	7,280,000	210,000	1,010,000	5,280,000
2	Container	85,000	8,530,000	8,530,000	2,170,000	44,030,000	1,100,000	5,360,000	28,040,000
3	Bulk Carrier	15,000	1,510,000	1,510,000	380,000	7,770,000	190,000	950,000	4,950,000
4	Gas	22,000	2,210,000	2,210,000	560,000	11,400,000	280,000	1,390,000	7,260,000
5	Passenger	75,000	7,530,000	7,530,000	1,920,000	38,850,000	970,000	4,730,000	24,740,000
6	OSV/AHTS	16,000	1,610,000	1,610,000	410,000	8,290,000	210,000	1,010,000	5,280,000
7	Tug	6,100	610,000	610,000	160,000	3,160,000	80,000	380,000	2,010,000

6 Comparison of Abatement Technologies

6.1 Introduction to Assessments

In this section the effectiveness of the abatement technologies is assessed through their costs both on a generic level and on a ship-type level, the latter exemplified with the Aframax example in section five.

The overall effectiveness of an abatement is calculated as the cost associated with a reduction in BC emissions compared to the base case using MDO as fuel. However, the final assessment of the abatement technologies also considers factors such as those mentioned in section 3 and 4, in particular the technological maturity, the technology's co-reduction with other regulated air pollutants and the applicability in the Arctic.

The Aframax Ship Type Example

Comparing the different methodologies regarding the costs relative to the benefits is the objective of this section. The costs and benefits, the latter measured as reduced amount of BC, are compared using the Aframax Tanker base case as an example, but the calculation is carried out for other ship types as well, including container, bulk carrier, gas carrier, passenger, offshore supply vessels/anchor handling tug supply vessels, and tugs. The calculations for all included ship types are provided in appendix C.

The data are provided in 2012 costs in USD similarly to section 5, but include depreciation and interest rate, remaining lifetime and a given number of operating days per year.

Table 24 Basic assumptions for cost-benefit assessment

Operating days per year	260
Interest rate	6%
Lifetime year	
Retrofit	10
Newbuilding	30

As mentioned earlier, the base case is a comparison to MDO, since a BC regulation is not expected to be introduced prior to the sulphur regulation in 2020, and no assumptions are made regarding geographical, ship type or timely limitations.

Cost-Effctiveness of the Technologies

The cost-effetiveness has been calculated according to the method of Corbett et al. [65] using the same input data as given in section 5 and these results are presented in appendix B. In the model time spent in ECAs or special areas can be modelled. The costs are presented for an all year operation in such areas (6,240 hours).

Table 25 Input parameters for cost-effectiveness after Corbett et al. [65]

Input parameter ranges		Low	Medium	High
∘ = Average engine load fraction	0.72	-	-	-
Total annual operating hours [h]	6,240	-	-	-
Interest rate	-	4%	7%	10%
BC emissions rate [g/kWh]	-	0.03	0.07	0.17
Time with system engaged [%]	-	100%	100%	100%
Φ = engine power [kW]	-	5,500	10,000	49,504
Fuel prices:	-			
MDO [USD/ton]	-	973	1,041	1,095
HFO [USD/ton]	-	642	659.8	671
LNG [USD/mmBtu]	-	10	10	10

6.2 Comparisons of Technologies

6.2.1 Yearly Reduction Potential for Abatement Technologies

Base Case MDO

The percentage of reductions of BC as estimated in section 3 were recalculated to mass, assuming the base fuel to be MDO.

Table 26 (overleaf) shows the calculated reduction of BC by the short-listed abatement technologies. The emission reduction rates were calculated from percentage reduction as given in Table 13 and with 0.07 g BC/kWh as the base case.

Table 26 Assessment of reduction of BC through abatement technologies in example vessel (14.4 MW)

	No abatement (using MDO and assuming EEDI)			Slow Steaming and De-Rating			WiFE			LNG		
	Low	Best	High	Low	Best	High	Low	Best	High	Low	Best	High
Reduction [%]	0	0	0	20	50	80	0	30.56	58.33	80	93.5	100
BC Emission rate [g/kWh]	0.07	0.07	0.07	0.056	0.035	0.014	0.07	0.049	0.029	0.014	0.005	0.00
BC Reduction rate [g/kWh]	0	0	0	0.014	0.035	0.056	0	0.021	0.041	0.056	0.065	0.07
Annual BC Emissions [g/y]	3.14E+06	3.14E+06	3.14E+06	2.52E+06	1.57E+06	6.29E+05	3.14E+06	1.52E+06	9.10E+05	6.29E+05	2.04E+05	0.00E+00

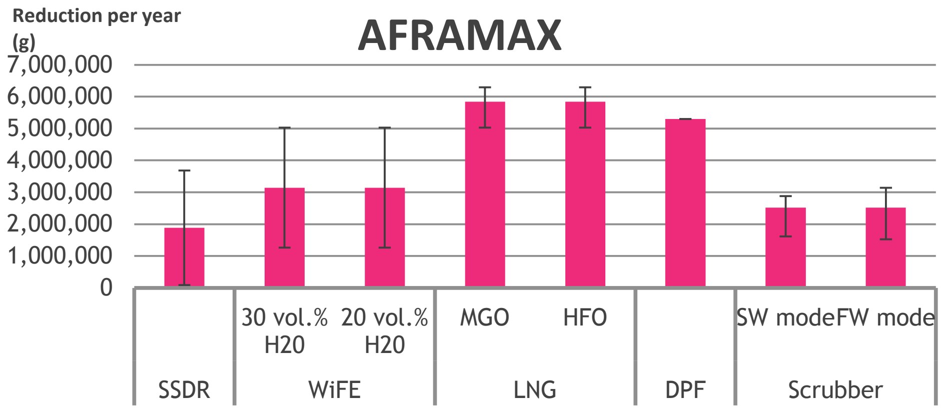
	DPF			SWS			FWS		
	Low	Best	High	Low	Best	High	Low	Best	High
Reduction [%]	70	85	90	25	40	50	25	40	50
BC Emission rate [g/kWh]	0.021	0.011	0.007	0.053	0.042	0.035	0.053	0.042	0.035
BC Reduction rate [g/kWh]	0.049	0.059	0.063	0.017	0.028	0.035	0.017	0.028	0.035
Annual BC Emissions [g/y]	9.43E+05	4.72E+05	3.14E+05	2.36E+06	1.89E+06	1.57E+06	2.36E+06	1.89E+06	1.57E+06

6.3 Cost of Reducing BC in Example Vessels

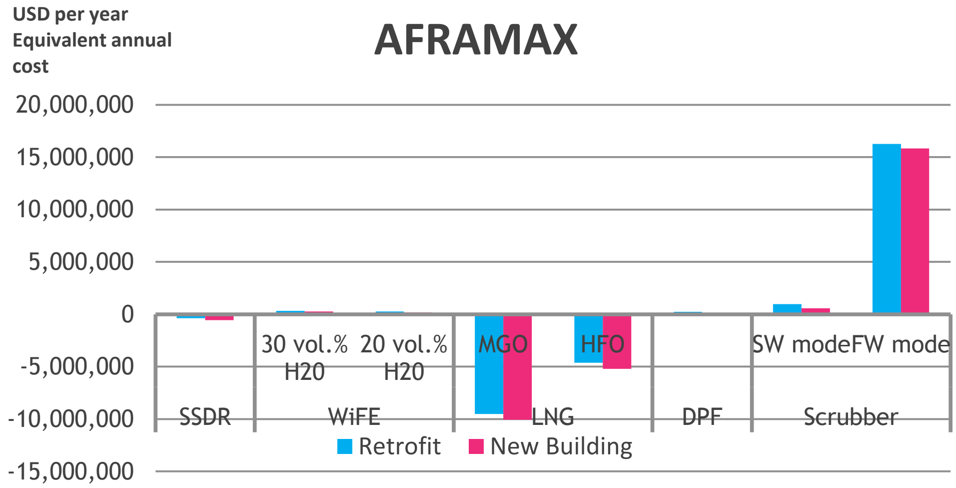
The price for reducing BC with the different abatement technologies is assessed through the BC reduction potential as provided in section 4 and the costs found in section 5. The cost in USD per reduced gram of BC was calculated including CAPEX and OPEX in a standard scenario for the Aframax Tanker example, where an existing vessel has 10 years of remaining trading life and a new vessel has 30 years (for other details see Appendix E).

6.3.1 Aframax Tanker 14.4 MW

The estimate for the reduction of BC is shown for the example case (14.4 MW Aframax Tanker as in section five), with the column showing the reduction based on the best estimate and the bars showing upper and lower ranges of estimates. In absolute amounts, the largest reductions are achieved by moving from HFO or MGO to LNG, or by introducing DPF, since both technologies yield >90% reductions in BC (bearing in mind the lack of experience with DPF in international shipping). The remaining technologies provide 30-50% reductions, although the data sets are not strong regarding BC and considerable ranges are seen between high and low estimates, except for the scrubber data.



A. Reduced BC per year (g)



B. Cost estimates for the technologies (USD/year)

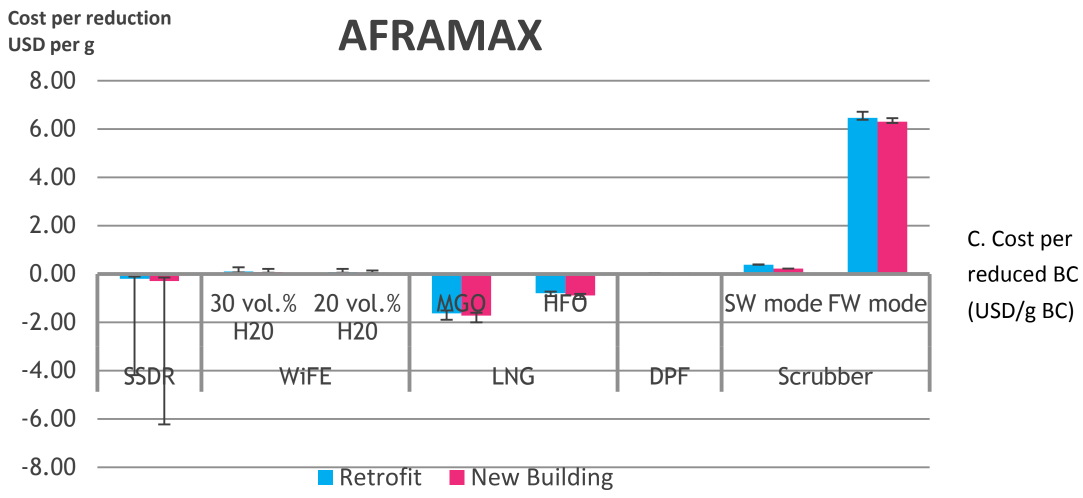


Figure 2 A-C The amount of BC reduced, the cost and the estimated cost-effectiveness of the abatement technologies in the example vessel. The cost assessment is given for Retrofit (blue) and Newbuilding (red)

Fuel Switch from HFO

The case where a fuel switch from HFO to distillate is introduced in the base case and the reductions are calculated from a base emission of 1.34 g BC/kWh [138].

Table 27 BC reduction with fuel switch from HFO

	HFO → Low sulphur distillate		
	Low	Medium	High
Reduction [%]	30	50	80
BC Emission rate [g/kWh]	1.34	1.34	1.34
BC Reduction rate [g/kWh]	0.40	0.67	1.07
Annual BC Emission [g/year]	8.45E+07	6.02E+07	2.43E+07

The cost-efficiency is relatively high, as the estimated cost is approximately USD 0.08 per g reduced BC.

6.3.2 Comparison over Range of Ship Types with 10 MW Installed Effect

Since the governing factors associated with abatement technology installation and operating costs are related to the installed effect, the overall pattern remains more or less the same across ship types, but nevertheless there are differences mainly related to the installation and off-hire costs for the vessel type.

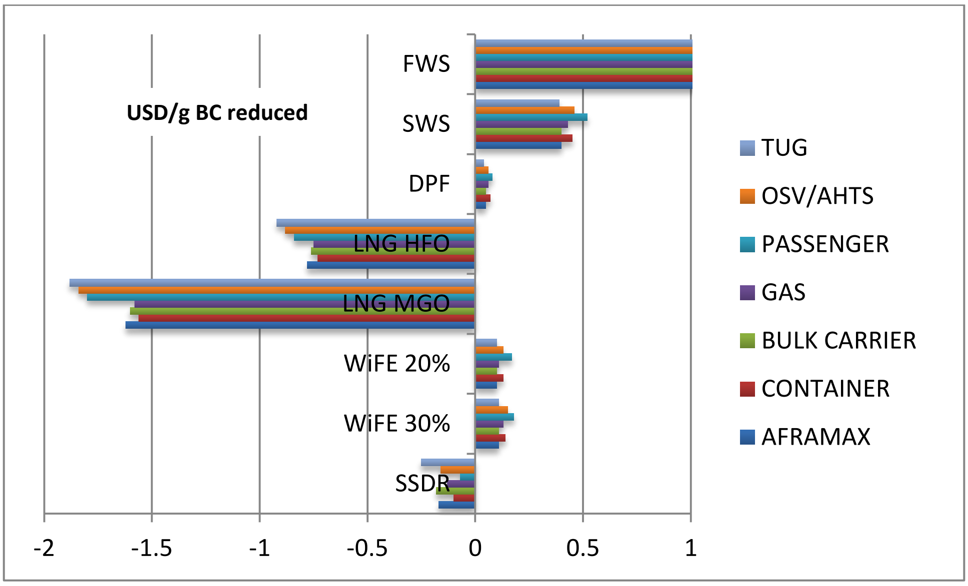


Figure 3 The cost in USD per gram reduced BC emissions for the short-listed abatement technologies over a range of vessels at similar installed effect (10 MW). Upper bars for freshwater scrubber are clustered around 6.5 USD/g BC and omitted for clarity (data from appendix B)

6.3.3 Sensitivity of Analysis

The table below provides estimates of the cost-effectiveness of BC reduction for the different abatement technologies: slow steaming, water-in-fuel emulsification (WiFE), switching to liquid natural gas (LNG), diesel particulate filters (DPF), sea water scrubbing (SWS) and fresh water scrubbing (FWS).

Table 28 Cost-effectiveness (USD/g BC reduced) in select combinations of the cost of fuel and the interest rate scenarios in High, Medium and Low. Thus, for example, high fuel cost and medium interest rate will be HFC-MIR. Numerical values of MDO costs are the lowest, currrent and highest MDO prices since March 2009, and the annual interest rates are 4%, 7% and 10%, respectively. All estimates are made for an engine power of 10,000 kW, total annual operating hours of 6,240, use of marine diesel oil (MDO) and an average engine load fraction of 0.72.

Cost-effectiveness (USD/g BC reduced)	Base case MFC-MIR	MFC-HIR	MFC-LIR	LFC-MIR	HFC-MIR
Slow steaming	-2.62	-2.60	-2.65	-0.76	-3.16
WiFE	0.07	0.08	0.06	0.05	0.07
LNG	-1.73	-1.7	-1.76	0.26	-2.31
DPF	0.21	0.21	0.21	0.12	0.23
SWS	0.31	0.35	0.28	0.24	0.33
FWS	8.92	8.95	8.89	8.76	8.96

The first observation is that the ranking of the methods in terms of USD/g BC reduced does not change regardless of the cost of fuel and the range of interest rates - except for LNG when MDO fuel price is low and the advantage of the fuel switch to LNG is less pronounced.

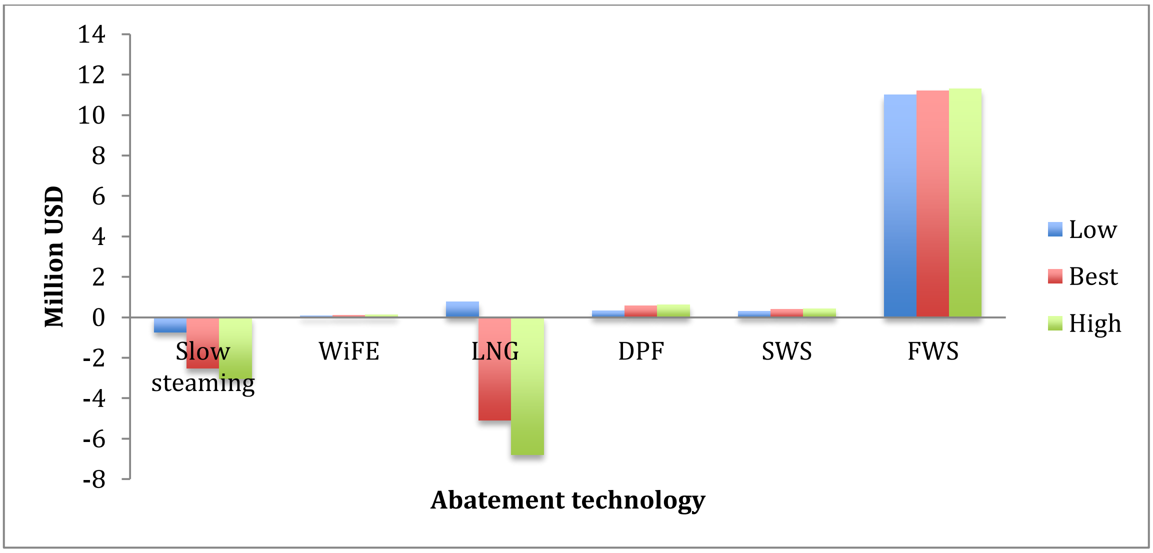


Figure 4 Total costs of the different abatement technologies using the best estimate MDO price of USD 1,011.8 USD/ton, the lowest MDO price of UDS 320/ton and the highest MDO price of USD 1,213/ton.

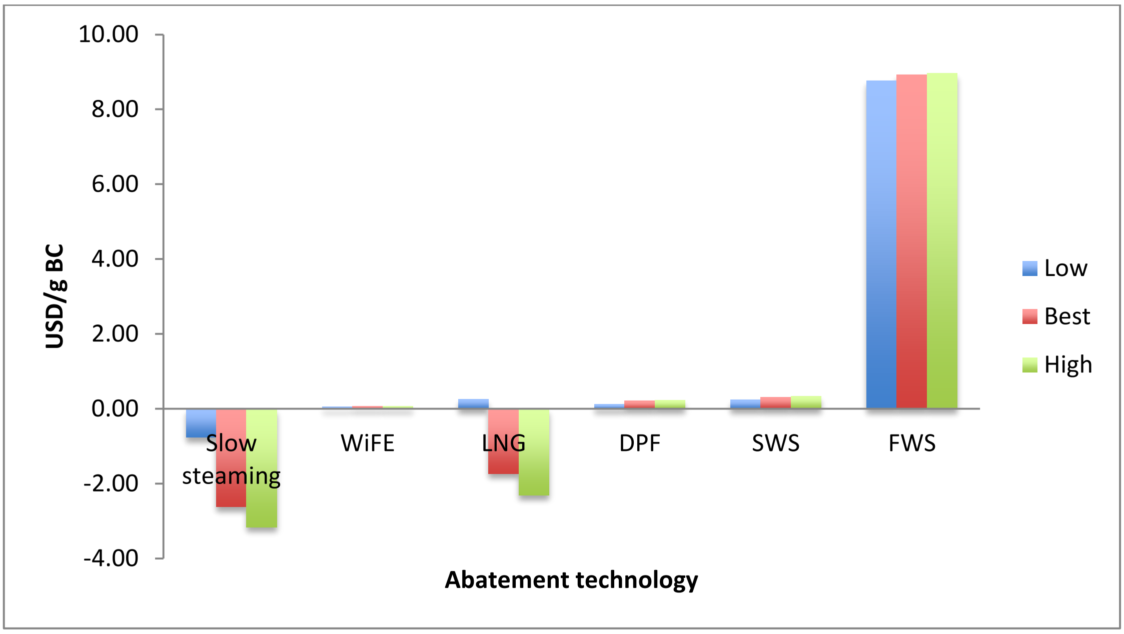


Figure 5 Cost effectiveness of the different abatement technologies using the best estimate MDO price of USD 1,011.8/ton, the lowest MDO price of USD 320/ton and the highest MDO price of USD 1,213/ton.

6.4 Assessment of Feasibility

The EEDI, which applies only to new ships, will lead to CO_2 and non-CO_2 emissions reductions. Many measures available for improving the EEDI of a new vessel are viable for existing vessels and will undoubtedly form part of the toolbox used to meet the requirements of the Ship Energy Efficiency Management Plan (SEEMP), applicable to all ships. Since the measures taken for an individual vessel regarding EEDI or SEEMP may include a number of options, the possible combinations with the BC abatement technologies are numerous and choices may, to a varying degree, impact one another. Most fuel efficiency measures will reinforce each other in terms of BC reductions; however, some efforts, such as slow steaming without de-rating, will counteract BC reductions from other technologies. Such multidimensional interactions have not been included in the costing exercise, but it has been estimated by DNV that the increased fuel efficiency will amount to 13% in 2030 from EEDI and 9% from SEEMP [136].

6.4.1 Slow Steaming - with De-Rating

Simply reducing vessel speed will not achieve any BC emissions reductions, and may in fact increase emissions unless the engine has electronically controlled injection and can adjusts to the load. Here, the assessment is done a the case where slow steaming is acheived with de-rating and the technology is actually generating savings of approximately USD 2.6 per reduced g of BC.

Regarding slow steaming, it is obvious that more tonnage is needed to transport the same total cargo volume when travelling at a slower speed. It can be estimated that 15-20% more tonnage is needed, although it is currently observed that slow steaming is used to absorb surplus tonnage in the market.

Since the estimations on abatement technology are concerned with the comparison of cost associated with the individual vessel, these are not included in the calculations.

As mentioned in section 3, many shipping companies have already pursued slow steaming and many more may do so in order to pursue fuel savings to meet EEDI requirements. Thus, reduction in BC emissions will be achieved through the fuel savings associated with EEDI. Slow steaming may be a preferred option for ships operating on the high seas, but the need for highly adjustable loads in Arctic waters during icy conditions may limit applicability in vessels operating there (particularly with engines with mechanical operation).

6.4.2 WiFE

WiFE produces significant BC reductions with the addition of 20-30% water to the fuel. WiFE is an abatement technology with fewer barriers and it provides a less costly reduction in BC at some 5-8 cents/g BC reduced. It is market ready and already in use for the purpose of reducing NO_X emissions. It must be kept in mind that many studies of WiFE were carried out with the objective of studying the reduction of nitrogen oxides. PM reductions were often measured albeit with limited direct measurements of BC reductions. Recent work suggests that both MDO and HFO water emulsions can be produced to achieve the NO_X, PM and BC benefits. Although the BC reductions are considered valid only few studies are available to further substantiate the reported fuel cost reductions of 10% or more at 15-20% water. To accomodate this uncertainty a sensitivity analysis is performed comparing a 10% fuel reduction scenario with the scenario of 1.5-2.0% fuel penalty used in the estimates above.

Substantial savings are associated if 10% SFOC are achieved in a WiFE. The cost of reducing one gram of BC at a 1.5-2.0% fuel penalty is 0.08-0.10 USD as seen in Table *28* whereas the 10% fuel reduction leads to a negative cost of 0.31-0.36 USD/g BC, i.e. savings, in the 10 MW Aframax model vessel.

6.4.3 LNG/DME

The use of natural gas as fuel for propulsion of ships is considered attractive in terms of its potential for reduction of SO_X and NO_X, but it has considerable potential for BC reduction also. However, the barriers are high for introduction, since the ships must undergo extensive retrofitting and may lose commercial space onboard, in addition to a widespread lack of bunkering facilities. The advantage, besides the reduction of emissions, is a fuel bonus rendering LNG a most cost-effective remedy generating savings of approximately USD 1.7 per gram BC reduced.

If the alternative fuel is MGO, as in ECAs when operating without a scrubber, the use of LNG is very attractive. For HFO, the case is less attractive but still positive. The use of LNG reduces the BC emissions considerably more than a simple switch to distillate fuels, although an LNG estimate using the High estimate will overestimate reality in a dual fuel engine since pilot fuel and lubricants will contribute some 2% BC in practice.

No detailed assessment of DME was performed, since the technology is not yet available beyond the initial test stage. Engine requirements are reportedly similar to LNG, but the use of DME for fuel is less dependent on costly infrastructure.

6.4.4 Diesel Particulate Filters

The advantage of DPFs is the great efficiency of the exhaust after treatment. Despite the technology's low cost, it suffers from a severe lack of maturity in maritime applications and, more importantly, the experience from land and inland water traffic with DPF is that the abatement technology currently can only be operated on (ultra) low-sulphur diesel. Results of an ongoing DPF test on a vessel operated on C Heavy fuel is awaited with interest. The ranking here reflects a situation where DPF can be operated on MDO.

The filters are well known from land-based applications for diesel and low-sulphur fuels, but it is an open question as to how marketable the DPFs are in the immediate future in the maritime market. The costs are comparable to abatement with the seawater scrubber solution.

6.4.5 Scrubbers - High Sulphur

Scrubbers, in both seawater and recirculation modes, are effective technologies for the reduction of BC. When applying scrubbers on the base fuel case of MDO to reduce BC, this technology is a suitable abatement technology at an approximate cost of 30 cents/g BC reduced. The vessel will often need to operate in freshwater mode close to port and the consumption of sodium hydroxide during this freshwater mode is a major cost that bears negatively on the BC reduction cost. This is a significant drawback, e.g. for tugs. It must be kept in mind that marine scrubbers are designed and developed for the reduction of sulphur oxides when operating on HFO, rather than reduction of BC, and their use in international shipping are expected to vastly expand with the introduction of a stricter sulphur regime in 2020.

The actual economical feasibility of this technology is therefore dependent on the trade pattern of the vessel with the expected operation in the vicinity of ports or in ECAs. Obviously, when scrubbers are required and installed for other reasons, the BC reduction comes as a collateral benefit. Scrubbers for the reduction of BC in low-sulphur fuels have not been assessed.

6.4.6 HFO - Low Sulphur Fuel

Significant reductions in BC are achieved when switching from HFO to a lower sulphur fuel, as in the case of distillate fuel. There are studies suggesting that there is no BC reduction or even increases in BC emissions as fuel quality improves, but most studies point to a genuine BC reduction potential, which is corroborated by the experience from land-based diesel engines (see section 3 for the discussion on this).

This is obviously also the case when choosing LNG as the alternative to HFO, and in both cases the shipowner's choice is influenced heavily by the sulphur regulation and the trading pattern with respect to ECAs. The costs are substantial but distributed quite differently, with the LNG option carrying a massive upfront investment and savings on operational costs, and the use of distillate fuel being virtually all operating costs.

6.5 Feasibility in a Regulatory Context

The future scenarios of emissions from a given vessel are extraordinary complicated over the next decade, with a number of possible interactions depending on the timing. As mentioned in the introductory part of the study, the future emissions of BC from shipping may be affected by the 2020 (or possibly

2025) reduction to 0.5% sulphur in fuel on a global scale and to 0.1% when travelling in ECAs, or by the corresponding reduction in sulphates (and particulate matter) arising from the use of exhaust gas cleaning systems. BC emissions will also be affected by the introduced Tier II and coming Tier III NO_X regulations.

6.5.1 Air Emissions Regulation and the No Action Option: Co-Reduction of BC

The requirements of MARPOL Annex VI regarding Tier II NO_X reduction entered into force on 1st of January,2011, and according to Dieselnet.com (Dieselnet 2010): *Tier II standards are expected to be met by combustion process optimization. The parameters examined by engine manufacturers include fuel injection timing, pressure, and rate (rate shaping), fuel nozzle flow area, exhaust valve timing, and cylinder compression volume.*

While some technical solutions to the Tier II requirement do not necessarily lead to reduced BC emissions, others do lead to notable BC effects, including WiFE, slide valves and de-rating combined with slow steaming.

Thus, given the renewal of the fleet, and in the perspective of a 2020 or 2030 horizon a significant part of the global fleet may, through EEDI, NO_X requirements and sulphur reductions, already have co-reduced BC emissions inadvertently. Since the mechanisms of the aforementioned requirements to achieve their objectives are not defined, the precise reduction in BC resulting hereof cannot be assessed.

Therefore, the timing of a BC emissions reduction regulation may have significant impact on the “value” of the regulatory action. If the IMO choose to implement BC regulation early, some abatement technologies acting on HFO (switching to low sulphur or using scrubbers) may be relevant, but if the action toward BC has a longer time frame, existing requirements under MARPOL will already have BC reduction potential through EEDI, SO_X and NO_X regulation.

A shipowner already facing investments regarding both sulphur and nitrogen oxides would possibly be positively inclined toward a BC abatement technology that was also addressing the other issues of air emissions, and, potentially, even fuel efficiency improvements.

The table below lists the six abatement technologies, of which some provide the BC reduction as part of a general reduction in fuel consumption.

Table 29 Tentative assessment of co-reduction of BC through other mechanisms for air pollution reduction

	Sulphur and/or SO_X	NO_X	BC	Fuel savings
Slow steaming with de-rating	YES	YES	YES	YES
Water-in-Fuel Emulsion	YES	YES	YES	YES
HFO to Distillate	YES	NO	YES	NO
LNG for propulsion	YES	YES	YES	YES
Diesel Particulate Filter	YES	NO	YES	NO
Scrubber - High Sulphur Fuel	YES	NO	YES	YES

6.5.2 Operational Pattern Relative to ECAs

Although it is not part of the current study to examine the effect of the operational pattern of a vessel, it is going to influence the shipowner's choice of the most beneficial BC abatement technology. For example, if all or most voyages take place in ECAs or on the high seas, as may be the case for ro-ro operations or large container vessels respectively, different abatement options might be considered. Operation in ECAs will favour certain technologies for which the alternative is low-sulphur marine gas oil. For the High Seas vessels a technology compatible currently with HFO and later with 0.5% Sulphur Marine Diesel Oil may be preferred. Also, technologies that address requirements regarding both sulphur and nitrogen oxides will gain an advantage beyond 2020.

6.5.3 Assessment of Abatement Technologies Regarding Specific Arctic Issues

The majority of vessels currently operating in the Arctic are vessels calling ports in the area rather than vessels transiting through the Northwest Passage or the Northern Sea Route. However, it is expected that the increase in traffic will be for vessels in transhipment such as tankers and bulkers, and for cruise ships and vessels operating for extended periods in the Arctic such as the OSV/AHTS and fishing vessels. Several of the abatement technologies may not be suited for vessels operating in the Arctic. This would include LNG, since the lack of bunkering infrastructure and relatively limited operational range of current designs of LNG-powered vessels does challenge the applicability.

The current study is directed at the ranking of various abatement technologies for the purpose of regulatory feasibility and, as such, not directed at assessing the cost for the global fleet composition - or an Arctic fleet given the possible trading patterns - and route viability in a future setting.

The global reduction in shipping's emissions of air pollutants will reduce the long-range transport of BC to the Arctic and will likewise reduce the locally generated BC originating from (international) shipping. The introduction of abatement technologies mentioned in this study may further reduce locally generated BC from international shipping by 50-90% depending on the actual technology.

6.6 Overview of Technologies

In the table overleaf the technologies are presented with the key characteristics regarding their feasibilty for existing vessels. The most feasible and cost-effective technologies may be found among slow steaming with de-rating, fuel switch to low sulphur or LNG. But WiFE is also a relatively simple technology with a reasonable cost-effectiveness.

Several of the BC abatement technologies may be used in combination with one another for increased efficiency or some are already under consideration for other purposes (SOX or NOX reductions) and a BC abatement technology may be added. While the available body of data on BC does not allow any detailed analyses and it is not within the scope of the current study to evaluate the multiple combinations possible it may be noted that some technologies lend themselves to this option: For example slow steaming operations (with engine retuning or de-rating) and diesel particulate filters will substantially reduce CO2 and particle emissions. A small fuel penalty for DPF operation will mean fuel savings will be slightly reduced. Alternatively operation of engines on high quality fuels, in combination with DPFs will produce significant SOX and PM reductions, although both of these options come with a cost penalty. An alternative combination of technologies is a combination of operational, fuel-based and after-treatment options such as slide valves, water in fuel emulsions and scrubbers (or DPF).

We caution that the efficiencies observed with one technology may not always be additive and both antagonistic and synergistic effects may be observed when combining operational, fuel-based and after-treatment measures. However, the efficiencies observed with one technology may not necessarily be additive and both antagonistic and synergistic effects may be observed when combining operational, fuel-based and after-treatment measures.

It is clear from the difficulties reported in monitoring BC in exhausts points toward certifying certain technologies, particularly if regulation is enacted within the coming decade. However, few technologies are in fact thoroughly studied with respect to BC, although data on particles and hydrocarbons are used as proxies and thus the current basis for certification is not strong.

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Table 30 Factors impacting feasibility of technology

	BC reduction %	Cost effectiveness	Ties and co-reduction	Barriers to retrofit	Other barriers	Arctic barrier	Enforcement mechanism
SSDR	15	High	Not directly linked, but strong fuel saving motivation	Not possible for mechanically controlled engine	-	Variable loads under ice conditions	Not readily certifiable
WiFE	70	Medium	Will increase with NO_X regulation	Lack of emulsification in distillates	Few	No	Certifiable
HFO - Distillate	52	High	Driven by Sulphur regulations	Few	Fuel availability	No	Certifiable
LNG	93.5	High	Driven by NO_X and Sulphur regulations	Design challenges in vessel with no deck space	-	Bunkering infrastructure missing	Certifiable
DPF	85	Medium	No incentive from other regulation	Footprint restrictions	Immature technology	-	Certifiable
SWS	60	Medium	Driven by Sulphur regulations	Footprint restrictions	-	May require heating	Certifiable
FWS	60	Low	Driven by Sulphur regulations	Footprint restrictions	-	Heating of NaOH solution above 18C to avoid crystalization	Certifiable

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Appendix

Appendix A - Cost Overview

Table 35 from Erria report

Cost Index			EEDI		De-Rating		Emulsion		LNG		HFO-Distillate /day		DPF		Scrubber	
1.	AFRAMAX			0.73		0.73		0.51		0.90		0.51		0.72		0.90
2.	CONTAINER		4.40	5.30	4.40	5.30	3.67	5.29	5.65	6.05	3.66	5.24	4.37	5.31	4.97	5.31
3.	BULK CARRIER		0.93	0.94	0.93	0.94	0.91	0.93	1.05	1.07	0.90	0.90	0.93	0.94	0.93	0.94
4.	GAS	COST INDEX	1.41	1.37	1.41	1.37	1.43	1.37	1.56	1.57	1.41	1.33	1.41	1.38	1.39	1.38
5.	PASSENGER		4.22	3.41	4.22	4.68	3.85	4.68	5.11	5.34	3.83	4.62	4.21	4.68	4.51	4.69
6.	OSV/AHTS		1.20	1.00	1.20	1.00	1.37	1.00	1.20	1.14	1.37	1.00	1.21	1.00	1.08	1.00
7.	TUG		0.41	0.38	0.41	0.38	0.44	0.39	0.44	0.43	0.44	0.38	0.41	0.38	0.39	0.38

Table 34 from Erria report

Off-hire rates	EEDI	De-Rating	WiFE	LNG	HFO-Distillate	DPF	Scrubber	Off Hire Rates
AFRAMAX	30	30	20	40	10	20	30	USD 20,000
CONTAINER	30	30	20	40	10	20	30	USD 40,000
BULK CARRIER	30	30	20	40	10	20	30	USD 18,000
GAS	30	30	20	40	10	20	30	USD 30,000
PASSENGER	30	30	20	40	10	20	30	USD 60,000
OSV/AHTS	30	30	20	40	10	20	30	USD 35,000
TUG	30	30	20	40	10	20	30	USD 10,000

Table 31 from Erria report

Cost per kW excl. Off-hire cost	AFRAMAX	CONTAINER	BULK CARRIER	GAS	PASSENGER	OSV/AHTS	TUG
EEDI	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100
Slow Steaming: With De-Rating	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100
WIFE	USD 26	USD 26	USD 26	USD 26	USD 26	USD 26	USD 26
LNG	USD 455	USD 518	USD 518	USD 518	USD 518	USD 518	USD 518
DPF	USD 63	USD 63	USD 63	USD 63	USD 63	USD 63	USD 63
HFO-Distillate	USD 13	USD 13	USD 13	USD 13	USD 13	USD 13	USD 13
Scrubber	USD 330	USD 330	USD 330	USD 330	USD 330	USD 330	USD 330

Table 28 from Erria report

SFOC (Specific Fuel Oil Consumption)				
	HFO	LS MGO	LNG	
2-Stroke	0.182	0.171	0.155	kg/kWhr
2-Stroke (de-rated)	0.171	0.161	0.145	kg/kWhr
4-Stroke	0.209	0.196	0.178	kg/kWhr
4-Stroke (de-rated)	0.196	0.185	0.167	kg/kWhr

Table 9 from Erria report

Fuel Price - World Wide			
	HFO 380 1-3.5%S	MGO 0.1%S	LNG
Singapore	USD 676.00	USD 995.00	USD 412.00
Rotterdam	USD 653.50	USD 975.00	USD 389.00
Houston	USD 671.50	USD 1,040.00	
Fujairah	USD 681.50	USD 1,026.00	
Los Angeles	USD 686.50	USD 1,097.00	
Durban		USD 1,131.50	
Tokyo	USD 718.50	USD 1,008.00	
New York	USD 663.50		
Average:	**USD 678.71**	**USD 1,038.93**	**USD 400.50**

Appendix B - Calculations according to Corbett

Table 31 to Table 35 provide estimates of energy use, total cost of technology, pollution reduction and cost-effectiveness of BC reduction for the different abatement technologies slow steaming, water-in-fuel emulsification (WiFE), switch to liquid natural gas (LNG), diesel particulate filters (DPF), sea water scrubbing (SWS) and fresh water scrubbing (FWS). All estimates are made for an engine power of 10,000 kW, total annual operating hours of 6240, use of marine diesel oil (MDO) and an average engine load fraction of 0.72. The base scenario uses a discount rate of 7% and MDO cost of 1011.8 USD/mt (Table 31). A sensitivity analysis assessing the impact on cost of changing discount rates and MDO costs has been made (Table 32 to 35). The lowest and the highest MDO price since March 2009 have been used.

Table 31 Best estimates for the different technologies using MDO fuel cost of 1011.8 USD/mt and a discount rate of 7%.

	Energy use [kWh/year]	Total cost [USD/year]	Pollution reduction [g/year]	Cost-effectiveness [USD/g BC]
Slow steaming	3.12E+07	-2.52E+06	9.61E+05	-2.62
WiFE	4.49E+07	1.04E+05	1.57E+06	0.07
LNG	4.49E+07	-5.09E+06	2.94E+06	-1.73
DPF	4.49E+07	5.58E+05	2.67E+06	0.21
SWS	4.49E+07	3.92E+05	1.26E+06	0.31
FWS	4.49E+07	1.12E+07	1.26E+06	8.92

Table 32 Estimates for the different technologies using MDO fuel cost of 1011.8 USD/mt and a discount rate of 10%.

	Energy use [kWh/year]	Total cost [USD/year]	Pollution reduction [g/year]	Cost-effectiveness [USD/g BC]
Slow steaming	3.12E+07	-2.49E+06	9.61E+05	-2.60
WiFE	4.49E+07	1.19E+05	1.57E+06	0.08
LNG	4.49E+07	-5.01E+06	2.94E+06	-1.7
DPF	4.49E+07	5.63E+05	2.67E+06	0.21
SWS	4.49E+07	4.34E+05	1.26E+06	0.35
FWS	4.49E+07	1.13E+07	1.26E+06	8.95

Table 33 Estimates for the different technologies using MDO fuel cost of 1011.8 USD/mt and a discount rate of 4%.

	Energy use [kWh/year]	Total cost [USD/year]	Pollution reduction [g/year]	Cost-effectiveness [USD/g BC]
Slow steaming	3.12E+07	-2.55E+06	9.61E+05	-2.65
WiFE	4.49E+07	9.06E+04	1.57E+06	0.06
LNG	4.49E+07	-5.16E+06	2.94E+06	-1.76
DPF	4.49E+07	5.54E+05	2.67E+06	0.21
SWS	4.49E+07	3.54E+05	1.26E+06	0.28
FWS	4.49E+07	1.12E+07	1.26E+06	8.89

Table 34 Estimates for the different technologies using MDO fuel cost of 320 USD/mt and a discount rate of 7%.

	Energy use [kWh/year]	Total cost [USD/year]	Pollution reduction [g/year]	Cost-effectiveness [USD/g BC]
Slow steaming	3.12E+07	-7.31E+05	9.61E+05	-0.76
WiFE	4.49E+07	7.49E+04	1.57E+06	0.05
LNG	4.49E+07	7.54E+05	2.94E+06	0.26
DPF	4.49E+07	3.25E+05	2.67E+06	0.12
SWS	4.49E+07	2.99E+05	1.26E+06	0.24
FWS	4.49E+07	1.10+07	1.26E+06	8.76

Table 35 Estimates for the different technologies using MDO fuel cost of 1213 USD/mt and a discount rate of 7%.

	Energy use [kWh/year]	Total cost [USD/year]	Pollution reduction [g/year]	Cost-effectiveness [USD/g BC]
Slow steaming	3.12E+07	-3.04E+06	9.61E+05	-3.16
WiFE	4.49E+07	1.13E+05	1.57E+06	0.07
LNG	4.49E+07	-6.79E+06	2.94E+06	-2.31
DPF	4.49E+07	6.26E+05	2.67E+06	0.23
SWS	4.49E+07	4.19E+05	1.26E+06	0.33
FWS	4.49E+07	1.13E+07	1.26E+06	8.96

Table 36 provides estimates of energy use, total cost of technology, pollution reduction and cost-effectiveness when switching from heavy fuel oil (HFO) to MDO. The estimates are made for an engine power of 10,000 kW, total annual operating hours 6240 and an average engine load fraction of 0.72. The best estimate uses a discount rate of 7%, HFO cost of 659.8 USD/mt and MDO cost of 1011.8 USD/mt (Table 36). A sensitivity analysis has been made where the discount rate and the fuel costs are varied. The lowest and the highest MDO price since March 2009 have been used together with the corresponding lowest and highest HFO for the given dates.

Table 36 Best estimates when switching from HFO to MDO and sensitivity analysis assessing the impact of changing discount rates and fuel costs.

HFO-> distillate	Energy use [kWh/year]	Total Cost [USD/year]	Pollution reduction [g/year]	Cost-effectiveness [USD/g BC]
Best estimate	4.49E+07	2.63E+06	1.57E+06	1.67
Interest rate 4%	4.49E+07	2.63E+06	1.57E+06	1.67
Interest rate 10%	4.49E+07	2.64E+06	1.57E+06	1.68
MDO cost 320 USD/mt, HFO cost 160 USD/mt	4.49E+07	1.28E+06	1.57E+06	0.81
MDO cost 1213 USD/mt HFO cost 903 USD/mt	4.49E+07	2.14E+06	1.57E+06	1.36

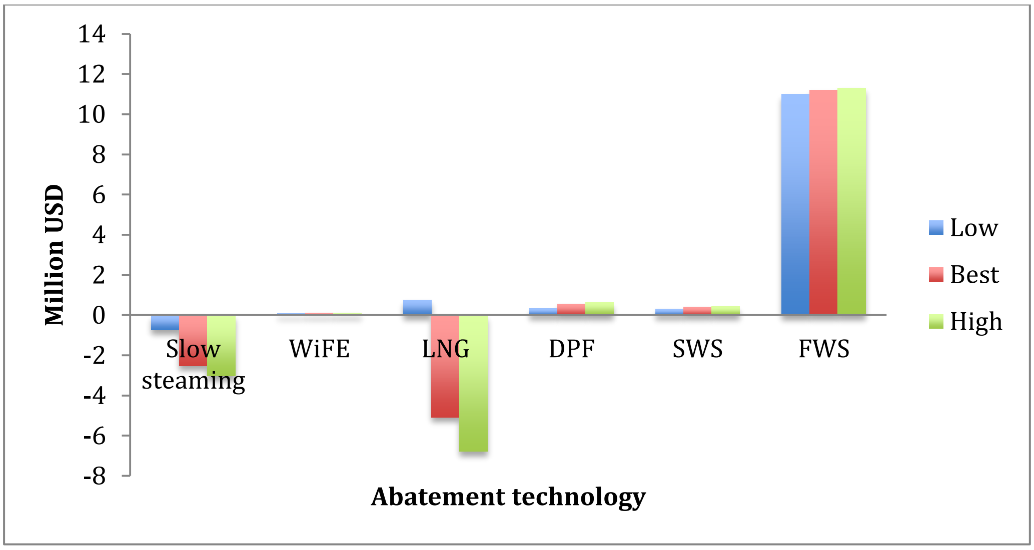

Figure 6 Total costs of the different abatement technologies using the best estimate MDO price of 1,011.8 USD/ton, the lowest MDO price of 320 USD/ton and the highest MDO price of 1,213 USD/ton.

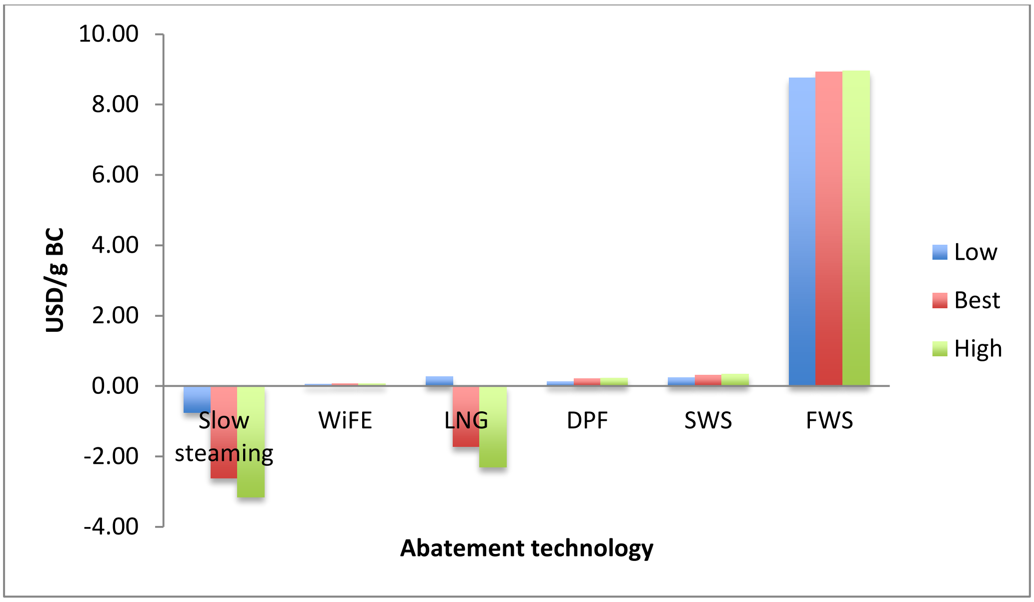

Figure 7 Cost effectiveness of the different abatement technologies using the best estimate MDO price of 1,011.8 USD/ton, the lowest MDO price of 320 USD/ton and the highest MDO price of 1,213 USD/ton

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Appendic C - Cost and BC Reduction Overview: Ship Types 10MW with Aframax Tanker Base Case

Input

CAPEX for 10 MW

	Shaft Power (kW) @100% MCR	EEDI (De-Rating)		SSDR		WiFE		LNG		DPF		Scrubber	
		Retrofit	New-building	Retrofit	New-building	Retrofit	New-building	Retrofit	New-building	Retrofit	New-building	Retrofit	New-building
1. AFRAMAX	10,000	1,600,000	1,000,000	1,600,000	1,000,000	660,000	260,000	5,350,000	4,550,000	1,030,000	630,000	3,900,000	3,300,000
2. CONTAINER	10,000	2,200,000	1,000,000	2,200,000	1,000,000	1,060,000	260,000	6,780,000	5,180,000	1,430,000	630,000	4,500,000	3,300,000
3. BULK	10,000	1,540,000	1,000,000	1,540,000	1,000,000	620,000	260,000	5,900,000	5,180,000	990,000	630,000	3,840,000	3,300,000
4. GAS	10,000	1,900,000	1,000,000	1,900,000	1,000,000	860,000	260,000	6,380,000	5,180,000	1,230,000	630,000	4,200,000	3,300,000
5. PASSENGER	10,000	2,800,000	1,000,000	2,800,000	1,000,000	1,460,000	260,000	7,580,000	5,180,000	1,830,000	630,000	5,100,000	3,300,000
6. OSV/AHTS	10,000	2,050,000	1,000,000	2,050,000	1,000,000	960,000	260,000	6,580,000	5,180,000	1,330,000	630,000	4,350,000	3,300,000
7. TUG	10,000	1,300,000	1,000,000	1,300,000	1,000,000	460,000	260,000	5,580,000	5,180,000	830,000	630,000	3,600,000	3,300,000

Addition to OPEX per day for 10 MW.

	Shaft Power (kW)@90% MCR	EEDI (De-Rating)		SSDR		WiFE		LNG comparison		DPF	Scrubber	
		2-Stroke	4-Stroke	2-Stroke	4-Stroke	30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1 AFRAMAX	9,000	-1,600	-	-1,600	-	500	400	-25,500	-13,800	107	400	37,200
2 CONTAINER	9,000	-1,600	-	-1,600	-	500	400	-25,500	-13,800	107	400	37,200
3 BULK	9,000	-1,600	-	-1,600	-	500	400	-25,500	-13,800	107	400	37,200
4 GAS	9,000	-1,600	-1,800	-1,600	-1,800	500	400	-25,500	-13,800	107	400	37,200
5 PASSENGER	9,000	-	-1,800	-	-1,800	600	500	-29,300	-15,800	123	500	37,300
6 OSV/AHTS	9,000	-	-1,800	-	-1,800	600	500	-29,300	-15,800	123	500	37,300
7 TUG	9,000	-	-1,800	-	-1,800	500	500	-29,300	-15,800	123	500	37,300

BC reduction rates [g/kWh]

	No abatement	SSDR	WiFE	LNG	DPF	SWS
Low	0	0.001	0.014	0.056	0.049	0.017
Base	0	0.021	0.035	0.065	0.059	0.028
High	0.000	0.041	0.056	0.070	0.063	0.035

Operating days, interest rate and lifetime

Operating days per year	260
Interest rate	6%
Lifetime year	
Retrofit	10
Newbuilding	30

Calculations

	Shaft Power (kW)@90% MCR	EEDI (De-Rating)		SSDR		WiFE		LNG comparison		DPF	Scrubber	
		2-Stroke	4-Stroke	2-Stroke	4-Stroke	30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1. AFRAMAX	-416,000	-	-416,000	-	130,000	104,000	-6,630,000	-3,588,000	3,068,000	104,000	9,672,000	-416,000
2. CONTAINER	-416,000	-	-416,000	-	130,000	104,000	-6,630,000	-3,588,000	3,068,000	104,000	9,672,000	-416,000
3. BULK CARRIER	-416,000	-	-416,000	-	130,000	104,000	-6,630,000	-3,588,000	3,068,000	104,000	9,672,000	-416,000
4. GAS	-416,000	-468,000	-416,000	-468,000	130,000	104,000	-6,630,000	-3,588,000	3,068,000	104,000	9,672,000	-416,000
5. PASSENGER	-	-468,000	-	-468,000	156,000	130,000	-7,618,000	-4,108,000	3,536,000	130,000	9,698,000	-
6. OSV/AHTS	-	-468,000	-	-468,000	156,000	130,000	-7,618,000	-4,108,000	3,536,000	130,000	9,698,000	-
7. TUG	-	-468,000	-	-468,000	156,000	130,000	-7,618,000	-4,108,000	3,536,000	130,000	9,698,000	-

AFRAMAX	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
			30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
Newbuilding	1,000,000	1,000,000	260,000	260,000	4,550,000	4,550,000	630,000	3,300,000	3,300,000
Addition to OPEX per year (USD)	-416,000	-416,000	130,000	104,000	-6,630,000	-3,588,000	27,749	0	104,000

Costs

Costs per year for retrofit [USD]

		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	9,000	-198,611	-198,611	219,673	193,673	-5,903,106	-2,861,106	167,693	633,885	10,201,885
2.	CONTAINER	9,000	-117,090	-117,090	274,020	248,020	-5,708,815	-2,666,815	222,040	715,406	10,283,406
3.	BULK CARRIER	9,000	-206,763	-206,763	214,238	188,238	-5,828,379	-2,786,379	162,258	625,733	10,193,733
4.	GAS	9,000	-157,851	-157,851	246,846	220,846	-5,763,162	-2,721,162	194,866	674,645	10,242,645
5.	PASSENGER	9,000	-87,570	-87,570	354,367	328,367	-6,588,121	-3,078,121	280,618	822,927	10,390,927
6.	OSV/AHTS	9,000	-189,471	-189,471	286,433	260,433	-6,723,989	-3,213,989	212,684	721,026	10,289,026
7.	TUG	9,000	-291,372	-291,372	218,499	192,499	-6,859,857	-3,349,857	144,750	619,125	10,187,125

Costs per year for newbuilding [USD]

		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	9,000	-343,351	-343,351	148,889	122,889	-6,299,447	-3,257,447	73,518	343,741	9,911,741
2.	CONTAINER	9,000	-343,351	-343,351	148,889	122,889	-6,253,679	-3,211,679	73,518	343,741	9,911,741
3.	BULK CARRIER	9,000	-343,351	-343,351	148,889	122,889	-6,253,679	-3,211,679	73,518	343,741	9,911,741
4.	GAS	9,000	-343,351	-343,351	148,889	122,889	-6,253,679	-3,211,679	73,518	343,741	9,911,741
5.	PASSENGER	9,000	-395,351	-395,351	174,889	148,889	-7,241,679	-3,731,679	77,749	369,741	9,937,741
6.	OSV/AHTS	9,000	-395,351	-395,351	174,889	148,889	-7,241,679	-3,731,679	77,749	369,741	9,937,741
7.	TUG	9,000	-395,351	-395,351	174,889	148,889	-7,241,679	-3,731,679	77,749	369,741	9,937,741

BC Reduction Overview

Reduction per year [g] per vessel

		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
2.	CONTAINER	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
3.	BULK CARRIER	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
4.	GAS	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
5.	PASSENGER	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
6.	OSV/AHTS	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
7.	TUG	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
1	AFRAMAX	9,000	-	1,179,360	1,965,600	1,965,600	3,650,400	3,650,400	3,313,440	1,572,480	1,572,480
	Decrease low		-	1,123,200	1,179,360	1,179,360	505,440	505,440	561,600	617,760	0
	Increase high		-	2,504,736	3,066,336	3,066,336	2,639,520	2,639,520	2,347,488	1,572,480	1,572,480

Cost per BC Reduction Overview

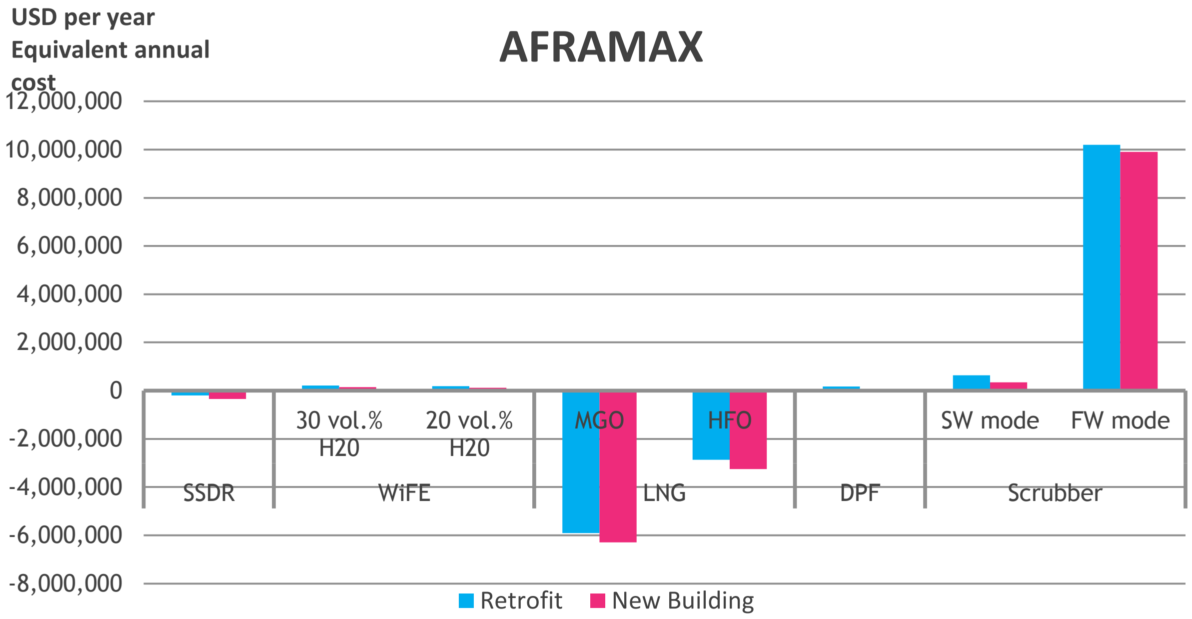
Cost per reduction for retrofit, base case [USD/g BC]

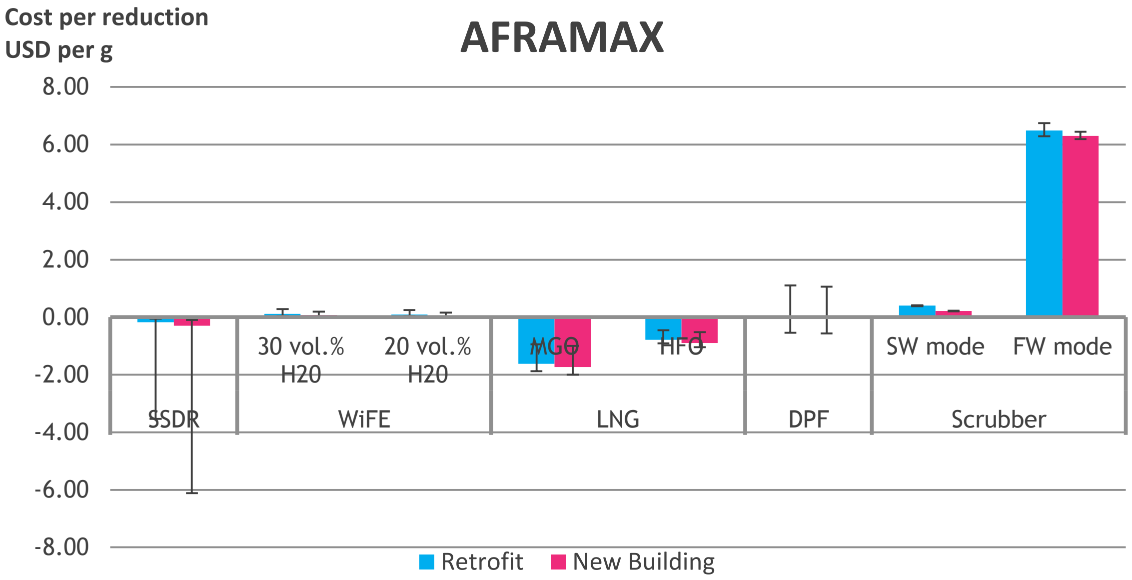
		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	9,000	-	-0.17	0.11	0.10	-1.62	-0.78	0.05	0.40	6.49
2.	CONTAINER	9,000	-	-0.10	0.14	0.13	-1.56	-0.73	0.07	0.45	6.54
3.	BULK CARRIER	9,000	-	-0.18	0.11	0.10	-1.60	-0.76	0.05	0.40	6.48
4.	GAS	9,000	-	-0.13	0.13	0.11	-1.58	-0.75	0.06	0.43	6.51
5.	PASSENGER	9,000	-	-0.07	0.18	0.17	-1.80	-0.84	0.08	0.52	6.61
6.	OSV/AHTS	9,000	-	-0.16	0.15	0.13	-1.84	-0.88	0.06	0.46	6.54
7.	TUG	9,000	-	-0.25	0.11	0.10	-1.88	-0.92	0.04	0.39	6.48
1	AFRAMAX	9,000	-	-0.17	0.11	0.10	-1.62	-0.78	0.05	0.40	6.49
	Decrease low		-	3.37	-0.17	-0.15	0.26	0.13	-0.01	-0.26	0.00
	Increase high		-	0.11	-0.07	-0.06	0.68	0.33	-0.02	-0.20	-3.24

Cost per reduction for newbuilding, base case [USD/g BC]

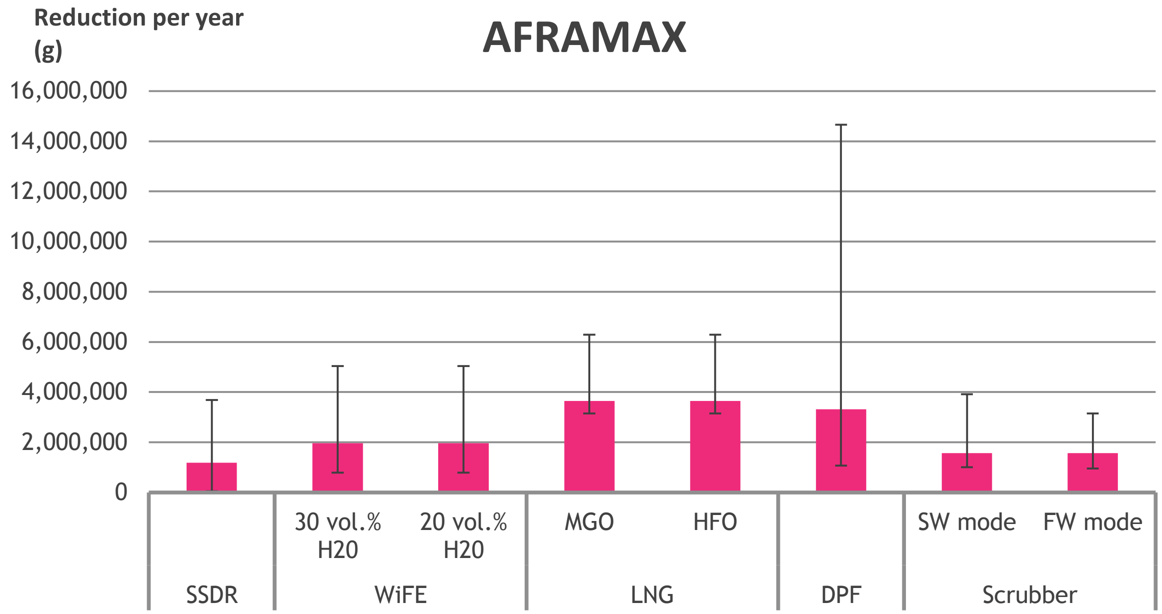
		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	9,000	-	-0.29	0.08	0.06	-1.73	-0.89	0.02	0.22	6.30
2.	CONTAINER	9,000	-	-0.29	0.08	0.06	-1.71	-0.88	0.02	0.22	6.30
3.	BULK CARRIER	9,000	-	-0.29	0.08	0.06	-1.71	-0.88	0.02	0.22	6.30
4.	GAS	9,000	-	-0.29	0.08	0.06	-1.71	-0.88	0.02	0.22	6.30
5.	PASSENGER	9,000	-	-0.34	0.09	0.08	-1.98	-1.02	0.02	0.24	6.32
6.	OSV/AHTS	9,000	-	-0.34	0.09	0.08	-1.98	-1.02	0.02	0.24	6.32
7.	TUG	9,000	-	-0.34	0.09	0.08	-1.98	-1.02	0.02	0.24	6.32
1	AFRAMAX	9,000	-	-0.29	0.08	0.06	-1.73	-0.89	0.02	0.22	6.30
	Decrease low		-	5.82	-0.11	-0.09	0.28	0.14	0.00	-0.14	0.00
	Increase high		-	0.20	-0.05	-0.04	0.72	0.37	-0.01	-0.11	-3.15

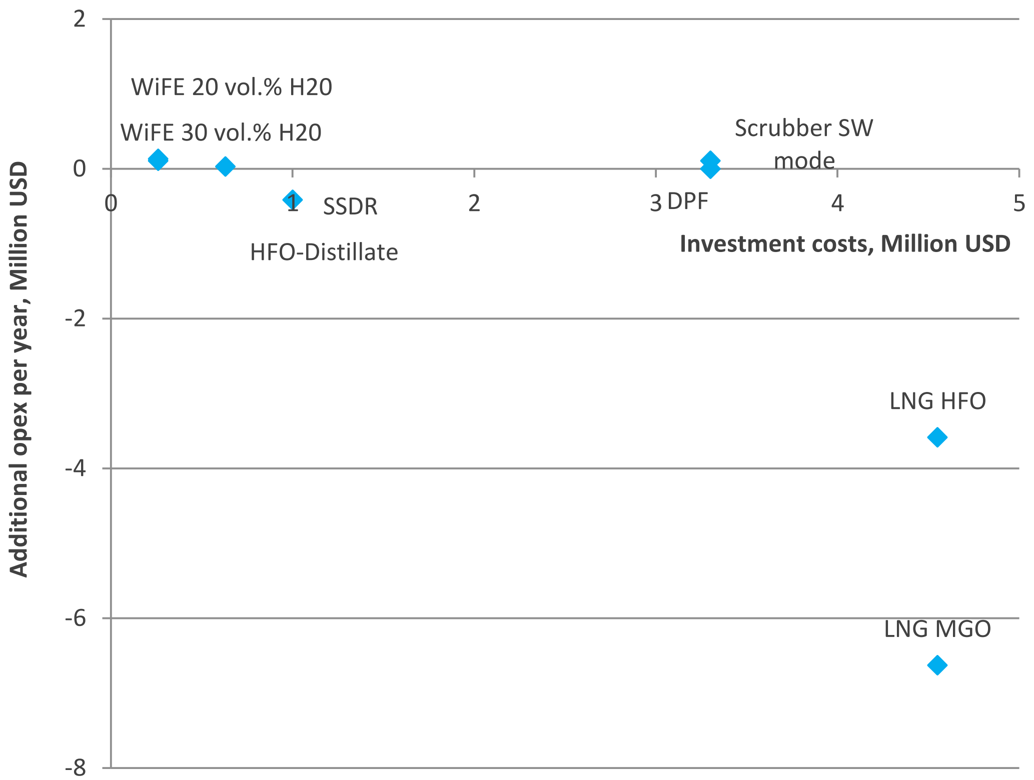
Figures - 10 MW Comparisson




Cost per reduction
USD per g
AFRAMAX
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
30 vol.% H20
20 vol.% H20
MGO
HFO
SW mode
FW mode
SSDR
WiFE
LNG
DPF
Scrubber
Retrofit
New Building

72


Reduction per year (g)
AFRAMAX
16,000,000
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
30 vol.% H20
20 vol.% H20
MGO
HFO
SW mode
FW mode
SSDR
WiFE
LNG
DPF
Scrubber


2
0
-2
-4
-6
-8
0
1
2
3
4
5
WiFE 20 vol.% H20
WiFE 30 vol.% H20
SSDR
HFO-Distillate
Scrubber SW mode
DPF
LNG HFO
LNG MGO
Investment costs, Million USD
Additional opex per year, Million USD

Appendix D - Cost and BC Reduction Overview: Similar Docking Size; Varying MW

Input

Input data, CAPEX

		Shaft Power (kW) @100% MCR	EEDI (De-Rating)		SSDR		WiFE		LNG		DPF		Scrubber	
			Retrofit	Newbuild-ing	Retrofit	Newbuilding	Retrofit	Newbuilding	Retrofit	Newbuilding	Retrofit	Newbuilding	Retrofit	Newbuild-ing
1.	AFRAMAX	16,000	2,210,000	1,610,000	2,210,000	1,610,000	810,000	410,000	8,080,000	7,280,000	1,410,000	1,010,000	5,880,000	5,280,000
2.	CONTAINER	76,500	9,730,000	8,530,000	9,730,000	8,530,000	2,970,000	2,170,000	45,630,000	44,030,000	6,160,000	5,360,000	29,240,000	28,040,000
3.	BULK CARRIER	13,500	2,050,000	1,510,000	2,050,000	1,510,000	740,000	380,000	8,490,000	7,770,000	1,310,000	950,000	5,490,000	4,950,000
4.	GAS	19,800	3,110,000	2,210,000	3,110,000	2,210,000	1,160,000	560,000	12,600,000	11,400,000	1,990,000	1,390,000	8,160,000	7,260,000
5.	PASSENGER	67,500	9,330,000	7,530,000	9,330,000	7,530,000	3,120,000	1,920,000	41,250,000	38,850,000	5,930,000	4,730,000	26,540,000	24,740,000
6.	OSV/AHTS	14,400	2,660,000	1,610,000	2,660,000	1,610,000	1,110,000	410,000	9,690,000	8,290,000	1,710,000	1,010,000	6,330,000	5,280,000
7.	TUG	5,490	910,000	610,000	910,000	610,000	360,000	160,000	3,560,000	3,160,000	580,000	380,000	2,310,000	2,010,000

Input data, addition to OPEX per day

		Shaft Power (kW)@90% MCR	EEDI (De-Rating)		SSDR		WiFE		LNG comparison		DPF	Scrubber	
			2-Stroke	4-Stroke	2-Stroke	4-Stroke	30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	14,400	-2,600		-2,600	-	900	600	-40,800	-22,000	171	700	59,500
2.	CONTAINER	76,500	-13,600		-13,600	-	4,500	3,400	-216,600	-117,100	907	3,600	316,100
3.	BULK CARRIER	13,500	-2,400		-2,400	-	800	600	-38,200	-20,700	160	600	55,800
4.	GAS	19,800	-3,500	-4,000	-3,500	-4,000	1,200	900	-56,100	-30,300	235	900	81,800
5.	PASSENGER	67,500	-	-13,800	-	-13,800	4,600	3,400	-219,500	-118,600	919	3,700	279,900
6.	OSV/AHTS	14,400	-	-2,900	-	-2,900	1,000	700	-46,800	-25,300	196	800	59,700
7.	TUG	5,490	-	-1,100	-	-1,100	400	300	-17,900	-9,600	75	300	22,800

Operating days per year	260
Interest rate	6%
Lifetime year	
Retrofit	10
Newbuilding	30

Calculations

Addition to OPEX per year [USD]

	Shaft Power (kW)@90% MCR	EEDI (De-Rating)		SSDR		WiFE		LNG comparison		DPF	Scrubber	
		2-Stroke	4-Stroke	2-Stroke	4-Stroke	30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1. **AFRAMAX**	14,400	-676,000	-	-676,000	-	234,000	156,000	-10,608,000	-5,720,000	44,398	182,000	15,470,000
2. **CONTAINER**	76,500	-3,536,000	-	-3,536,000	-	1,170,000	884,000	-56,316,000	-30,446,000	235,865	936,000	82,186,000
3. **BULK CARRIER**	13,500	-624,000	-	-624,000	-	208,000	156,000	-9,932,000	-5,382,000	41,623	156,000	14,508,000
4. **GAS**	19,800	-910,000	-1,040,000	-910,000	-1,040,000	312,000	234,000	-14,586,000	-7,878,000	61,048	234,000	21,268,000
5. **PASSENGER**	67,500	-	-3,588,000	0	-3,588,000	1,196,000	884,000	-57,070,000	-30,836,000	238,991	962,000	72,774,000
6. **OSV/AHTS**	14,400	-	-754,000	0	-754,000	260,000	182,000	-12,168,000	-6,578,000	50,985	208,000	15,522,000
7. **TUG**	5,490	-	-286,000	0	-286,000	104,000	78,000	-4,654,000	-2,496,000	19,438	78,000	5,928,000

AFRAMAX	**EEDI (De-Rating)**	**SSDR**	**WiFE**		**LNG**		**DPF**	**Scrubber**	
			30 vol.% H20	**20 vol.% H20**	**MGO**	**HFO**		**SW mode**	**FW mode**
Newbuilding	1,610,000	1,610,000	410,000	410,000	7,280,000	7,280,000	1,010,000	5,280,000	5,280,000
Addition to OPEX per year (USD)	-676,000	-676,000	234,000	156,000	-10,608,000	-5,720,000	44,398	0	182,000

Cost Overview

Costs per year retrofit

		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	14,400	-375,732	-375,732	344,053	266,053	-9,510,187	-4,622,187	235,972	980,904	16,268,904
2.	CONTAINER	76,500	-2,214,005	-2,214,005	1,573,528	1,287,528	-50,116,345	-24,246,345	1,072,812	4,908,779	86,158,779
3.	BULK CARRIER	13,500	-345,471	-345,471	308,542	256,542	-8,778,481	-4,228,481	219,610	901,915	15,253,915
4.	GAS	19,800	-487,451	-487,451	469,607	391,607	-12,874,064	-6,166,064	331,425	1,342,683	22,376,683
5.	PASSENGER	67,500	-2,320,352	-2,320,352	1,619,908	1,307,908	-51,465,447	-25,231,447	1,044,688	4,567,936	76,379,936
6.	OSV/AHTS	14,400	-392,591	-392,591	410,813	332,813	-10,851,439	-5,261,439	283,319	1,068,044	16,382,044
7.	TUG	5,490	-162,360	-162,360	152,912	126,912	-4,170,310	-2,012,310	98,241	391,855	6,241,855

Costs per year newbuilding

		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	14,400	-559,035	-559,035	263,786	185,786	-10,079,116	-5,191,116	117,774	565,586	15,853,586
2.	CONTAINER	76,500	-2,916,305	-2,916,305	1,327,648	1,041,648	-53,117,268	-27,247,268	625,264	2,973,075	84,223,075
3.	BULK CARRIER	13,500	-514,300	-514,300	235,607	183,607	-9,367,518	-4,817,518	110,640	515,612	14,867,612
4.	GAS	19,800	-749,446	-749,446	352,683	274,683	-13,757,802	-7,049,802	162,030	761,431	21,795,431
5.	PASSENGER	67,500	-3,040,954	-3,040,954	1,335,486	1,023,486	-54,247,590	-28,013,590	582,620	2,759,334	74,571,334
6.	OSV/AHTS	14,400	-637,035	-637,035	289,786	211,786	-11,565,741	-5,975,741	124,360	591,586	15,905,586
7.	TUG	5,490	-241,684	-241,684	115,624	89,624	-4,424,429	-2,266,429	47,045	224,024	6,074,024

BC Reduction Overview

Reductions per year [g] per vessel

		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	14,400	-	1,886,976	3,144,960	3,144,960	5,840,640	5,840,640	5,301,504	2,515,968	2,515,968
2.	CONTAINER	76,500	-	10,024,560	16,707,600	16,707,600	31,028,400	31,028,400	28,164,240	13,366,080	13,366,080
3.	BULK CARRIER	13,500	-	1,769,040	2,948,400	2,948,400	5,475,600	5,475,600	4,970,160	2,358,720	2,358,720
4.	GAS	19,800	-	2,594,592	4,324,320	4,324,320	8,030,880	8,030,880	7,289,568	3,459,456	3,459,456
5.	PASSENGER	67,500	-	8,845,200	14,742,000	14,742,000	27,378,000	27,378,000	24,850,800	11,793,600	11,793,600
6.	OSV/AHTS	14,400	-	1,886,976	3,144,960	3,144,960	5,840,640	5,840,640	5,301,504	2,515,968	2,515,968
7.	TUG	5,490	-	719,410	1,199,016	1,199,016	2,226,744	2,226,744	2,021,198	959,213	959,213
1	AFRAMAX	14,400	-	1,886,976	3,144,960	3,144,960	5,840,640	5,840,640	5,301,504	2,515,968	2,515,968
	Decrease low		-	1,797,120	1,886,976	1,886,976	808,704	808,704	898,560	988,416	0
	Increase high		-	1,797,120	1,886,976	1,886,976	449,280	449,280	359,424	628,992	628,992

Cost per BC Reduction Overview

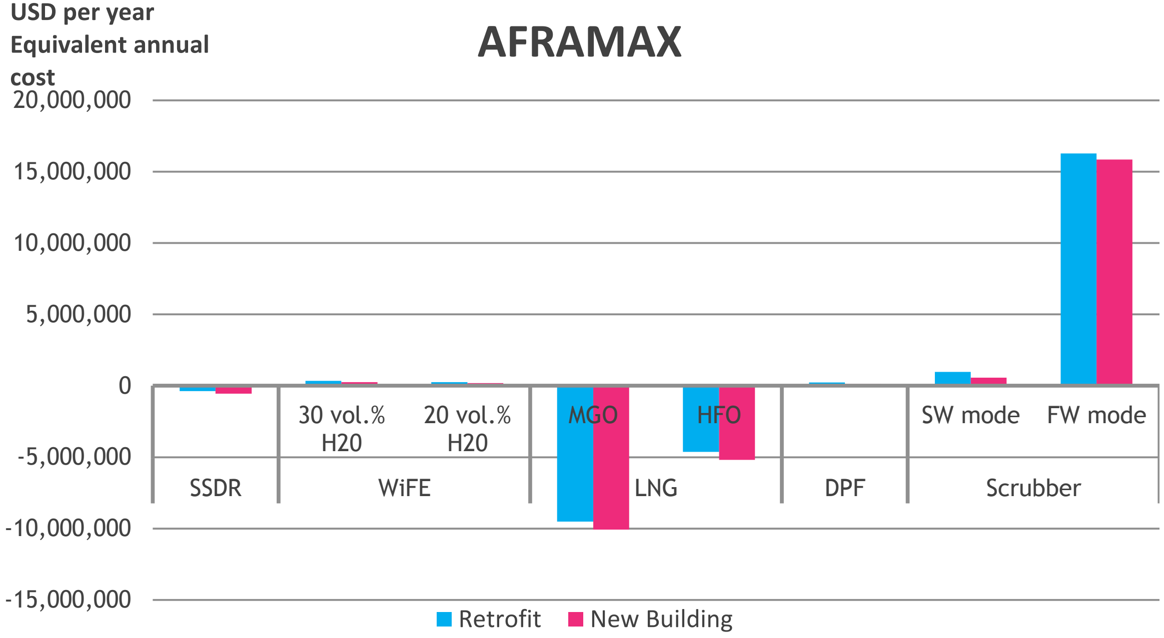
Costs per reduction retrofit [USD/g]

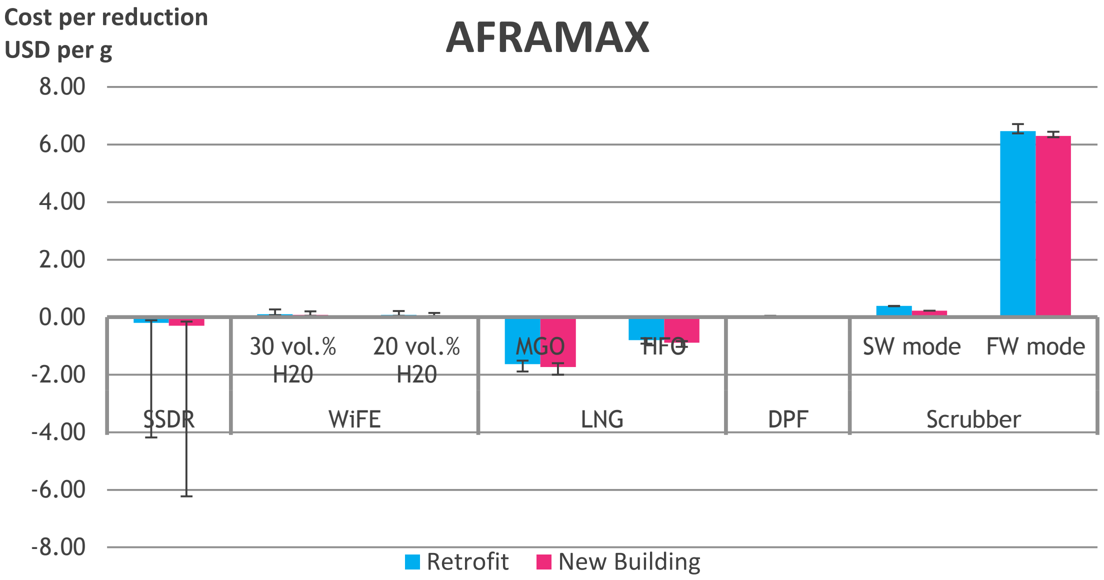
		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	AFRAMAX	14,400	-	-0.20	0.11	0.08	-1.63	-0.79	0.04	0.39	6.47
2.	CONTAINER	76,500	-	-0.22	0.09	0.08	-1.62	-0.78	0.04	0.37	6.45
3.	BULK CARRIER	13,500	-	-0.20	0.10	0.09	-1.60	-0.77	0.04	0.38	6.47
4.	GAS	19,800	-	-0.19	0.11	0.09	-1.60	-0.77	0.05	0.39	6.47
5.	PASSENGER	67,500	-	-0.26	0.11	0.09	-1.88	-0.92	0.04	0.39	6.48
6.	OSV/AHTS	14,400	-	-0.21	0.13	0.11	-1.86	-0.90	0.05	0.42	6.51
7.	TUG	5,490	-	-0.23	0.13	0.11	-1.87	-0.90	0.05	0.41	6.51
1	AFRAMAX	14,400	-	-0.20	0.11	0.08	-1.63	-0.79	0.04	0.39	6.47
	Decrease low		-	3.98	-0.16	-0.13	0.26	0.13	-0.01	-0.25	0.00
	Increase high		-	0.10	-0.04	-0.03	0.12	0.06	0.00	-0.08	-1.29

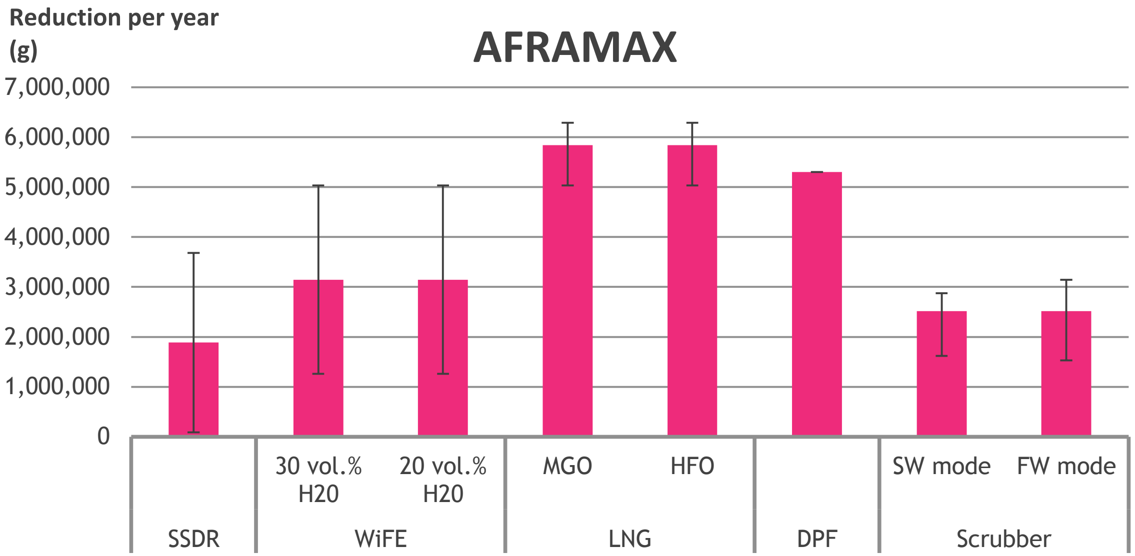
Costs per reduction newbuilding [USD/g]

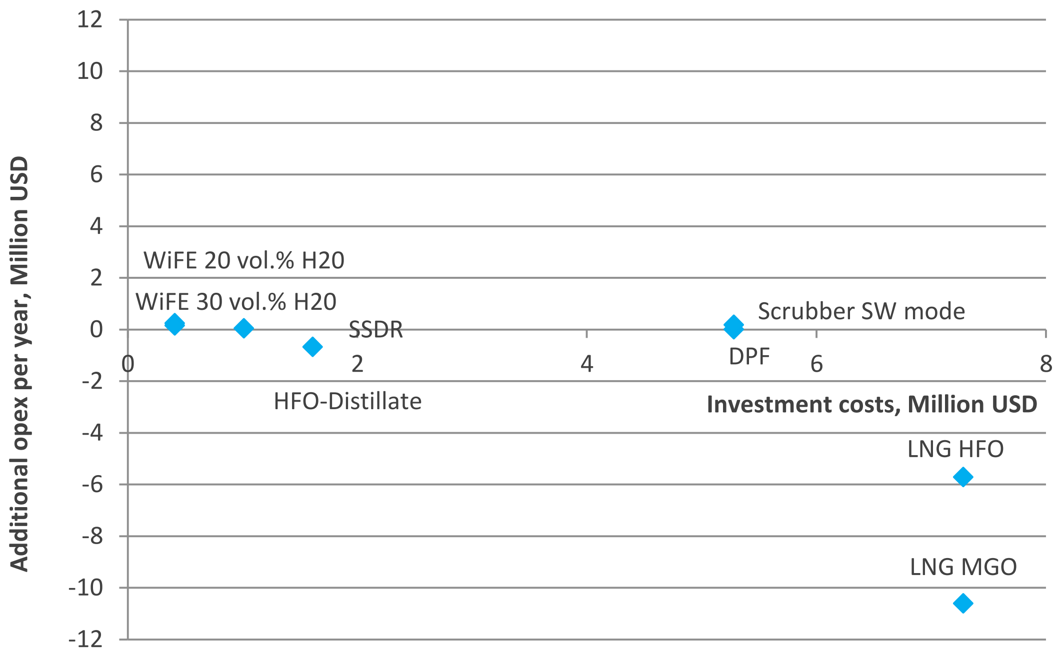
		Shaft Power (kW) @90% MCR	EEDI (De-Rating)	SSDR	WiFE		LNG		DPF	Scrubber	
					30 vol.% H20	20 vol.% H20	MGO	HFO		SW mode	FW mode
1.	**AFRAMAX**	14,400	-	-0.30	0.08	0.06	-1.73	-0.89	0.02	0.22	6.30
2.	**CONTAINER**	76,500	-	-0.29	0.08	0.06	-1.71	-0.88	0.02	0.22	6.30
3.	**BULK CARRIER**	13,500	-	-0.29	0.08	0.06	-1.71	-0.88	0.02	0.22	6.30
4.	**GAS**	19,800	-	-0.29	0.08	0.06	-1.71	-0.88	0.02	0.22	6.30
5.	**PASSENGER**	67,500	-	-0.34	0.09	0.07	-1.98	-1.02	0.02	0.23	6.32
6.	**OSV/AHTS**	14,400	-	-0.34	0.09	0.07	-1.98	-1.02	0.02	0.24	6.32
7.	**TUG**	5,490	-	-0.34	0.10	0.07	-1.99	-1.02	0.02	0.23	6.33
1	**AFRAMAX**	14,400	-	-0.30	0.08	0.06	-1.73	-0.89	0.02	0.22	6.30
	Decrease low		-	5.93	-0.13	-0.09	0.28	0.14	0.00	-0.15	0.00
	Increase high		-	0.14	-0.03	-0.02	0.12	0.06	0.00	-0.04	-1.26

Figures


USD per year
Equivalent annual cost
AFRAMAX
20,000,000
15,000,000
10,000,000
5,000,000
0
-5,000,000
-10,000,000
-15,000,000
30 vol.% H20
20 vol.% H20
MGO
HFO
SW mode
FW mode
SSDR
WiFE
LNG
DPF
Scrubber
Retrofit
New Building


Cost per reduction
USD per g
AFRAMAX
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
SSDR
30 vol.% H20
20 vol.% H20
WiFE
MGO
HFO
LNG
DPF
SW mode
FW mode
Scrubber
Retrofit
New Building


Reduction per year (g)
AFRAMAX
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
SSDR
30 vol.% H20
20 vol.% H20
WiFE
MGO
HFO
LNG
DPF
SW mode
FW mode
Scrubber


Additional opex per year, Million USD
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0
2
4
6
8
Investment costs, Million USD
WiFE 20 vol.% H20
WiFE 30 vol.% H20
SSDR
HFO-Distillate
Scrubber SW mode
DPF
LNG HFO
LNG MGO

1. September 2012/REL

Appendix E - Erria Report

1. *Introduction*

The below technical and cost analysis report has the intention of clarifying and cost evaluating the selected seven abatement measures available on the market to reduce Black Carbon (BC). The selected abatement measures are applied to the Base Case, Aframax Tanker as listed in table 35,, where we have summarized and calculated capital investment cost and application to seven vessels, of which five similar capacity vessels and two smaller but also very relevant vessels were selected. The five vessels are similar in capacity but have very different power requirements, due to application and speed requirement. After analysing costs of the equipment from different makers, we could conclude that there was a linear relationship between price of the equipment and the power of the main engine, except for the EEDI, which is dependent on other parameters as well. The procedure to estimate the cost for each vessel type, was to take quotes from makers and calculate a rough cost, USD / kW, for each abatement measure and scale up or down to the relevant vessel. We would like to advise that the estimates could vary 10-20%.

Due to the fact that the Capital investment of the abatement measures is approximately 80-90% of the total retrofitting cost, which makes it quite irrelevant which part of the world the equipment is installed at. The Charter rates of each vessel type was also taken into consideration, as we estimated some of the retrofitting cases to take up to 40 days, which is a considerable cost to consider. Our conclusion is that if possible, the abatement measures are to be installed at Newbuilding stage to reduce the CAPEX, between 40-60%, depending on off-hire rates and installation time. During the design phase of a Newbuilding, many of the smaller modifications to the standard design can be absorbed into the Contract Price. The cost difference between Newbuilding and Retrofitting is illustrated in Table 35.

Consideration for the additional operating costs per day, have also been taken into account and illustrated in table 36. The reason for not including the vessel's individual OPEX, is simply because the different vessels and owners, managers, use different nationalities of crew, which could influence the OPEX drastically. Crewing costs are often approximately 50% of the total OPEX of a vessel, depending on complexity and Flag of Registration.

2. *EEDI (Energy Efficiency Design Index)*

At the intercessional meeting in Norway 2008, the word Energy Efficiency Design Index was introduced first time,
The word is a bit controversial as EEDI can be lowered, simply by reducing the speed, even though the propulsion efficiency is low. However in order to obtain the lowest possible EEDI at the highest speed, the total propulsion efficiency shall be as high as possible. Several attempts have been made to make EEDI speed independent. There are three major means to reduce EEDI, speed reduction, decrease in steel weight and increase in length.
When considering the options to reduce the EEDI and taking into consideration the limitations of retrofitting an abatement measure, we chose slow steaming: with De-Rating, where the same number of off-hire days as per the De-Rating case were used. This solution is one of the most effective solutions to reduce EEDI with one of the lowest CAPEX's, if having to retrofit. If your vessel has an Electronic engine, your CAPEX will be reduced approximately 45-50% compared to the Standard Mechanical Injection Engine (e.g. MC, MC-C or RTA.)

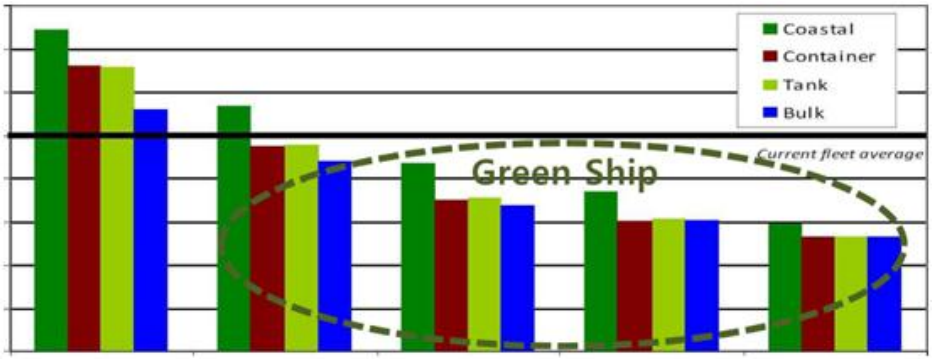


Figure 8, Estimated required EEDI

EEDI base line defintion

$$\text{EEDI value} = CF \cdot \frac{SFC_{ME} \cdot \sum_{j=1}^{NME} P_{MEi} + SFC_{AE} \cdot P_{AE}}{\text{Capacity} \cdot V_{ref}}$$

- $CF_{ME} = CF_{AE} = CF = 3.1144$ g CO_2/g fuel
- $SFC_{ME} = 190$ g/kWh
- $SFC_{AE} = 215$ g/kWh
- $P_{MEi} = 0.75 \cdot MCRi$
- (MCR) > 10,000 kW: $P_{AE} = 250 + 0.025 \cdot \sum_{j=1}^{NMEi} MCR_{MEi}$
- (MCR) <= 10,000 kW: $P_{AE} = 0.05 \cdot \sum_{j=1}^{NMEi} MCR_{MEi}$

EEDI – Definitions

V_{ref} is the ship speed, measured in nautical miles per hour (knot), on deep water in the condition corresponding to the *Capacity* as defined in paragraph 1 – 4 below at the shaft power of the engine(s) corrected for PTI and PTO and assuming the weather is calm with no wind and no waves.

Capacity is defined as follows:

1 For bulk carriers, tankers, gas tankers, ro-ro cargo , general cargo ships, refrigerated cargo carrier and combination carriers, deadweight should be used as *Capacity*.

2 For passenger ships and ro-ro passenger ships, gross tonnage in accordance with the International Convention of Tonnage Measurement of Ships 1969, Annex I, regulation 3 should be used as *Capacity*.

3 For containerships, 70% of the deadweight should be used as *Capacity*.

4 ***Deadweight*** means the difference in tonnes between the displacement of a ship in water of relative density of 1,025 kg/m^3 at the summer load draught and the lightweight of the ship. ***The summer load draught*** should be taken as the maximum summer draught as certified in the stability booklet approved by the administration or an organization recognized by it.

Figure 9, EEDI (Base line definition)[(i)]

Additional requirements and restrictions:

- IMO 15 July 2011: Mandatory measures to reduce emissions of greenhouse gases (GHGs) from international shipping were adopted.
- The Amendments to MARPOL Annex VI Regulations for the prevention of air pollution from ships, scheduled to enter into force on 1 January 2013, add a new chapter 4 to Annex VI on Regulations on energy efficiency for ships to make mandatory the Energy Efficiency Design Index (EEDI), for new ships, and the Ship Energy Efficiency Management Plan (SEEMP) for all ships.[(i)]
- EEDI only applies to new vessels, which could give an unfair advantage to vessels built before 1 January 2013, due to the fact that the EEDI restricted vessels will possibly be forced to operate at lower speeds and forcing the owner to introduce more vessels into a trading pattern to move the same amount of cargo during a limited amount of time. The Capital investment for the EEDI restricted vessels are estimated to be 25-30%, which will reduce their profit margin compared to existing vessels. The fuel savings with EEDI implementation measures in many cases do not benefit the owners, as it is the charterer or operator that procures the fuel.
- No Limitations for Polar Operation
- No limitations in respect to Class rules on the listed vessels

3. *Slow Steaming: with De-Rating*

Slow Steaming was started during the end of 2007 by mainly container vessel owners and operators, when the charter rates dropped drastically at the beginning of the financial down turn in the US. Vessels were instructed by owners to reduce Main Engine load to approximately 40% MCR, which decreased the speed with approximately 20%. An average

FOC *(Fuel Oil Cost*) saving of approximately 42% without de-rated engine and 45% with a de-rated motor can be calculated below in Table 37, Slow Steaming (40%MCR) without and with De-Rated Engine.

	Shaft Power	Speed (Knots)	Distance (Nautical Miles)	Time	Total Fuel Consumption	**Fuel Oil Savings (%)**
90% MCR (kW)	14256	15,0	10000	667	1730	0%
40% MCR (kW) without derating	6336	11,4	10000	877	1012	42%
40% MCR (kW) with derating	6336	11,4	10000	877	951	45%

Table 37, Slow Steaming (40%MCR) without and with De-Rated Engine

From January 2010, owners started to investigation Super Slow Steaming, down to below 35% MCR, as low as 10% MCR. Engine Makers were initially hesitant due to the lack of experience but in June 2011, MAN Diesel issued a Service Letter (SL11-544 MTS) permitting owners to reduce engine load down to 10% MCR with certain recommendations. Several problems arise with low load operation e.g. Loss of Main Engine Turbocharger and propeller efficiency, fouling of hull, economizer soot build up etc. Electronic engines (ME, ME-B and RT-FLEX) engines are more flexible for slow steaming, therefore it is recommended to convert all mechanical injection Main engines to electronically controlled engines[ii].
This conversion is costly, estimated at approximately USD 100 USD / kW, including Slide fuel valves, which are highly recommended by Engine makers.

A Danish Initiative, *Green Ship Of The Future*, presented in Copenhagen 2012, a *'Vessel Emissions Study'* [130], where MAN Diesel estimated the conversion cost of the *'MT Nord Butterfly'* from a MC engine (Mechanical Injection) to a ME-B engine (Electro hydraulic, common rail injection). The conversion was from a 6S50MC-C (9.480 kW) motor to a 6S50ME-B, with the same effect. With our experience from MAN Diesel retrofits, it is possible to calculate a *Table 45, Cost per kW*, to scale the CAPEX to the specific vessel in Table 35.. If your vessel already has installed an Electronic engine, your CAPEX will be reduced approximately 45-50%.

NORD Butterfly ME-B Conversion	9480	kW
CAPEX	USD 800,000	
Cost per kW for ME-B conversion	84	USD / kW

Table 38, Green Ship of The Future: Vessel Emission Study (Copenhagen 2012)[130]

Engine makers are offering de-rated engines from newbuilding, where there is a larger CAPEX but reducing the SFOC by 3-6% reduces the fuel costs. If the Propeller is redesigned to a more flexible operating curve, a further 6-10% can be achieved, resulting in a total SFOC reduction of 10-15%[ii]. Only reduced SFOC was included into

.

When Slow Steaming, less cargo is transported from point A to B, thus additional vessels need to be included to transport the same amount of cargo as the ships operating at normal speeds. We have not included this scenario into *Table 37, Slow Steaming (40%MCR) without and with De-Rated Engine* due its complexity. Only the reduced fuel consumption with a de-rated engine is included into

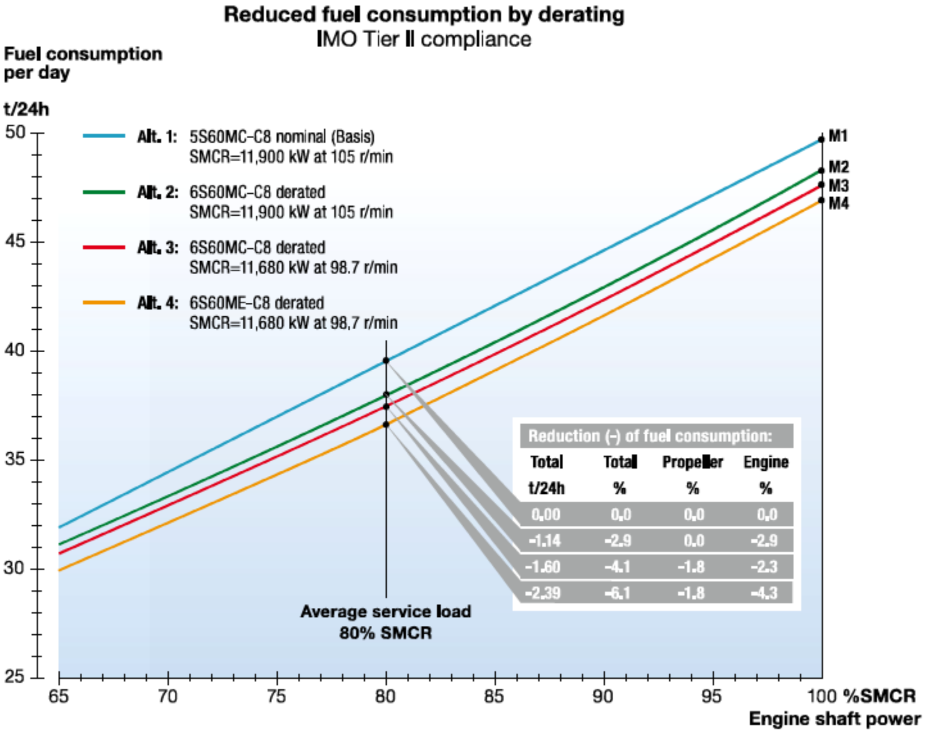


Figure 10, De-Rated S60MC MAN Diesel Engine (ii)

CO_2 index from FORCE study

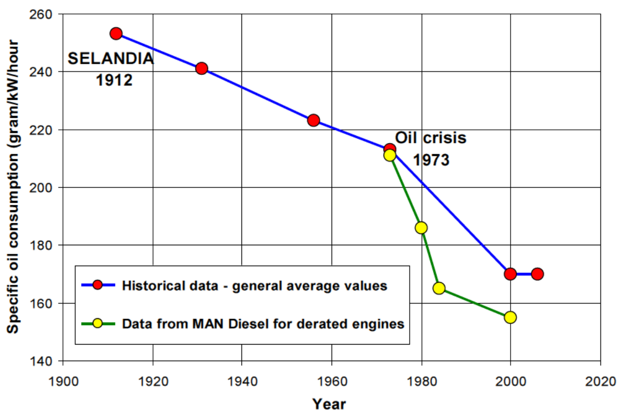


Figure 11, SFOC Reduction Past 100 Years (iii)

<u>Additional requirements and restrictions:</u>

- (Guidance from Lloyds Register)(iii)
  If the de-rated engines have been de-rated after delivery, a new de-rated certificate has to be issued which would have to comply with NOx requirements as per MEPC.1/Circ.678(iv), on how to have . Unusually, for such requirements, the certification can be undertaken by the Administration of any signatory to MARPOL Annex VI and hence this will not necessarily be a particular ship's flag State. In practice it is probable that, as with much of the NOx Technical Code certification, the actual approval will be undertaken by one of the Recognised Organisations acting on behalf of an Administration (Classification Society).
- No Polar Limitiations

4. *Water in Fuel Emulsion (WiFE)*

In WiFE water is added continuously to the fuel supply and a homogeneous mixture is ensured by mechanical measures. When the mixture is injected the additional heat required to heat up liquid water to the boiling point, the evaporation itself, as well as the super heating of the water vapour significantly lowers the combustion temperatures, and hence the NOx formation. Previous experience shows that as a rule of thumb the NOx emission is reduced approximately 1% per 1% water present in the mixture (on a total mass basis) (Eckert, Velji, & Spicher, 2007)(v). Some deviation from this rule of thumb has been observed (Henningsen, 1994; Pedersen, Andreasen, & Mayer, 2010)(v) thus it should not be taken too literally and applicable to any condition.

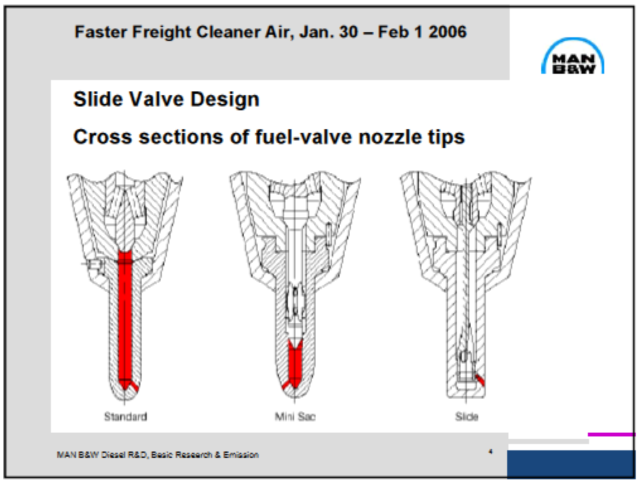


Figure 12, Slide fuel Valve (MAN Diesel)(vi)

To retrofit a WiFE system to a standard engine the following components need to be installed or replaced.

- A Homogenizer unit, which heats the water and mixes it with fuel to form an emulsion prior injection, is to be installed. A presentation by MAN Diesel in 2006, estimated a cost of USD 400.000 investment cost excl. retrofit on a 40.000 kW engine[vi]. We estimate a 20% price increase from 2006 to 2012, this gives a USD / kW estimate of approximately USD 12 / kW. If we include retrofitting costs but excl off-hire, we can expect an average cost per kW of USD 27 / kW. On the Aframax Tanker base case we estimated a retrofit time of 20 days with an off-hire rate of USD 20.000 / day, which increases the Cost per kW to USD 52 / kW.

Engine Power	40,000	kW
Emulsifier unit Cost & Slide Fuel valves	USD 500,000	
Cost per kW	13	USD / kW

Table 39, MAN Diesel: Emulsion Cost overview(vi)

- A possible increase in fresh water (FW) storage capacity onboard, as standard FW generator cannot keep up with the FW consumption of the WiFE system thus additional FW is to be stored onboard.
- Slide Fuel Valves are to replace the standard fuel valve (Fuel Injector), due to the more efficient atomization of the fuel and optimizing the combustion.. The cost of the New Slide Fuel Valves are included in the total cost as per Table 39, MAN Diesel: Emulsion Cost overview([vi]).

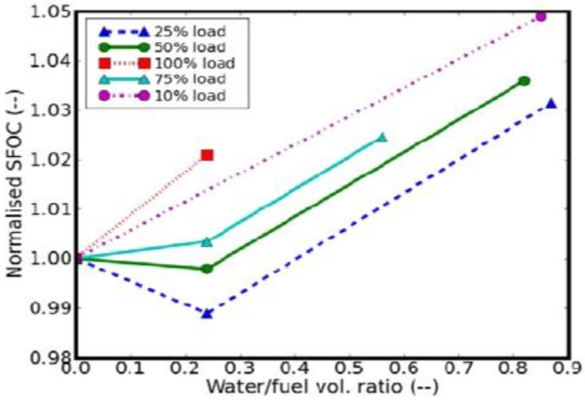


Figure 13, SFOC - vol. % added H_2O

The SFOC (Specific Fuel Oil Consumption) is shown as a function of applied water content at various engine loads in Figure 13, SFOC - vol. % added H_2O. It is observed that the SFOC generally increases for the larger additions of water. This is due to energy required to heat up the injected water to its saturation temperature, subsequent evaporation at the saturation temperature and further super-heating to the temperature in the combustion zone. In previous work, the SFOC penalty at 30 vol.% added water is estimated to be approximately *2,8%* when considering evaporation and super heating only. It should be noted that the water may contribute with work in the expansion process thereby reducing the actual SFOC penalty [137].

Another recent unpublished estimate taking the heating of water in the liquid phase to saturation temperature and subsequent evaporation (neglecting super-heating) and taking the expansion work into account leads to a SFOC penalty of approx. *1,5%* at 30 vol. % water added. We have estimated an approximate 2% penalty at 30% vol. % water added, *Table 40, Additional Energy Consumption of WiFE*, which is included in Table 36, additions to OPEX.

	SFOC Penalty 20vol. % H_2O
SFOC increase @ 20vol. % H2O added	1,5%
SFOC increase @ 30vol. % H2O added	2,0%

Table 40, Additional Energy Consumption of WiFE[vi]

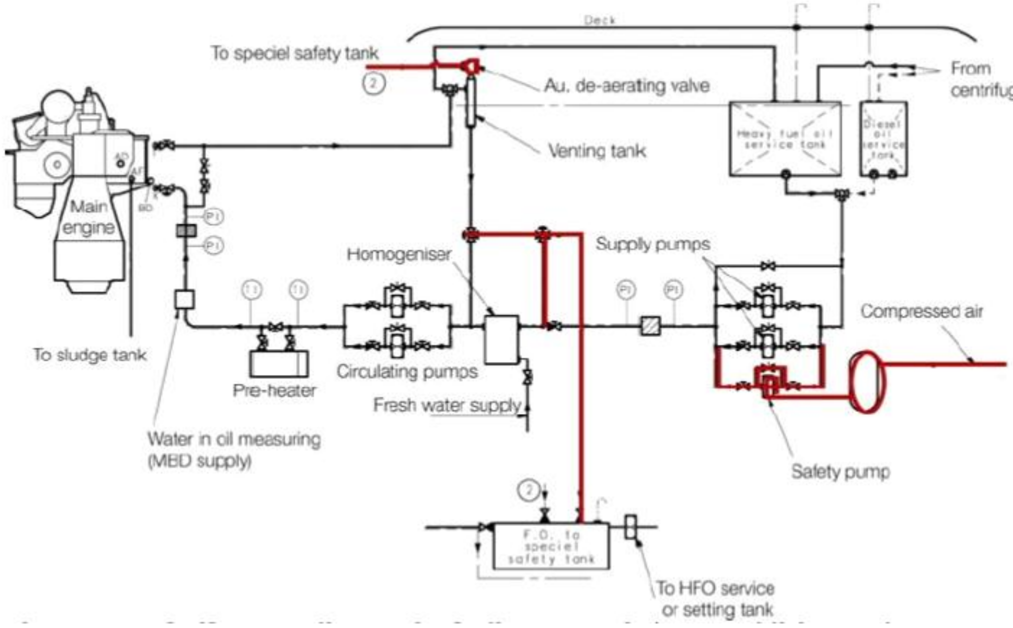


Figure 14, WiFE Layout(vi)

Additional requirements and restrictions:

- The WiFE application is still fairly new, thus little is known to the corrosive effects the water will have on the fuel system, and other machinery related to the fuel system.
- When operating on MGO instead of HFO emulsion, it is recommended to add additives to stabilize the emulsion.
- The Installation is to comply with IMO Tier III requirements. The Engine Maker or equipment manufacturer will test and issue certification.
- Fresh water tank volume of up to 50% of the Fuel tank volume.
- Possible installation of additional fresh water generators if Fresh water tank volume is limited.
- No Polar restrictions, except for heating is required in the fresh water tanks and piping to avoid freezing.
- No Classification Society restrictions.

5. LNG

Liquefied Natural Gas (LNG) is lighter than air and has a narrow flammability interval. It can be combusted in 2-stroke gas engines as Diesel Cycle and in 4-stroke, applying the Otto principle. 2-Stroke slow speed engines are generally only using diesel fuel as pilot fuel, (functioning on heat of compression and not with a spark plug).

The 2-stroke engines can operate on diesel fuel only but at low loads, due to the fact that the pilot fuel valves are dimensioned only for efficient operation between 1-20% diesel fuel, depending on engine load, when at low load operation the pilot fuel ratio to LNG is approximately 5-20% but as the load increases the ratio drops to as low as 1%.

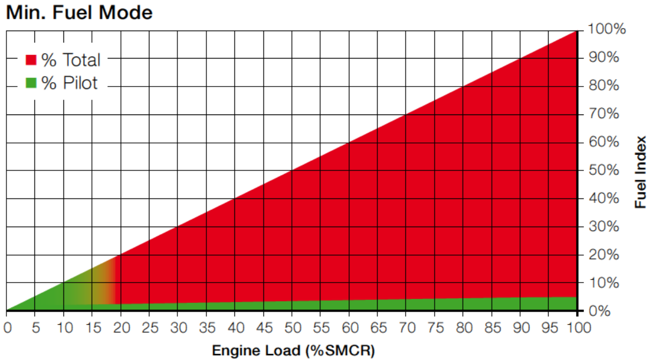


Figure 15, MAN ME-GI Dual Fuel Engines

Dual fuel 4-Stroke medium speed LNG engines are based upon the Otto technology. The primary fuel is natural gas but they are designed to operate interchangeably with diesel as a 'pilot' ignition source (functioning on heat of compression and not with a spark plug). These engines can also operate on 100% diesel fuel. When idling these engines tend to operate on 100% diesel. As the engine begins to move to full load performance, an increasing amount of natural gas replaces the diesel fuel to 90% or more.

This makes LNG engines especially valuable in circumstances where the use of natural gas is desired for environmental or economic reasons but if the natural gas supply is not available in all locations, the Engines can run on Pilot MGO. (2-Stroke Engines will only be able to run at approximately 50% load due to the Pilot fuel system only supplies 20% fuel)

Generally the larger vessels with constant load and RPM use the 2-stroke LNG engines and the variable load vessels e.g. cruise liners, supply vessels and tugs will use the 4-Stroke Dual fuel engines, with Diesel Electric propulsion units for better efficiency. Exhaust gas emissions such as SOx and PM are negligible. LNG contains less carbon than fuel oils, reducing the CO_2 emissions first and foremost from tank to propeller. Liquefied Natural Gas (LNG) is natural gas stored as liquid at -162°C. The predominant component is methane with some ethane and small amounts of heavy hydrocarbons.

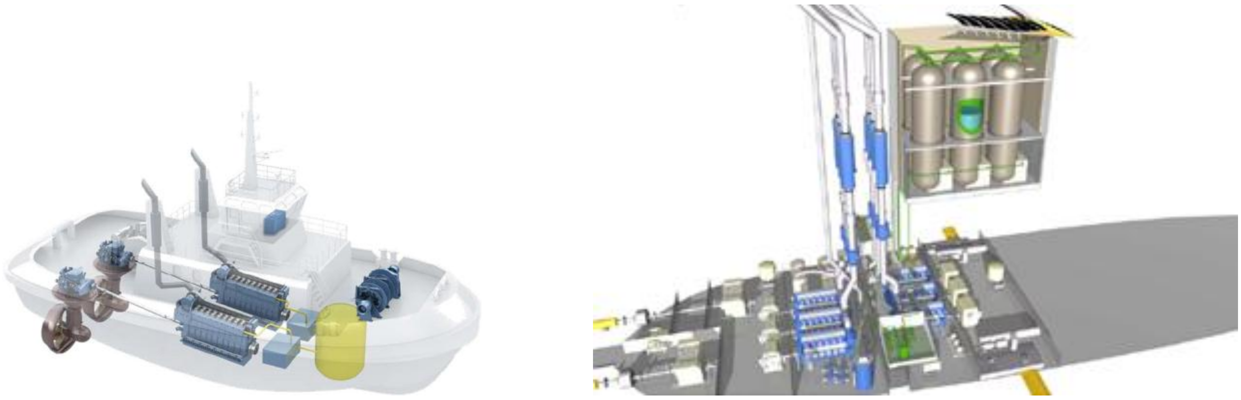


Figure 16, LNG Installation on Harbour Tug and Cruise Liner (Rolls Royce & Wartsila)

The LNG tank volume is selected to give the AFRAMAX base case vessel half-round-trip endurance. This controls investment costs but increases exposure to volatile fuel prices. Costs for LNG system include costs for the tanks, bunker station, gas preparation (cryogenic plant), gas line, main engine (Electronic controlled common rail *(ME-B)* Conversion). If the existing engine is an electronic controlled common rail engine (*ME-B, RT-Flex*), the cost saving could be up to 20%.

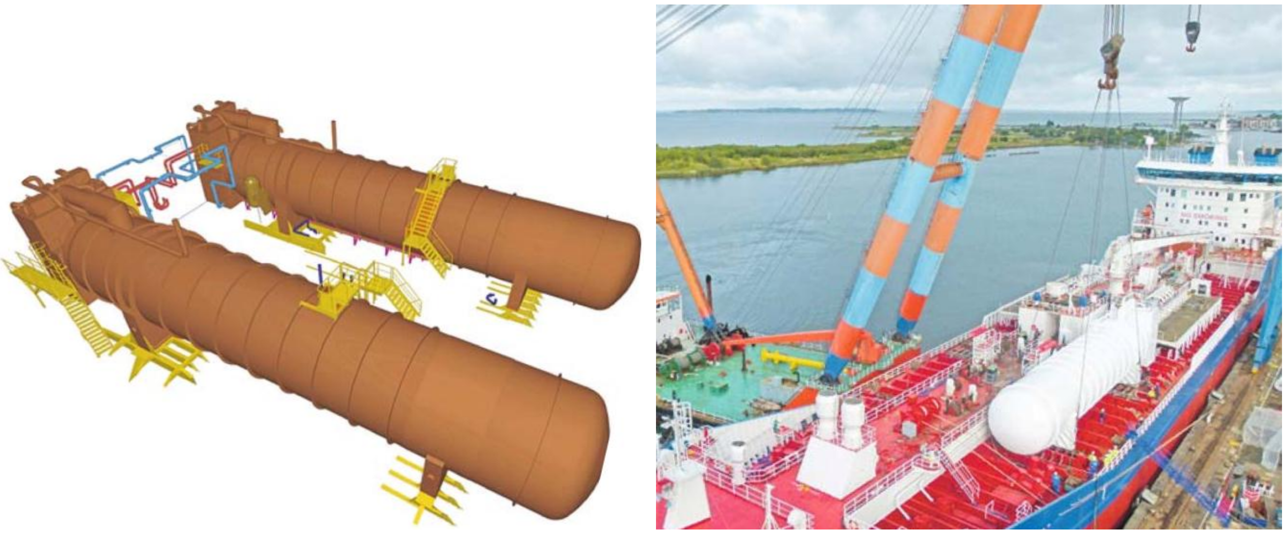
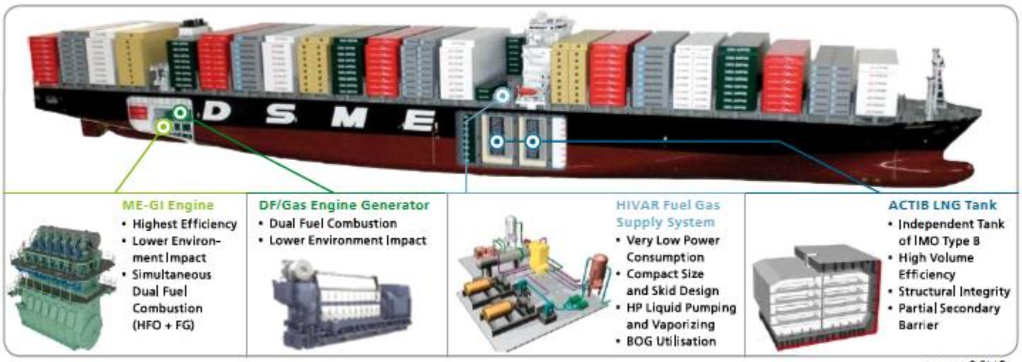


Figure 17, LNG Fuel Tank installation on a tanker vessel[vii]

Due to the low temperature, LNG has to be stored in cryogenic tanks. LNG storage tanks require double the space compared to traditional fuel oil tanks. For the AFRAMAX base case vessel, where the HFO capacity is approximately 1000m^3, where the replacement LNG Capacity is estimated to 2000m^3, in our Table 41, LNG Conversion Estimates. We have received estimates from MAN Diesel and GL[(viii)], for the construction cost of LNG tanks. Estimates from USD 1000/m^3 - USD 5000/m^3 for the LNG tanks. The AFRAMAX tanker LNG tank cost was estimated at USD 1000/m^3 but becomes more costly if the tanks cannot be installed on the main deck. For example, Cruise liners, Container vessels, Bulk Carriers, LNG Tankers and Supply vessels will need more complicated shapes to fulfill space restrictions. The LNG Tank cost was estimated at USD 1500/m^3. Some vessels will experience reduced cargo capacity in some cases, depending on type of vessel, type of fuel tank and potential for adequate location of the LNG tanks on-board. LNG tanks are assumed to consume TEU slots on Container vessels, resulting in lost earnings, assumed only for every second voyage. The large-sized container vessels (8 500 TEU and 15 000 TEU) have losses with a maximum of about 1,5% of the total available TEU slots.



source: DSME

Figure 18, LNG layout onboard a Large Container vessel[(ix)]

A Cryogenic Plant is required to pump the LNG fuel from the fuel tanks at a pressure LNG has a high auto ignition temperature and therefore needs an additional ignition source, i.e. a pilot fuel, to ignite in combustion engines. Expected MGO consumption (pilot fuel) 1-5% & Cryogenic Plant fuel consumption penalty of 1,2%. We have used 2% percent for Pilot fuel consumption and a total fuel penalty of 3,2% in, Table 41, LNG Conversion Estimates. The Cryogenic Plant is reported by MAN Diesel to cost approximately USD 1.500.000 (for our base case AFRAMAX Tanker), which were used in Table 35...

The Following large costs are involved with the LNG Installation on AFRAMAX:

Cryogenic Plant	USD 1.500.000	
LNG Tank cost per m^3	USD 1.000	
LNG Tank Capacity	2000	m^3
LNG Machinery Conversion	42	USD / kW
Green Ship of The Future: Vessel Emission Study (ME-B Conversion)		
NORD Butterfly ME-B Conversion	9480	kW
CAPEX	USD 800.000	
ME-B Conversion Cost per kW	84	USD / kW
Total Engine LNG Conversion	**126**	USD / kW
Fuel consumption Penalty for LNG Pilot fuel and Cryogenic plant		
Pilot Fuel consumption	2,0%	kg/kWhr
Cryogenic pump fuel penalty	1,2%	kg/kWhr
Total Penalty	**3,2%**	**kg/kWhr**

Table 41, LNG Conversion Estimates

The bigger needed volume of LNG fuel tanks is a one of the disadvantages of LNG use. The localization of LNG fuel tanks can take into account the ship type and safety requirements. The largest share of the additional investment is related to the LNG tank. Average costs are between USD 1000/ m^3 – USD 5000 /m^3. For the AFRAMAX, Bulk Carrier, LNG Tanker, OSV and Tug, USD 1000 / m^3, was used but for more complex Container and Cruise Liner, USD1500/m^3 was used.

The price of LNG depends for many years on HFO price, but often is cheaper. Taken into account the cost of LNG is about 60% of HFO. On gas carriers the cost of boil-off gas is decreasing due to savings of re-liquefaction process. Natural gas prices (including LNG) have been reduced the last couple of years due to the introduction of shale gas in the US market. This is a reason that LNG has improved its competitiveness to HFO, especially in ECA areas, where SOx and NOx regulations have been enforced. The basic question is what will be the price of HFO in the future. We must remember the middle of 2008 when the price of HFO IFO380 was over 1000 $ per metric ton. In the middle of 2011 was about 650 $ like in 2007 and first half-year 2008, *Figure 19, LNG prices compared with HFO and MGO (GL)*, It may be seen the increasing price of MDO and MGO fuels. In our opinion the price of LNG will be more stable than HFO, because it depends on the industry price.

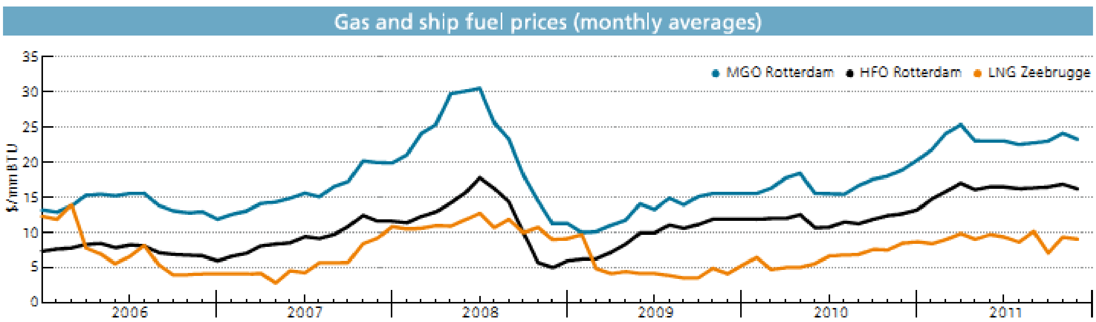


Figure 19, LNG prices compared with HFO and MGO (GL)[viii]

MGO seems to be an attractive wait-and-see strategy with low investment costs for actors who believe that LNG may have a breakthrough sometime in the mid-term future, however, if many actors use that strategy the MGO demand – and hence price – will increase (and LNG development may be slower).

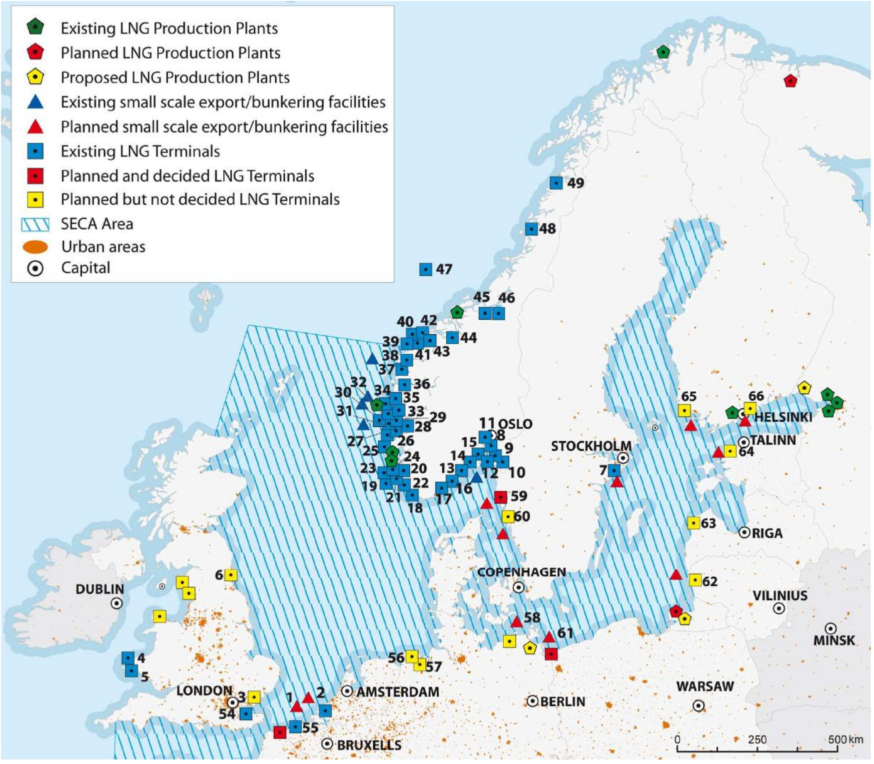


Figure 20, ***Existing and planned production plants and LNG terminals in the SECA***

<u>Additional requirements and restrictions:</u>

- The IMO Interim Guidelines for gas as ship fuel (Resolution MSC.285 (86)) contain the state of the art on safety concepts for using gas as a ship fuel. These are voluntary to the flag states. GL (Germanische Lloyd) issued its own guidelines in April 2010, adding own interpretations. The IMO subcommittee BLG is working on the International Gas as Fuel Code (IGF) which will supersede the interim guidelines and which is planned to enter into force with the SOLAS 2014 edition. In parallel, work has started at ISO TC 67 on standards for LNG bunkering

- LNG supply is under rapid development in the SECA, ***Figure 20, Existing and planned production plants and LNG terminals in the SECA***, but is rarely available as bunker fuel outside of EU. Singapore is developing a large terminal for local land based supply, which could possibly be extended to Marine fuel supply, as it is one of the world's largest bunker ports.

Other operational costs (OPEX), such as crew, spare parts and maintenance are assumed to be 10% higher than the standard Fuel Oil fueled vessels. This cost is not included in the our Table 36, due to the complexity of OPEX calculations, e.g. different Nationalities, trade routes and Flag Registry.

- Some vessels will experience reduced cargo capacity in some cases, depending on type of vessel, type of fuel tank and potential for adequate location of the LNG tanks on-board, due to the fact that LNG requires twice the space of Fuel Oil.

- No polar restrictions.

6. <u>HFO – Heavy Fuel Oil (Residual Fuel Oil) – MGO (Distillate Fuel):</u>

Running on distillate fuels for a long period of time is the straight forward solution to comply with the forthcoming emissions regulations on maximum allowable sulphur content in the fuel oil and reduction of BC.

There are two main challenges when running on MGO, Fuel viscosity and Main Engine Cylinder Lubrication(x).
The fuel systems for engines, boilers and other machinery required to comply with above IMO regulations, would be recommended to have a cooler or a chiller arrangement fitted, to meet the fuel viscosity requirements for a safe opera-

tion of the engine's fuel system. Vessel's in the future will probably not experience problems running without a chiller due to the fact that engine and pump makers are designing their equipment to run on the lower viscosity fuels but it is not recommended, due increased wear on fuel systems. Cooling of the MGO is a not a straight forward solution since several parameters should be considered before deciding the appropriate method of cooling.

- There are three methods that can cool the MGO in order to increase its viscosity to at least 3 cSt in order to be handled by the pumps without leakages.
- Cooling by sea water coolers
- **Cooling by refrigerating compressors of direct expansion connected by a cooler (Chosen solution for our CAPEX)**
- Cooling using water chillers in connection with coolers.

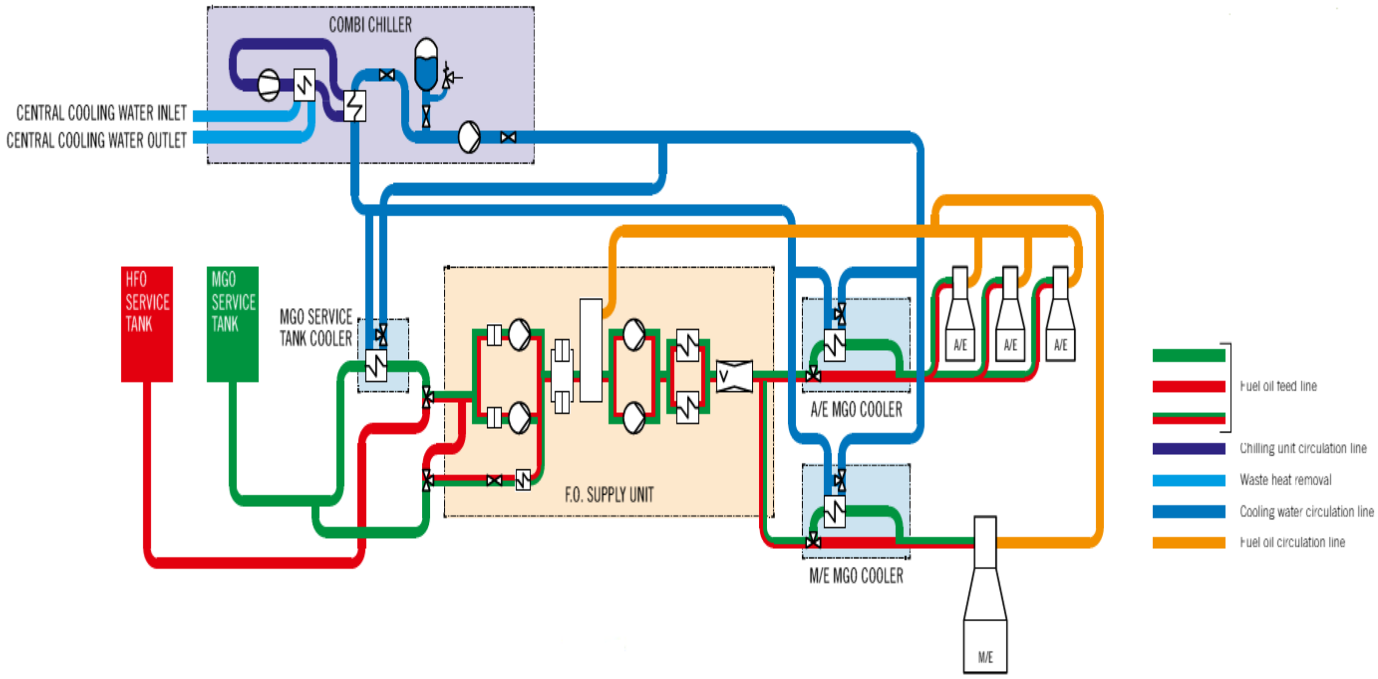


Figure 21, MGO Chiller Plant Layout

Example 1:
When MGO 2 cSt @40°C is used and 3 cSt Viscosity is required the temperature is to be cooled to approximately 18°C.
Example 2:
MGO with viscosity of 3 cSt @ 40°C is entering the engines at 55°C. According to the curves the viscosity is then between 2 and 3 cSt, approximately 2,3 cSt.

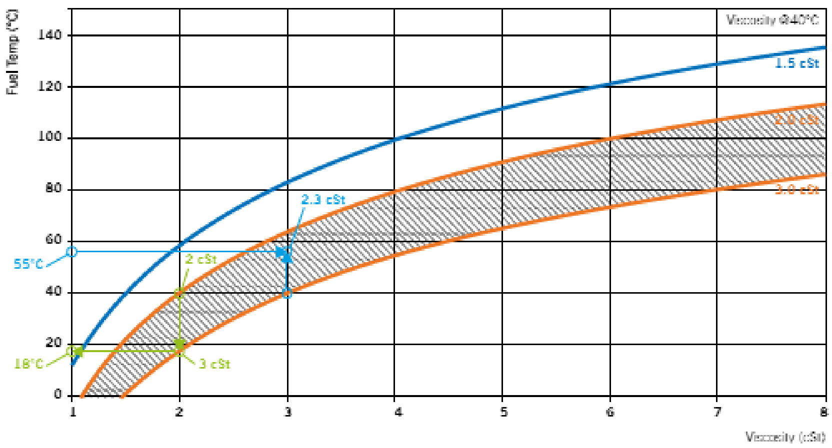


Figure 22, Fuel Temperature vs. Viscosity

Depending on the installation, the viscosity of MGO should be minimum, 2-3cSt for optimal operation of fuel pumps and fuel valves. The examples below refer to Figure 22, Fuel Temperature vs. Viscosity.

There is a correlation between Low sulphur fuels and BN or TBN (Base Number), thus when using low sulphur fuels below 1% sulphur, the cylinder lubricaiton rate is to be lowers to the minimum dosage, recommended by engine makers, but if using BN 70, the liner would be overadditivated. Therefore Engine Makers recommend to change to low BN cylinder Lub oils of BN 40-50 if using low sulphur fuels below 1% sulphur for prolonged periods of time. Automatic cylinder feed rate regulating systems, e.g. Alfa Lubricator, are recommended on newer engines to regulate the dosage automatically during different engine loads(x).

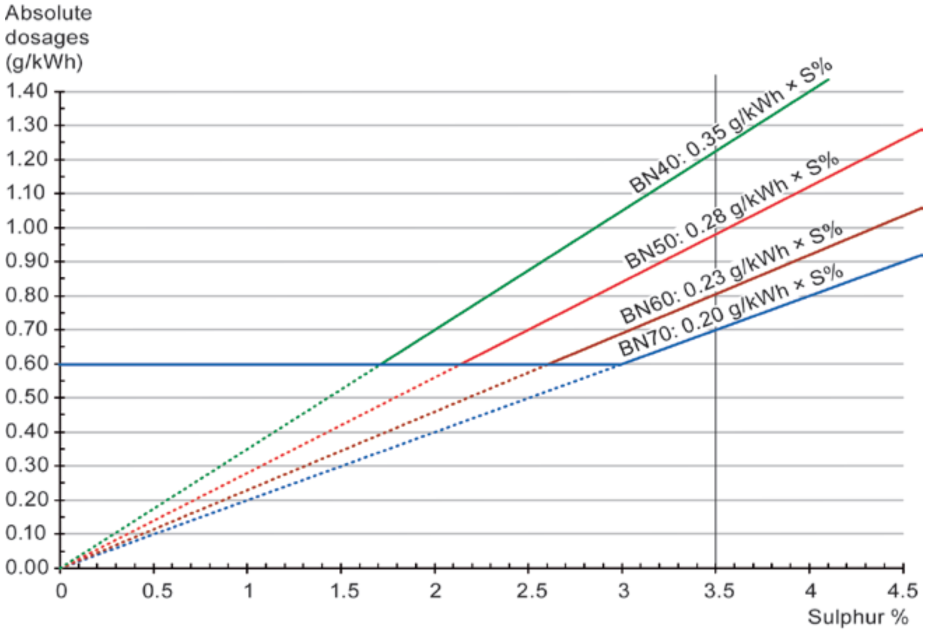


Figure 23, Use of BN40, BN50, BN60 and BN70 Cylinder oils

In the shipping field the following type of classification is used for fuel oils (http://en.wikipedia.org/wiki/Shipping):

CCAI and CII are two indexes which describe the ignition quality of residual fuel oil, and CCAI is especially often calculated for marine fuels. Despite this marine fuels are still quoted on the international bunker markets with their maximum viscosity (which is set by the ISO 8217 standard) due to the fact that marine engines are designed to use different viscosities of fuel. The unit of viscosity used is the cSt and the fuels most frequently quoted are listed below in order of cost, the least expensive first-

- IFO 380 - Intermediate fuel oil with a maximum viscosity of 380 cSt (<3.5% sulphur)
- LS 380 - Low-sulphur (<1.0%) intermediate fuel oil with a maximum viscosity of 380 cSt
- MDO - Marine diesel oil.
- MGO - Marine gasoil.
- LSMGO - Low-sulphur (<0.1%) Marine Gas Oil - The fuel is to be used in EU community Ports and Anchorages. *EU Sulphur directive 2005/33/EC*

A Chiller unit costs approximately USD 70.000 for the AFRMAX, which is USD 4 /kW for the Chiller Unit. The calculated cost per kW for the Chiller Unit and Installation is USD 13 / kW excluding the expected 10 Off-hire days. This price could vary, depending on which system and maker is chosen.

SFOC (Specific Fuel Oil Consumption)				
	HFO	LS MGO	LNG	
2-Stroke	0,182	0,171	0,155	kg/kWhr
2-Stroke (de-rated)	0,171	0,161	0,145	kg/kWhr
4-Stroke	0,209	0,196	0,178	kg/kWhr
4-Stroke (de-rated)	0,196	0,185	0,167	kg/kWhr

Table 42, Specific Fuel Oil Consumption

Due to the significantly higher cost of MGO compared to HFO, we have calculated the increase in running cost, with MGO, compared to running the main engine on HFO in table 36, MGO has a higher Calorific value, which reduces the SFOC as per Table 42, Specific Fuel Oil Consumption.

Additional requirements and restrictions:

- Latest Emission Control Regulations - The International Maritime Organisation (IMO)
  The IMO Annex VI of MARPOL 73/78, Regulations for the Prevention of Air Pollution from Ships has been in force since May 2005. Thus, the SOx limit applies to all vessels in the category of ships with an engine power output of more than 130 kW. The general international limit on sulphur is reduced from 5% to 4.5% through the ISO 8217 fuel standard. IMO has specified that, in future, further limitations will be imposed on SOx as well as on other components in the exhaust gas. Figure 24, Sulphur Reduction 'road map' illustrates the IMO SOx limits or both ECAs (Emission Controlled Areas) and for international waters. CARB (California Air Resources Board) has introduced limits on the use of sulphur for MGO and MDO, respectively.

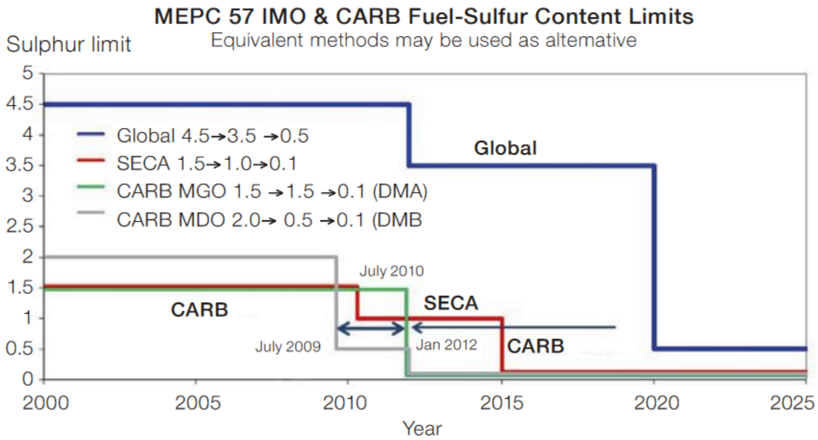


Figure 24, Sulphur Reduction 'road map'

- No special requirements or regulations govern the use of Distillate fuels except that the fuels are to comply with ISO 8217 standard. There are concerns regarding the safety of the use of distillate fuels (LS MGO) on oil fire boilers
- There exists a concern during a fuel changeover from HFO to distillate fuel (LS MGO) because the pipes and other parts of the fuel oil pumping system are heated when using HFO. MGO flowing through the same hot piping may vaporize creating vapour locks and causing irregular fuel flow to injectors resulting in engine stoppage. Therefore, MGO is not to be used through heated pipes to engines.
- Distillate fuels (LS MGO) is rarely found in isolated ports and is often only available by truck, which at times is a problem due to ISPS control at high profile ports.
- Engine maker's recommendation for an MGO chiller or cooling plant.
- No restrictions by Classification Society
- No Polar Restrictions

7. ***Exhaust Gas Scrubber:***

An EPA report from November 2011 (EPA-800-R_11_006)(xi) reports results of preliminary studies of Exhaust Gas Scrubber installations on 3 vessels. In November 2006, the Puget sound Clean Air Agency received funding from the EPA to evaluate whether a seawater scrubbing system could be successfully designed, retrofitted and operated with in the tight confines of an existing cruise vessel. In April 2007, Holland America Line installed a seawater scrubber in the stack of one of the five 9 MW diesel generators on the cruise ship MS Zaandam.

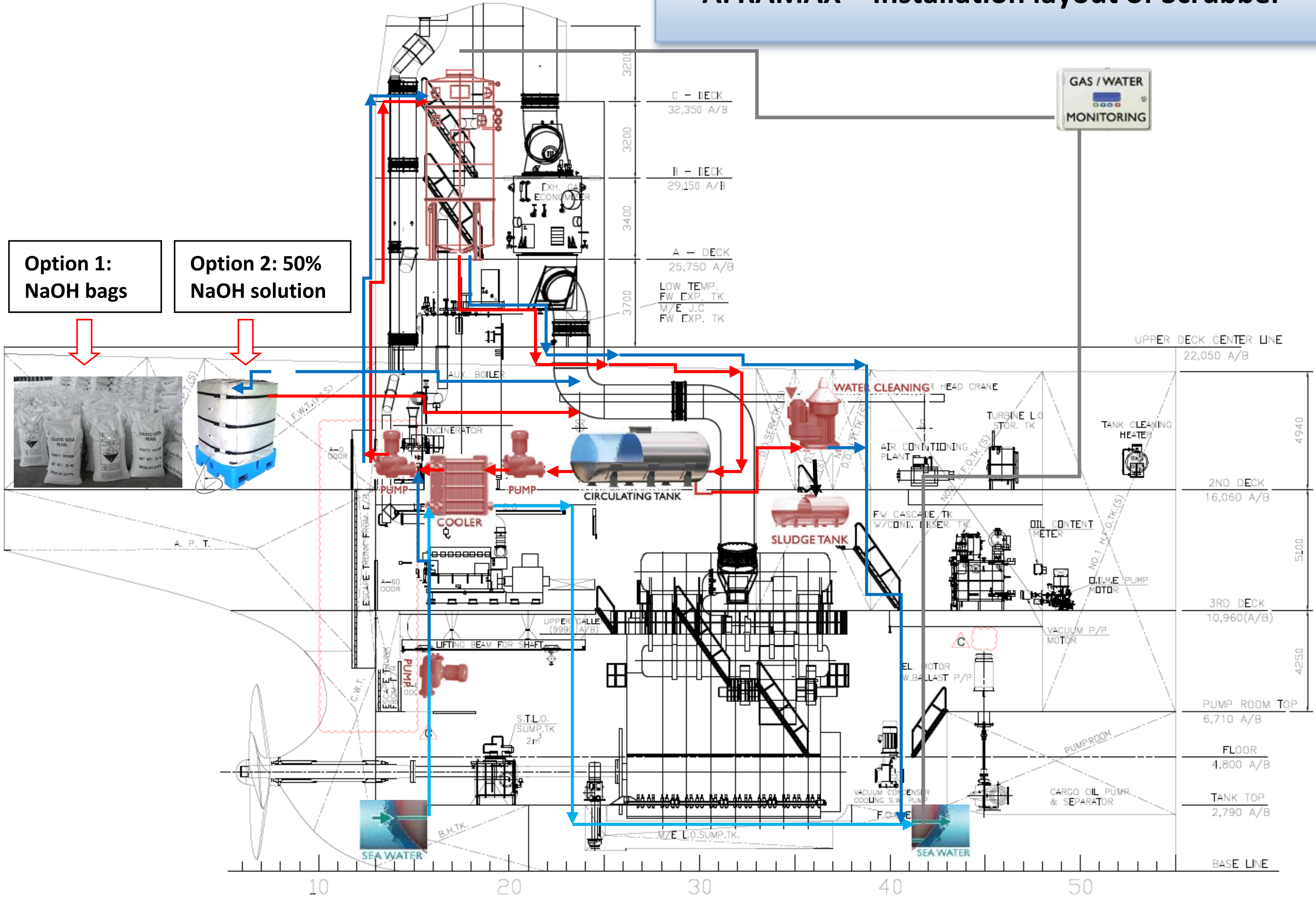
We have investigated one recent exhaust gas scrubber systems installed in the DFDS Ro-Ro vessel, Facaria Seaways[xii], as a retrofit option. We received an equipment quote from the Scrubber maker, Alfa Laval/Aalborg Industries [xiii] for the base case vessel, AFRAMAX tanker with a total motor effect of 15.840 kW. The quote for the equipment alone is EUR 2.510.000, ≈ USD 3.162.600, (EUR – USD exchange rate ≈ 1,26)(xiii) excluding installation and off-hire at a Shipyard. We estimated a retrofit time of 30 days for each type of vessel. After researching the average costs of the equipment, are we able to confirm that an average USD / kW price can be used to scale the price of the equipment linearly according to the Power requirement for the specific vessel. The ***Table 45, Cost per kW***, for the Scrubber is USD 330 /kW – excl. off-hire and dry docking, which would be a typical newbuilding cost and USD 368 / kW – incl. off-hire and dry docking, which would be a retrofit case.

Figure 25, External Exhaust Gas Scrubber

NaOH can be supplied as a 50% solution by tanker trucks at most major ports around the world, as it is used in many industries to produce paper, soap, detergents etc. The vessel can be supplied with large 5m^3 IBC containers with heat insulation. NaOH flakes or pellets can also be supplied, where the crew will manually have to blend the dry product with water onboard. This option is not recommended to avoid spillage and human contact.

Figure 26, Alfa Laval Scrubber installation on DFDS RoRo

AFRAMAX – Installation layout of Scrubber



Freshwater mode (FW):
While operating in FW mode, the scrubber recycles freshwater in which sodium hydroxide (NaOH) is continuously added in order to balance pH at a slightly alkaline value.

A 167 kW[xiv] pump has been estimated on the base case, AFRAMAX, to supply water to the scrubber. At full engine load (90% MCR, 16,000kW), this corresponds to max 1 % of the engine power. The scrubber is causing an additional back pressure of up to 30 mbar, which will also cause some additional energy consumption on the main engine. The additional energy consumption associated with the scrubber back pressure is within the uncertainties of the engine performance measurements – this is difficult to measure but estimated to 0,4 % by MAN Diesel & Turbo[xiv], Table 43, Fuel consumption Penalty for Scrubber. In FW mode, energy for producing NaOH must also be taken into account. NaOH can be produced by several methods; most common is Diaphragm Cell Electrolysis, which requires 5000 kWh/ton. This corresponds to a 2 % emissions penalty of energy in the HFO, Table 43, Fuel consumption Penalty for Scrubber. The consumption of NaOH at 90%MCR of the Main Engine on the base case AFRAMAX, is estimated to 265 Ltr/hr[xiv] @ an average cost of USD 9 / Litre. This cost including the Additional Energy Consumption can be seen in Table 36. The consumption will most probably be reduced from 90% MCR, due to vessel operating at reduced RPM (15-40% MCR).

Seawater mode (SW)
While operating in SW mode, the scrubber uses the natural alkalinity of seawater to absorb and bind the SO_X from the exhaust gas, thus no NaOH is needed for in the scrubbing process. There is an increase SW requirement through the scrubber in SW mode requiring 206kW pumps[xiv]. This increases the power requirement to 1,2% of the engine power.

	SW Scrubbing	FW Scrubbing
Pumps	1,2%	1,0%
Engine back pressure	0,4%	0,4%
NaOH production emmsions penalty	0	2%
Total	**1,6%**	**3,4%**

Table 43, Fuel consumption Penalty for Scrubber[xiv]

Additional requirements and restrictions:

- An Exhaust Gas Scrubber requires significant space onboard, depending on engine output. Retrofitting challenges are to be expected on smaller vessels and vessels with restricted space in the funnel casing, e.g. tugs, fishing vessels, cruise liners and container feeder vessels etc.

- Special precautions should be taken when sailing to Polar Regions where temperatures could drop below freezing point. Heating Elements are to be installed into the fresh water tanks and heat tracing cabling installed around all fresh water piping to avoid pipe bursts under extreme sub-zero conditions. The below installation picture is not recommended in Polar Operation areas, due to exposure to the elements. The NaOH, is required to be kept above 18°C, to avoid crystallization. NaOH is not to be stored in Aluminium containers to avoid a violent reaction. It is recommended that crew is made aware of the dangers of NaOH before any operation.

- MEPC 184(59) – 2009 Guidelines for Exhaust Gas Cleaning Systems[xv] specifies the requirements for the test, certification and in-service verification of SO_X scrubbing systems. The Guidelines apply to any SOx scrubber fitted to fuel oil combustion machinery (excluding incinerators) as an alternative method of compliance with Annex VI, Regulation 14.
  There are two schemes available:
  Scheme A under which the SOx scrubber is subject to initial certification of SOx reduction performance followed by continuous monitoring of operating parameters and a daily spot check of emissions performance; or Scheme B in which there is no requirement for initial certification, but continuous emissions monitoring using an approved system and a
  daily spot check of operating parameters are required.

- Currently the EC only accepts continuous emissions monitoring and the US Coastguard also appears to be predisposed to continuous emissions monitoring. Each ship fitted with a scrubbing system will require a SOX Emissions Compliance Plan (SECP). The plan, prepared by the ship operator, must demonstrate how the ship in its entirety will comply with Regulation 14 and must be approved by the administration. It is required to cover all fuel oil combustion units on the ship, whether fitted with scrubbers or not.

8. *Diesel Particle Filter (DPF)*

A well known Japanese Shipping Line have started preliminary tests of a DPF on a 2-Stroke engine in November 2011[xvi], and the DPF system has already operated smoothly for over 500 hours. With research support from the Japanese Classification Society, they have jointly developed a DPF system for marine diesel engines, which run on C heavy oil. The use of particle filters in Inland waterway vessels and Highway Trucks have been very successful.

A paper by Eelco den Boer, *'Emissions from the Legacy Fleet'*[xvii], estimates the installation cost of DPF on inland waterway vessels. The Estimated CAPEX cost was reported EUR 50 / kW ≈ USD 63 /kW, (EUR – USD exchange rate ≈ 1,26) and the CAPEX including installation costs for a typical retrofit case would be EUR 110 / kW ≈ USD 139 / kW (EUR – USD exchange rate ≈ 1,26).

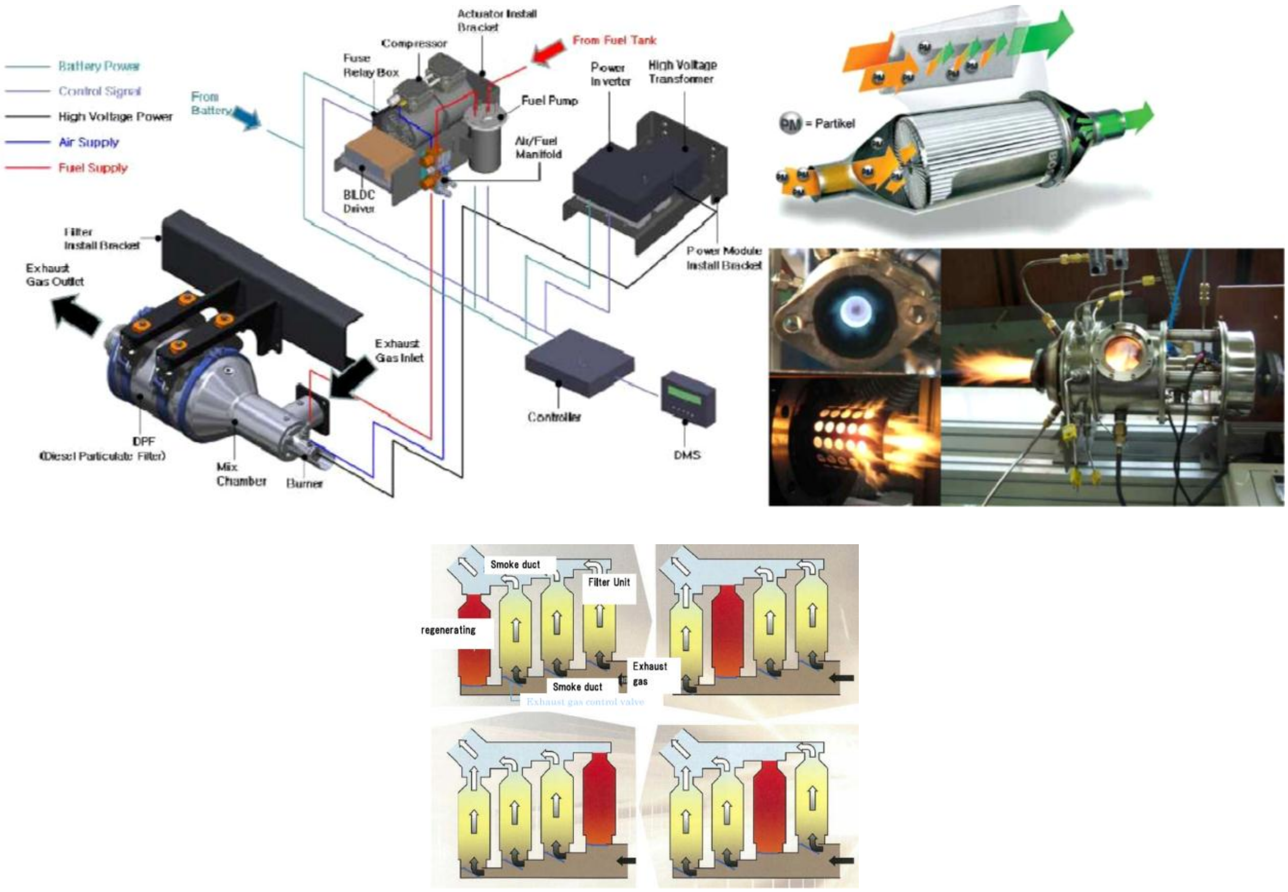


Figure 27, DPF (Diesel Particle Filter)[xviii]

This system incorporates a filter that relies on silicon carbide ceramic fibers. The filter collects particulate matter (PM) when exhaust gas goes through it. It is also a self-cleaning system that automatically combusts and eliminates PM buildup in the filter. This allows for continual operation without clogging of the filter, and requires no maintenance by seafarers. The test is scheduled for about one year (operating time: about 4,000 hours) to verify the system's PM collection performance. After that, its durability will be assessed. We estimate an additional energy penalty, due to exhaust back pressure, to be approximately 0,4% of Shaft Power[xviii].

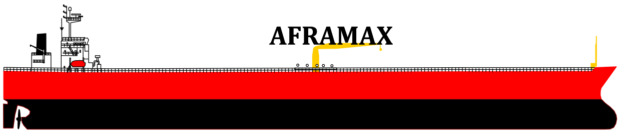
Additional requirements and restrictions:

- The down side of the DPF solution is that it requires a lot of space, approximately two or three times engine volume. This is not a problem with Inland waterway vessels, with small engine capacity but is a challenge on the large commercial vessels with 2-Stroke Engines or cruise vessels. Installation is recommended in the design phase of the Newbuilding vessels, as the size of the installation can be taken into consideration when designing the Engine Room, exhaust trunking and funnel casing.

- No Classification Society Restrictions
- No Polar Restrictions.

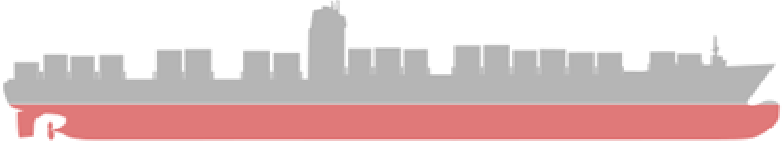
Table 44, Classification of Vessels

AFRAMAX



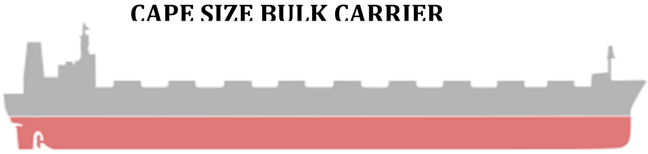
80.000 – 120.000 DWT	
Length	245 m
Beam	34 m
Draft	20 m
Cargo	120.000 m³

10 000 – 13 000 TEU CONTAINER VESSEL



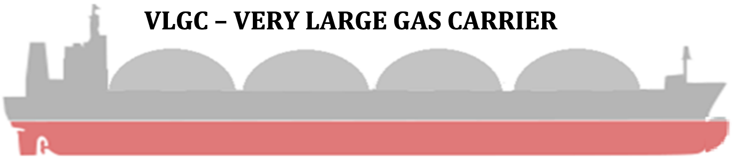
120.000 – 180.000 DWT	
Length	350 m
Beam	56 m
Draft	15.5 m
Cargo	156.000 m³
Power	85.000 kW

CAPE SIZE BULK CARRIER



150.000 – 180.000 DWT	
Length	280 m
Beam	43 m
Draft	18 m
Cargo	175.000 m³
Power	15.000 kW

VLGC – VERY LARGE GAS CARRIER



75.000 – 80.000 DWT	
Length	345 m
Beam	53.8 m
Draft	12 m
Cargo	162.000 m³
Power	22.000 kW

OCEAN LINER

120.000 – 150.000 DWT	
Length	345 m
Beam	45 m
Draft	10 m
Power	75.000 kW

OSV/AHTS

3.000 – 8.000 DWT	
Length	90 m
Beam	21 m
Draft	7,5 m
Power	16.000 kW

TUG

200 - 500 DWT	
Length	36 m
Beam	11 m
Draft	3-4 m
Power	6.100 kW

Abatement	AFRAMAX	CONTAINER	BULK CARRIER	GAS	PASSENGER	OSV/AHTS	TUG
EEDI (De-rating)	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100
Slow Steaming: With De-Rating	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100	USD 100
WIFE	USD 26	USD 26	USD 26	USD 26	USD 26	USD 26	USD 26
LNG	USD 455	USD 518	USD 518	USD 518	USD 518	USD 518	USD 518
DPF	USD 63	USD 63	USD 63	USD 63	USD 63	USD 63	USD 63
HFO-Distillate	USD 13	USD 13	USD 13	USD 13	USD 13	USD 13	USD 13
Scrubber	USD 330	USD 330	USD 330	USD 330	USD 330	USD 330	USD 330

Table 45, Cost per kW excl. Off-hire cost

From the Table, we can see that the *Retrofitting* of the Abatement Measures are more costly compared to *New-building*, due to the fact that the Fixed Investment Cost of the equipment is approximately 80-90% of the Capital investment. Shipyard rates around the world are relatively constant for the Retrofitting of the specialized equipment. Once the Abatement measure become mainstream, the equipment will become more cost effective and Shipyards will also reduce the retrofitting costs, due to familiarization of the installation process. This proves that there is a relatively linear relation between Shaft Power and the Capital Investment. The Shaft Power of the vessel is taken as 100%MCR, Table 46, Shaft Power (kW)@100%MCR
Table 47, Shaft Power (kW) @ 90%MCR, to dimension the equipment to maximum engine ouput.

Vessel Type	Shaft Power (kW)
AFRAMAX	16.000
CONTAINER	85.000
BULK CARRIER	15.000
GAS	22.000
PASSENGER	75.000
OSV/AHTS	16000
TUG	6.100

Table 46, Shaft Power (kW)@100%MCR

Vessel Type	Shaft Power (kW)
AFRAMAX	14.400
CONTAINER	76.500
BULK CARRIER	13.500
GAS	19.800
PASSENGER	67.500
OSV/AHTS	14.400
TUG	5.490

Table 47, Shaft Power (kW) @ 90%MCR

From Table 36, the additional operational costs for each abatement measure is calculated. This illustrates if the operational cost is a financial benefit and an approximate pay back time can be calculated for each vessel type and equipment type. The Shaft Power of the vessel is taken as 90% MCR**,** Table 46, Shaft Power (kW)@100%MCR Table 47, Shaft Power (kW) @ 90%MCR**,** due to the fact that the vessels budgetary figures are calculated on 90% MCR, where the engines are most efficient.
To retrofit the *Abatement Measures*, an *Off-hire* rate per day, *Table 48, **Off-Hire Rates**,* is to be estimated and multiplied by the estimated number of days the specific *Abatement Measure* takes to be installed and completed.

Vessel Type	EEDI (De-rating)	De-Rating	WiFE	LNG	HFO-Distillate	DPF	Scrubber	Off Hire Rates
AFRAMAX	30	30	20	40	10	20	30	USD 20.000
CONTAINER	30	30	20	40	10	20	30	USD 40.000
BULK CARRIER	30	30	20	40	10	20	30	USD 18.000
GAS	30	30	20	40	10	20	30	USD 30.000
PASSENGER	30	30	20	40	10	20	30	USD 60.000
OSV/AHTS	30	30	20	40	10	20	30	USD 40.000
TUG	30	30	20	40	10	20	30	USD 10.000

*Table 48, **Off-Hire Rates***

CAPEX (USD) Table 35		Shaft Power (kW) @100% MCR	EEDI (De-rating)		De-rating		Emulsion		LNG		Chiller (HFO-Distillate)		DPF		Scrubber	
			Retrofit	Newbuild-ing	Retrofit	Newbuild-ing	Retrofit	New-building	Retrofit	Newbuild-ing	Retrofit	New-building	Retrofit	New-building	Retrofit	Newbuild-ing
1	AFRAMAX	16,000	2,210,000	1,610,000	2,210,000	1,610,000	810,000	410,000	8,080,000	7,280,000	410,000	210,000	1,410,000	1,010,000	5,880,000	5,280,000
2	CONTAINER	85,000	9,730,000	8,530,000	9,730,000	8,530,000	2,970,000	2,170,000	45,630,000	44,030,000	1,500,000	1,100,000	6,160,000	5,360,000	29,240,000	28,040,000
3	BULK CARRIER	15,000	2,050,000	1,510,000	2,050,000	1,510,000	740,000	380,000	8,490,000	7,770,000	370,000	190,000	1,310,000	950,000	5,490,000	4,950,000
4	GAS	22,000	3,110,000	2,210,000	3,110,000	2,210,000	1,160,000	560,000	12,600,000	11,400,000	580,000	280,000	1,990,000	1,390,000	8,160,000	7,260,000
5	PASSENGER	75,000	9,330,000	7,530,000	9,330,000	7,530,000	3,120,000	1,920,000	41,250,000	38,850,000	1,570,000	970,000	5,930,000	4,730,000	26,540,000	24,740,000
6	OSV/AHTS	16,000	2,660,000	1,610,000	2,660,000	1,610,000	1,110,000	410,000	9,690,000	8,290,000	560,000	210,000	1,710,000	1,010,000	6,330,000	5,280,000
7	TUG	6,100	910,000	610,000	910,000	610,000	360,000	160,000	3,560,000	3,160,000	180,000	80,000	580,000	380,000	2,310,000	2,010,000

Addition to OPEX (USD) Table 36		Shaft Power (kW)@90% MCR	EEDI (De-rating)		De-rating		Emulsion		LNG comparison		Chiller (HFO-Distillate)		DPF	Scrubber	
			2-Stroke	4-Stroke	2-Stroke	4-Stroke	30 vol.% H20	20 vol.% H20	MGO	HFO	MGO (-chiller)	MGO (+chiller)		SW mode	FW mode
1	AFRAMAX	14,400	- 2,600		- 2,600	-	900	600	- 40,800	- 22,000	18,700	18,900	171	700	59,500
2	CONTAINER	76,500	- 13,600		- 13,600	-	4,500	3,400	- 216,600	- 117,100	99,500	100,600	907	3,600	316,100
3	BULK CARRIER	13,500	- 2,400		- 2,400	-	800	600	- 38,200	- 20,700	17,600	17,700	160	600	55,800
4	GAS	19,800	- 3,500	- 4,000	- 3,500	- 4,000	1,200	900	- 56,100	- 30,300	25,800	26,000	235	900	81,800
5	PASSENGER	67,500	-	- 13,800	-	- 13,800	4,600	3,400	- 219,500	- 118,600	100,900	101,800	919	3,700	279,900
6	OSV/AHTS	14,400	-	- 2,900	-	- 2,900	1,000	700	- 46,800	- 25,300	21,500	21,700	196	800	59,700
7	TUG	5,490	-	- 1,100	-	- 1,100	400	300	- 17,900	- 9,600	8,200	8,300	75	300	22,800

The first set of columns, Table 49, Index Summary of the Short List BC Abatement Option for 2-Stroke Engines*,* under *Relevance,* are divided into *Retrofit* and *New Building*, which is illustrating if the specific abatement measure is possible on the different type of vessels. Following relevance is the engine types, e.g. 2-Stroke or 4-Stroke. Approximately 90% of the world commercial fleet uses 2-stroke engines for propulsion, and due to propulsion power requirement for 90-98% of all power consumption onboard, all other consumers are negligible, except for in *Table 7,* where 4-Stroke engines are the main source of power for propulsion.

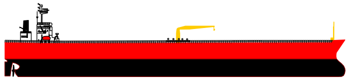
The second set of columns *Table 15****, Index Summary of the Short List BC Abatement Option for 2-Stroke Engine***Table 49, Index Summary of the Short List BC Abatement Option for 2-Stroke Engines under *Cost Index,* are divided into *Retrofit* and *New Building*. This is due to the cost implications involved when retrofitting the abatement options e.g. Dry Docking, Off-hire, Classification Society, Design, Machinery Modification, Additional steel/piping/cabling etc. When designing and installing the abatement measures from the *New Building* stage, a considerable cost saving is found and recommended. The Cost Index varies considerably between vessel classes due to the large variances in Shaft Power and Off-hire rates. E.g. due to the minimum available knowledge of the daily charter rate for a cruise liner, we estimated a rate of USD 60.000 / day.

The third set of columns, Table 49, Index Summary of the Short List BC Abatement Option for 2-Stroke Engines under *Reduction Index,* The *Reduction Index* is summarising all emissions, which are being discussed during this report, e.g. NOx, SOx, Black Carbon, CO_2 etc. The reduction of emissions is directly related to the *Fuel Consumption* of each vessel type, which in turn is related to the *Shaft Power*. There could be a minor improvement in reducing emissions from *New building* stage compared to *Retrofit*, but the difference is very small and thus negligible.

(1) 90% of the Commercial bulk fleet use 2-stroke engines, so the 4-stroke engines are not relevant in our estimates except for Gas vessels and Ocean Liners.
(2) De-Rating of 4-stroke medium speed engines usually requires the engines to be replaced. Only during the New Building design phase will this be viable.
(3) Diesel Particle filters are being tested on inland water way vessels but the technology needs to mature to gain more experiences and data.
(4) De-Rating & slow steaming has been taken as the most cost effective way to reduce the EED Index.
(5) 2-Stroke engines are not possible on Ocean Passenger Liners, Supply vessels and tugs.
(6) Retrofit of de-rated propulsion plants for 4-stroke engines is not an option due to the complete propulsion plant needs replacement and pay-back time is not realistic. De-Rated engines are an option in the design phase of a New Building Slow Steaming is an option with 4-stroke propulsion, as most Ocean Liners, Supply vessels and tugs as Diesel-Electric driven. This gives the vessel flexibility to reduce number of generators.
(7) LNG retrofit for Tugs is not possible due to the space requirement. If the vessel is designed to accommodate the LNG tanks, then the system can be incorporated.

If the abatement option *Cost* or *Reduction Index* per comparative vessel exceeds the AFRAMAX tanker, the specific *Index* will exceed *Index 100* and vice versa if the *Cost* or *Reduction Index is less.*

Table 49, Index Summary of the Short List BC Abatement Option for 2-Stroke Engines

	AFRAMAX TANKER					
	Relevance				Cost Index	
	Retrofit		New Building		Retrofit	New Building
	2-Stroke	4-Stroke	2-Stroke	4-Stroke		
EEDI	✓[4]	-[1]	✓[4]	-[1]	100[4]	71[4]
Slow Steaming: with De-Rating	✓	-[1]	✓	-[1]	100	71
Water-in-Fuel Emulsion	✓	-[1]	✓	-[1]	100	48
LNG	✓	-[1]	✓	-[1]	100	89
HFO-Distillate	✓	-[1]	✓	-[1]	100	71
Diesel Particle filters	✓[3]	-[1]	✓[3]	-[1]	100[3]	69[3]
Scrubbers-High Sulphur	✓	-[1]	✓	-[1]	100	90
	13000-15000 TEU CONTAINER VESSEL					
	Relevance				Cost Index	

	Retrofit		New Building		Retrofit	New Building
	2-Stroke	4-Stroke	2-Stroke	4-Stroke		
EEDI	✓(4)	-(1)	✓(4)	-(1)	433(4)	530(4)
Slow Steaming: with De-Rating	✓	-(1)	✓	-(1)	433	530
Water-in-Fuel Emulsion	✓	-(1)	✓	-(1)	358	530
LNG	✓	-(1)	✓	-(1)	561	605
HFO-Distillate	✓	-(1)	✓	-(1)	440	536
Diesel Particle filters	✓(3)	-(1)	✓(3)	-(1)	429(3)	530(3)
Scrubbers-High Sulphur	✓	-(1)	✓	-(1)	494	531

	**CAPE SIZE BULK CARRIER**					
	Relevance				**Cost Index**	
	Retrofit		New Building		Retrofit	New Building
	2-Stroke	4-Stroke	2-Stroke	4-Stroke		

EEDI	✓[4]	-[1]	✓[4]	-[1]	93[4]	94[4]
Slow Steaming: with De-Rating	✓	-[1]	✓	-[1]	93	94
Water-in-Fuel Emulsion	✓	-[1]	✓	-[1]	92	95
LNG	✓	-[1]	✓	-[1]	105	107
HFO-Distillate	✓	-[1]	✓	-[1]	93	94
Diesel Particle filters	✓[3]	-[1]	✓[3]	-[1]	92[3]	93[3]
Scrubbers-High Sulphur	✓	-[1]	✓	-[1]	93	94
	**VLGC (VERY LARGE GAS CARRIER)**					
	Relevance				**Cost Index**	
	Retrofit		New Building		Retrofit	New Building
	2-Stroke	4-Stroke	2-Stroke	4-Stroke		
EEDI	✓[4]	✓[4]	✓[4]	✓[4]	141[4]	137[4]
Slow Steaming: with De-Rating	✓	✓	✓	✓	141	137

Water-in-Fuel Emulsion	✓	✓	✓	✓	144	138
LNG	✓	✓	✓	✓	156	157
HFO-Distillate	✓	✓	✓	✓	141	138
Diesel Particle filters	✓(3)	✓(3)	✓(3)	✓(3)	141(3)	137(3)
Scrubbers-High Sulphur	✓	✓	✓	✓	139	137

Table 50, Index Summary of the Short List BC Abatement Option for 4-Stroke Engines

	**OCEAN LINER**					
	Relevance				**Cost Index**	
	Retrofit		New Building		Retrofit	New Building
	2-Stroke	4-Stroke	2-Stroke	4-Stroke		
EEDI	-(5)	✓(4)	-(5)	✓(4)	419(4)	341(4)
Slow Steaming: with De-Rating	-(5)	✓(2)	-(5)	✓	419 (2)	341
Water-in-Fuel Emulsion	-(5)	✓	-(5)	✓	381	468

LNG	-[5]	✓	-[5]	✓	508	534
HFO-Distillate	-[5]	✓	-[5]	✓	423	472
Diesel Particle filters	-[5]	✓[3]	-[5]	✓[3]	416[3]	467[3]
Scrubbers-High Sulphur	-[5]	✓	-[5]	✓	450	469
	**OSV/AHTS**					
	Relevance				**Cost Index**	
	Retrofit		New Building		Retrofit	New Building
	2-Stroke	4-Stroke	2-Stroke	4-Stroke		
EEDI	-[5]	✓[4]	-[5]	✓[4]	122[4]	100[4]
Slow Steaming: with De-Rating	-[5]	✓[2]	-[5]	✓	122 [2]	100
Water-in-Fuel Emulsion	-[5]	✓	-[5]	✓	139	100
LNG	-[5]	✓	-[5]	✓	121	114
HFO-Distillate	-[5]	✓	-[5]	✓	121	100

Diesel Particle filters	-(5)	✓(3)	-(5)	✓(3)	123(3)	100(3)
Scrubbers-High Sulphur	-(5)	✓	-(5)	✓	108	100

	TUG					
	Relevance				Cost Index	
	Retrofit		New Building		Retrofit	New Building
	2-Stroke	4-Stroke	2-Stroke	4-Stroke		
EEDI	-(5)	✓	-(5)	✓	41	38
Slow Steaming: with De-Rating	-(5)	✓(2)	-(5)	✓	41(2)	38
Water-in-Fuel Emulsion	-(5)	✓	-(5)	✓	44	38
LNG	-(5)	✓(7)	-(5)	✓	44(7)	43
HFO-Distillate	-(5)	✓	-(5)	✓	41	38
Diesel Particle filters	-(5)	✓(3)	-(5)	✓(3)	42(3)	38(3)
Scrubbers-High Sulphur	-(5)	✓	-(5)	✓	39	38

We have based our comparative index, Table 49, Index Summary of the Short List BC Abatement Option for 2-Stroke Engines, on an AFRAMAX tanker. We have given all the abatement options Index 100, for this vessel. All the following vessels that have similar Length/Breadth dimensions are given a calculated Index based on our AFRAMAX tanker.

We have calculated an average *Cost* and *Reduction Index,* Table 49, Index Summary of the Short List BC Abatement Option for 2-Stroke Engines*,* for each vessel, based on Shaft Power (kW average), If the comparative vessel has an increased power requirement, then the Cost Index*,* is directly proportional to the power, Table 31 and 32.

References for appendix E:

[i] Kristensen HO, et al. (2012) Energy Efficiency Design Index Regulations from IMO (MEPC), Latest update – January 2012

[ii] MAN Diesel, (2012) Improved Efficiency and Reduced CO_2

[iii] Lloyd's Register, (2012) MARPOL Annex VI – Approved Method (http://www.lr.org/compliance/codes/203236-MARPOLAnnexVIApprovedMethod.aspx)

[iv] MEPC.1/Circ.678 (2009), DEFINITIONS FOR THE COST EFFECTIVENESS FORMULA IN REGULATION 13.7.5 OF THE REVISED MARPOL ANNEX VI

[v] Andreasen A (MAN Diesel) & Nyggard KB (Danisco) (2011), Danish Ministry of the Environment (Water-in-fuel emulsion as marine engine fuel for reduced NOx and particulate emissions -*Environmental Project No. 1380 2011)*

[vi] MAN Diesel (2006), Faster Freight Cleaner Air

[vii] Wartsila Technical Journal (2012), LNG Conversions for Marine Installations

[viii] Germanischer Lloyd & MAN Diesel (2012), Cost and benefits of LNG as ship fuel for container vessels

[ix] DSME, DSME Green Ship Technology is Certified by Classifications. (http://www.dsme.co.kr/epub/ds/td/dstd030Q.do?dt_type=etod&dt_seq_no=2604&currentPageNo=1)

[x] MAN Diesel, Operation on Low-Sulphur Fuels

[xi] United States Environmental Protection Agency (2011), Exhaust Gas Scrubber Wastewater Effluent (Report # EPA-800-R-11-006)

[xii] Hansen JP Ph.D. Chem. Eng. (2012), Alfa Laval & Danish Ministry of the Environment (Exhaust Gas Scrubber Installed Onboard MV Ficaria Seaways

[xiii] Alfa Laval (2012), Budgetary Quotation for PureSOx

[xiv] Alfa Laval (2012), Technical Specification – PureSOx comb 128-Multiple inlet-Hybrid System

[xv] MEPC 184(59) – 2009 Guidelines for Exhaust Gas Cleaning Systems

[xvi] Mitsui O.S.K Lines (MOL) (2010), MOL Develops Marine Use Diesel Particulate Filter

[xvii] den Boer E (2011), (CE Delft) *'Emissions from the Legacy Fleet'*

[xviii] Korean Register (KR) (2010), Energy & Environmental Business Center

Background and Summary of Update

In 2012 the International Maritime Organization (IMO) commissioned a consultant report to investigate the possible technologies for the abatement of black carbon (BC) emissions from commercial shipping (1).

The report included ship BC abatement options, BC removal rates and uptake options and availability of abatement technologies, in addition to modelling of implementation costs of the most highly ranked abatement options.

Ongoing discussions in this area, and five years of intervening research have provided a need to update the original report. Included herein is an update to the BC abatement options, removal rates and availability. Cost modelling of the implementation of the highest ranked options is beyond the scope of this update. Data and results within this update must be considered in conjunction with the 2012 report.

The summary of the top 6 ranked BC abatement potential options reported in 2012 is shown in Table 1. These technologies were ranked based on BC emissions reductions, and concomitant reductions in other pollutants (such as CO_2, SO_X and NO_X). All of the six technologies listed showed immediate or short-term uptake potential (1-5 years) and all but diesel particulate filters were commercially available.

Table 2 shows the summary results of the review of studies from this report. For all technologies the minimum, mid-range and maximum BC changes are reported in that sections summary table if available. Based on this updated review of literature BC abatement potential was unchanged for all but diesel particulate filters, scrubbers and a switch from HFO to distillate fuel. Investigations into the fuel quality parameters affecting BC emissions are also included.

We note that implementation of any of the top rated technologies, without new BC emission regulations, will rely on robust financial returns on investment from reduced fuel consumption or compliance with current emissions regulation.

Major Findings from this Review

1) *New studies provide more certainty that a switch from residual fuel to distillate fuel reduces BC emissions by at least 33%. Low sulphur fuel blends will likely not lead to BC reductions.*
2) *Diesel particulate filters show high BC removal rates for distillate fuel, advances to technology for high sulphur fuel and more commercial availability.*
3) *Exhaust gas scrubbers remove, on average, 45% of BC, however many studies fail to explicitly measure BC.*
4) *Studies investigating the fuel quality parameters that lead to higher BC emissions are scant and should be encouraged. Focus on the impacts of the hydrocarbon complexity (e.g. asphaltenes and poly-aromatics) of different fuels is suggested.*

Table 1 Technologies short-listed for BC abatement in the 2012 report

Technology	BC Reduction
LNG	93.5%
Diesel Particulate Filters	85%
Water in fuel emulsion	70%
Scrubbers – High Sulfur Fuel	60%
Scrubbers – Low Sulfur Fuel	37.5%
HFO to distillate fuel	45%
Slow Steaming with de-rating	15%

Table 2 Summary of BC abatement technologies from this update

BC Reduction Strategies	***BC Reduction***	***Drawbacks***
LNG	93.5%	New engine investment
DPF – Low Sulphur Fuel	≥99%	Economic Incentives
DPF – High Sulphur Fuel	85%	Technology maturity
WiFE	70%	Technology maturity
Scrubbers – High Sulphur Fuel	45%	Retrofit + capital and maintenance costs
Scrubbers – Low Sulphur Fuel	37.5%	Retrofit + capital and maintenance costs
HFO – Distillate	33%	Increased fuel costs
Slow Steaming – De-Rating	15%	Complex fleet dynamics
Alternative Fuel Strategies		
Biodiesel – 100%	50-75%	
Biodiesel Blend – 20%	10-30%	
Methanol – DME	97%	
Nuclear	95%	
Engine Options		
Slide Valves	10-50%	
Exhaust Treatment		
Electrostatic Precipitators	10-90%	
Selective Catalytic Reduction	0-30%	
Operational/Design Strategies		
EEDI Achieved with SEEMP and following design strategies:	10%/20%/30%	For newbuild ships after 2015/2020/2025
Ballast Water and Trim	1-5%	
Propeller Optimization	3-20%	
Construction Weight	5%	
Air Lubrication	3.5-15%	
Aerodynamics	3-4%	
Hull Coatings	2-9%	
Hull Cleaning	3-10%	
Wind – Flettner Rotors	3.6-12.4%	

Solar	5-17%
Weather Routing	2-10%
Autopilot Upgrades	0.5-4%

1 Introduction

The format and methods of the 2012 report are followed in this update.

1.1 Black Carbon

The 2012 IMO report (1) can be referenced for a discussion on BC definition, impacts on health and environment, and emissions from shipping. It is worth noting that in 2015 the IMO accepted a definition for BC (2) as follows:

Black Carbon is "a distinct type of carbonaceous material, formed only in flames during combustion of carbon-based fuels" and distinguishable from other forms of "carbon and carbon compounds contained in atmospheric aerosol" due to a unique combination of four physical properties:

1) It strongly absorbs visible light with a mass absorption cross section of at least $5m^2g^{-1}$ at a wavelength of 550nm;

2) It is refractory; that is, it retains its basic form at very high temperatures, with vaporization temperature near 4000K;

3) It is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol;

4) It exists as an aggregate of small carbon spherules.

This definition is derived from the most recent review of BC research (3), and is measurement neutral, allowing for all of the above-mentioned properties to be utilized in the measurement of BC.

1.2 Measurement and Data Availability

This report utilizes the same criteria as the 2012 report for assessment of BC abatement. This includes using studies that measured BC based on the physical properties described in section 1.1 (e.g. elemental carbon, light absorption) in addition to studies that utilized BC proxies (such as particulate mass and size), and fuel efficiency changes as a proxy for BC change. All measurements, regardless of instrument, are reported as "BC" (rather than EC, eBC, rBC or estimated-BC) to eliminate the need for the detailed discussion on nomenclature (refer to Petzold, *et al.* (4)) and measurement uncertainty. Reported BC measurements are assumed to be accurate except where obvious concerns exist. Discussion on this assumption can be found in the study of Lack, *et al.* (5). Very few studies adequately discuss measurement uncertainties for their specific experiments. Reporting abatement potential as a reduction ratio of emission factors (rather than absolute changes) helps to minimize biases in the measurement method and units of emission factors. This approach maintains consistency with the 2012 report and inclusivity towards as much data as possible.

For all technologies the minimum and maximum BC changes are reported in that sections summary table. Mid-range values are also reported if there were more than two individual studies. Average and standard deviations were reported if there were sufficient studies to allow for this analysis.

Refer to section 2 of the 2012 report for the details of measurement and data availability.

1.3 Technology Maturity

Technology maturity assessment from the 2012 report is applied to this update:

CM: ***C**ommercially Available* – **M**ultiple units operational in the shipping sector.

CF: ***C**ommercially Available* – **F**ew units operational in the shipping sector.

DE: ***De**monstration* – Feasibility demonstrated in the shipping sector, but it is not commercially available yet.

OS: ***O**ther **S**ectors* – Technology is commercially available in other sectors and potentially applicable in shipping.

NA: ***N**ot **A**vailable* – Technology may not be available in the long term.

1.4 Technology Uptake Time

Technology uptake time assessment from the 2012 report is applied to this update:

IM: **Im**mediate - <12 months. Commercially available.

IN: **In**termediate - 1-5 years. Commercially available, but major retro-fit or new-build required.

MT: **M**edium **T**erm -5-10 years. Not commercially available. Design/experimental stage and will require further development, research and commercialization.

LT: **L**ong-**T**erm - > 10 years. Major design, safety and commercialization effort necessary.

UI: **U**nlikely **I**mplementation – Technology unlikely to be implemented.

2 Black Carbon Abatement Options

BC abatement technologies are assessed within the following categories:

- Fuel Efficiency – Vessel Design
- Fuel Efficiency – Engine Options
- Fuel Efficiency – Monitoring Options
- Slow Steaming
- Fuel Treatments
- Fuel Quality (Traditional Fuels)
- Alternative Fuels
- Exhaust Treatment

For a number of technologies, very little new information was found on review to change the conclusions of the 2012 report. Where this is the case the data reported in the 2012 report is reproduced.

2.1 Fuel Efficiency - Vessel Design

2012 Conclusion:

- *Fuel efficiency gains for new ship builds of 10%, 20% and 30% by 2015, 2020 and 2025 are mandated by the EEDI.*

- *Equivalent BC reductions are expected in line with fuel efficiency gains.*

2017 Update:

The IMO energy efficiency design index (EEDI) (6), adopted in 2011, requires new ships to adhere to stepwise energy efficiency improvements (10%, 20% and 30% reduction in CO_2 per tonne-mile from 2015, 2020 and 2025, respectively). Specific design improvements are not mandated, rather decided by the ship designer.

Since 2012, there have been several reports of ship new-builds under the EEDI exceeding these requirements by 20 – 32% (7-9). Assuming that in-use BC emissions drop proportionally to fuel efficiency improvements, these reports provide evidence that the EEDI will, at a minimum, provide CO_2 (and BC) reductions at the levels anticipated (assuming operational conditions are similar to the "ideal" conditions underpinning the EEDI).

2017 Conclusion:

- *Unchanged since 2012*

- *Fuel efficiency improvements triggered by the EEDI will continue to contribute to BC reductions for new-build vessels only.*

Table 3 EEDI (excludes engine and fuel options).

Abatement Measure	⇓CO_2 % 2015|2020|2025	⇓BC % 2015|2020|2025	Technology Maturity	Uptake Time	Remarks/ Limitations
EEDI	10|20|30	10|20|30	CM	2015/ 2020/ 2025	Required due to regulation. Newbuilds, >400 tonnes

2.2 Fuel Efficiency – Vessel Retrofit

2012 Conclusion:

- *Multiple retrofit options available to improve fuel efficiency (and therefore BC emissions) by up to 20%.*

- *Many deemed to be currently commercially available and cost neutral.*

2017 Update:

The Ship Energy Efficiency Management Plan (SEEMP), a plan agreed to at the IMO at the same time as the EEDI, aims to provide guidelines for ship efficiency improvements via retrofit options. These options are numerous and were included in the 2012 report under many categories. For example, propeller design, hull coatings, hull cleaning, aerodynamic superstructures and air lubrication are just some of the retrofit options discussed. Both the EEDI and SEEMP rely on the most cost effective fuel-efficient options to be utilized in new-builds or retrofits, and numerous reports suggest that there is a cost-neutral fuel efficiency gain of 30% available to the industry (10). However, there has been investigations into the efficiency gap for the shipping industry (11) and whether the SEEMP is capable of realizing these cost-neutral efficiency gains. According to Johnson, *et al.* (11), the SEEMP does not include industry best practices to allow efficiency retrofits to take place effectively. They concluded that the any fuel efficiency gains in the shipping industry will be reliant on the longer term EEDI (new builds), rather than retrofits. Research into fleet wide energy efficiency continues (12) and will contribute to closing the efficiency gap issues described by Johnson, *et al.* (11).

2017 Conclusion:

- *Unchanged since 2012*
- *Retrofit options will continue to be driven by cost-effectiveness, however it some reports suggest the SEEMP process to encourage uptake is insufficient* (e.g. 11).

Table 4 SEEMP (excludes engine and fuel options). (nr: not reported). Data reported taken from 2012 BC abatement report (1).

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks/ Limitations
Ballast Water & Trim	1|4|5	1|4|5	CM	IM	
Propeller Optimisation[b]	3|nr|20	3|nr|20	CM	IM	
Construction Weight	nr|5|nr	nr|5|nr	CF	IN	New-build required
Air Lubrication	3.5|10|15	3.5|10|15	CF	IM	Retro-fit or new build required
Aerodynamics	3|nr|4	3|nr|4	DE	IN	Retro-fit or new build required
Hull Coatings	2|5|9	2|5|9	CM	IM	Material and dry dock costs
Hull Cleaning	3|5|10	3|5|10	CM	IM	Labor and dry dock costs
Wind – Flettner Rotors	3.6|nr|12.4	3.6|nr|12.4	DE	MT	Design, commercialization

Wind – Sail/Kites	2|nr|26	2|nr|26	CF	IM	Capital costs
Solar	5|nr|17	5|nr|17	DE	IN	Retro-fit or new build required

2.3 Fuel Efficiency – Monitoring Options

2012 Conclusion:

- *Fuel efficiency gains of up to 10% possible for weather routing and auto-pilot upgrades.*

2017 Update:

There is no new evidence since 2012 that monitoring options will provide fuel efficiency reductions greater than those reported in 2012. Continued research into more efficient weather routing algorithms and journey monitoring continues (13, 14) and will likely provide incremental improvements to fuel efficiency into the future.

2017 Conclusion:

- *Unchanged since 2012*

Table 5 Fuel Efficiency Options (Monitoring Options). (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time
Weather Routing	2|nr|10	2|nr|10	CM	IM
Auto-Pilot Upgrades	0.5|nr| 4	0.5|nr| 4	CM	IM

2.4 Fuel Efficiency – Engine Options

2012 Conclusion:

- *Slide valves can potentially decrease BC emissions by 10%-50%.*
- *Engine tuning and de-rating can provide up to 4% fuel efficiency gains.*

2017 Update:

Fuel efficiency improvements within the shipping industry will be driven by the fuel cost savings, the IMO EEDI and SEEMP processes and any future regulatory measures. As such, improvements to the fuel efficiency of the engine will continue so long as there is competitive advantage to the manufacturers to produce engines that maximize energy efficiency under a wider range of conditions, such as slow steaming, variable load environments or mandated emissions reductions.

Slide Valves, Fuel Injection Timing/Pressures, other engine options

Current technologies for slide valves and fuel injection timing and pressures are standard fittings on newer engines, while slide valve retrofit options are available for older engines.

Literature surveys did not reveal any recent technological advances to engine efficiency through the use of slide valves, dynamic fuel injection timing and pressure.

Advances in ship engine gearboxes, producing fuel efficiency gains of 8%, have become available for vessels operating in multiple operational modes (such as ferries, support vessels etc.) (15).

It must also be noted that the IMO NO_X regulations are an important driver of engine technology. NO_X, CO_2, or PM emissions reductions may occur at the expense of the other so engine technologies must be carefully assessed for both gas and particle phase emissions.

De-Rating

Engine de-rating, or optimization of cylinder pressures based on engine speed and load, can potentially reduce fuel consumption by up to 12% if concurrent retrofit of propellers is conducted (16). This is in contrast to the 4% fuel efficiency improvements for de-rating reported in 2012.

2017 Conclusion:

- *Slide Valves: Unchanged since 2012*
- *Engine tuning/de-rating: up to 12% fuel efficiency gains now predicted.*

Table 6 Fuel Efficiency Options (Engine Options)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks/ Limitations
Slide Valves	1|0|-1	10|25|50	CM	IM	Motivated by IMO NO_X regulations. Hardware Cost
Real Time Tuning, De-Rating	1|6.5|12	1|6.5|12	CM	IM	New engine, retrofit

2.5 Slow Steaming

2012 Conclusion:

- *Slow steaming, without engine de-rating can increase BC emission factors by up to 30%.*

- *With slow steaming and de-rating, BC emission factors are likely to remain constant while resulting in absolute BC emission reductions of up to 30% due to reduced absolute fuel consumption.*

- *Fuel efficiency gains of 7% to 29% (assuming engine load shift of 100%-40%) are possible depending on overall fleet behaviour.*

2017 Update:

Since 2012 there has been substantial research into the economics and emissions impacts of slow steaming (17-21). The third IMO greenhouse gas study (22) showed a 10% reduction in shipping CO_2 emissions between 2007 and 2012, triggered by the trend in slow steaming triggered by capacity oversupply during the global economic downturn. These reductions, and motivation for slow steaming more generally, come about via the dynamics between freight rates, shipping capacity and fuel cost with environmental benefits being a byproduct. The recent research (17-21, 23) concludes that, without speed limit regulations, continuation of the practice will be dictated primarily by freight rates with contributions from threshold fuel prices. The absolute changes in BC emissions will be determined by the emission factor at various speeds and fuel consumption and, as shown in Lack and Corbett (24, Fig 4), without de-rating, absolute BC emissions can increase despite the reduced fuel consumption at lower speeds. For the example of Maersk, shown in Lack and Corbett (24), absolute BC emissions decline initially, however, without de-rating, BC emissions increase once vessel speed drops to a critical level.

The 2012 BC report discussed the requirement for engine de-rating, if BC reductions were to occur alongside the CO_2 reductions, particularly at loads less than 80%. If de-rating does not occur, it is possible that absolute BC emissions could increase, based on measurements that show BC emission factors increase as engine load decreases. The net impact in such circumstances will depend on individual cases.

BC Emissions and Engine Load

Since 2012 there have been numerous studies that reported BC emission factor trends with engine load, which can be added to the previous datasets. Several studies (25-30) presented data that reinforced the relationship presented in the 2012 report, originally published in Lack and Corbett (24). Another study (31) presented BC and engine load emission factors although the presentation of results made it difficult to interpret the relationship. It appears as though this study shows a decrease in BC emissions as load decreases, opposite to the majority of studies presented here. Buffaloe*, et al.* (32) measured emission factors for 135 exhaust plumes from over 100 vessels, and presented an aggregated BC emissions/engine load relationship. This study showed, similar to the study of Lack*, et al.* (33), that a BC vs engine load relationship cannot be discerned from data aggregated for single plume intercepts for a fleet of ships. Buffaloe*, et al.* (32) concluded that the variability of the fleet engine, operational and maintenance characteristics would swamp any BC/load relationship, and that to investigate such a relationship would require intensive measurement of a single ship, rather than aggregated data from many ships.

When added to the dataset of Lack and Corbett (24), these recent results do not change the overall average relationship of BC emission factors increasing as engine load decreases. It is recognized that some studies do show the opposite trend (which was also presented in Lack and Corbett (24)) however for turbocharged in service engines the dominant trend is for increasing BC emission factors with decreasing engine load. These results support the need for engine de-rating if BC emissions are to drop linearly with CO_2 emissions as ship speed and engine load decrease during slow steaming operations.

2017 Conclusion:

- *BC emission factor changes same as reported for 2012*
- *Numerous new studies confirming BC – Engine load relationships.*

- *Any reductions in ship speed will increase BC emission factors unless engine de-rating is implemented.*

- *Absolute BC emission changes will depend on reduced fuel consumption and increases in BC emission factors*

Table 7 Summary of Slow Steaming as an Abatement Option (100% load -> 40% load). (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks
Slow Steaming: No De-Rating	7|nr|25	0|nr|-30[a]	CM	IM	Fuel Savings, increased travel time
Slow Steaming: With De-Rating/ Re-Tuning/slide valves	8|nr|29	0|nr|30[a]	CM	IM/IN	Retrofit or new engine needed

[a]BC reductions are for emission factors based on the load changes presented in the references provided.

2.6 Fuel Treatments

2.6.1 Colloidal Catalysts

2012 Conclusion:

- *No evidence of BC reductions*

2017 Conclusion:

- *No additional data available since 2012.*

2.6.2 Water-in-Fuel Emulsion (WiFE)

2012 Conclusion:

- *BC reductions of 50% to 90% depending on water content*
- *CO_2 reductions of up to 18% reported.*

2017 Update:

Since 2012 there has been comprehensive literature reviews on WiFE technologies (34-37) each of which confirmed the extensive NO_X, particulate and BC reductions, and the fuel efficiency gains of the technology. Some recent studies also confirmed the 2012 results (38).

The most important advance since 2012 is that there have been numerous reports of WiFE technology being commercially developed (at least 4 companies in the last 7 years) (39, 40) many of which include successful on-board trials of the technology. In addition, a four year trial of the technology on a bulk carrier was reported in 2015 (41). It should be noted that a number of the studies reviewed represent data from commercial suppliers of the technology.

Independent data and long-term application of the technology will certainly narrow the bounds of BC reduction as well as improve the limited acceptance and uptake of the technology.

2017 Conclusion:

- *No additional data available since 2012.*
- *Availability of abatement technology appears to have improved.*

Abatement Measure	**⇓CO_2 % LOW|MID| HIGH**	**⇓BC % LOW|MID| HIGH**	**Technology Maturity**	**Uptake Time**	**Remarks**
Colloidal Catalyst	2|nr|10	nr	OS	IM	
Water-in-Fuel-Emulsion	-1.5|nr|18	50|nr|90	CF	IM	Depends on % H_2O. NOx emissions also reduced

Table 8 Summary Fuel Treatments as an Abatement Option. (nr: not reported)

2.7
2.8 Fuel Quality – Traditional Fuels - HFO to Distillate

2012 Conclusion:

- *A switch to distillate fuels from HFO comes with a 6%-8% energy content advantage and so BC and CO_2 emissions are reduced by this amount through this mechanism alone.*

- *Use of distillate fuel appears to have a BC reduction effect of 45% with a wide range (0% - 80% change) reported.*

- *Impediments to uptake include fuel cost and availability.*

2017 Update:

Since 2012 the relationship between HFO, distillate fuels and changes to BC emissions has gained interest. The 2012 report reviewed all available industry reports and peer reviewed literature and found that an average BC reduction of 45% results from a HFO-distillate switch.

Fuel sulphur content has been used as a proxy for fuel quality in addition to being used as an indicator of BC reduction potential. It is recognized that fuel sulphur content is only a proxy for fuel quality and will not primarily represent the combustion quality of the fuel, particularly if residual fuels are blended to achieve lower sulphur content.

The search for the underlying parameters that impact BC emissions when a fuel is switched from HFO to a cleaner fuel is multi-dimensional. Fuel factors such as heavy metal, oxygen, asphaltene and poly-aromatic hydrocarbon and ash content contribute to combustion characteristics (42). Engine factors such as speed of combustion, fuel injection timing and cylinder pressures also contribute to combustion quality. It is apparent that more data is needed to understand the fuel parameters that lead to higher BC emissions. This topic is addressed in section 2.11.

Studies focusing on BC emissions with a switch from HFO to distillates have been published since 2012. These studies (and those prior to 2012) are referenced and summarized in Table 13 (section 2.11). Generally these studies fall within the estimates of the 2012 report (0% to 80% reduction in BC switching to higher quality fuel). One study showed a 180% increase in BC (25), although the authors comment that the test bed system was not optimized for distillate fuels.

The results from an extensive ship emission study by Johnson, *et al.* (29) found that BC reductions "varied from a few percent to as much as 60% less BC with lower sulfur [distillate] fuels" (29, p124). A large study by EUROMOT (30) sampled BC emissions from over 30 engines, distillate and residual fuels and various engine loads. When averaged across the entire experiment, BC emissions dropped by 60 to 80% when switching from residual to distillate fuels.

Most studies reported emissions from medium speed diesel engines.

Table 9 summarizes the average and median BC reductions obtained from the analysed data. The results of the study by Ristimaki, *et al.* (43) were removed from the analysis due to serious data inconsistencies described in Lack and Corbett (24). Aggregation of the data suggested an average BC reduction of 33% is consistently observed with a switch from HFO to distillate fuels. Three recent studies suggest that BC reductions result from the switch from residual to distillate fuel, rather than a switch from high sulphur residual to low sulphur residual fuel (28, 30, 44) (more detail provided in section 2.11).

This reduction in BC emissions is also consistent with the 36% average reduction in BC seen when comparing emissions from hundreds of ships in an unrestricted fuel zone (where most ships were using HFO) and in an emission control area where mostly low sulphur distillate fuel was in use (32).

Of the 57 data points included for analysis 85% showed BC emissions reductions with the fuel switch. Eight studies (15%) showed BC emissions increases, most of these being results from test bed engines that showed difficulty in representing in-service conditions such as fuel injection and natural vs. turbocharged aspiration. It is worth noting for future studies and discussion that it is imperative that test bed environments are controlled for in service conditions.

Although this report concludes a 33% reduction in BC emissions (down from 45% in the previous report), this value is more statistically robust based on the increased number of studies analysed.

Table 9 Summary of average BC reductions from fuel switching.

Data Type	↑ or ↓ BC Emissions
All	↓ 33% (± 45%)
All (Median)	↓ 34%
High Loads (≥60%)	↓39% (± 39%)
Two Stroke	↓31%
Four Stroke	↓34%

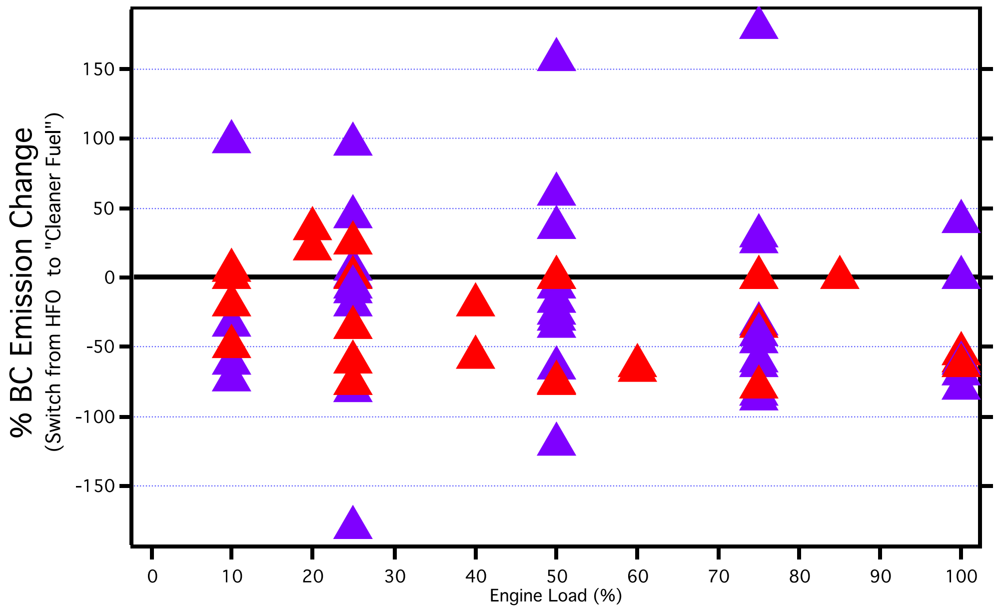


Figure 1 Relative BC emissions changes with a switch from HFO to a lower sulphur, or higher quality fuel. Data colour coded by 2 stroke (red) and 4 stroke (blue) engines.

2017 Conclusion:

- *Additional studies appear to support the 2012 results that a shift from HFO to distillate fuels will result in an average BC reduction of 33% (±45%) (down from 45% since 2012 report due to addition of more studies).*
- *As with the data reviewed in the 2012 report significant variability exists.*
- *Some data points (8 of 57) did show increases in BC emissions with a shift to distillate fuels with these studies having fuel injection and aspiration methods inconsistent with in service operations.*
- *It appears as though BC emission changes are more variable for 4-stroke marine engines compared to 2-stroke engines.*
- *It is apparent that BC reductions are dependent on many variables and the fuel quality parameters such as heavy metal, oxygen, poly-aromatic hydrocarbon and ash content will need to be investigated to determine their impact.*

Table 10 Fuel Switch as an abatement option. (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks/ Limitations
HFO – Distillate – energy content	6|nr|8	6|nr|8	CM	IM	Fuel cost
HFO – Distillate	0	-12|33|78*	CM	IM	Fuel cost

* Range reported is + and – standard deviation of all data

2.9 Alternative Fuels

2.9.1 Biodiesel

2012 Conclusion:

- *100% biodiesel reduced BC emissions by 50% - 75% with a 5%-11% CO_2 penalty.*
- *20% biodiesel blends reduce BC emissions by 10%-30% with a 1%-3% CO_2 penalty.*
- *Possibility of immediate uptake with significant fuel availability drawbacks.*

2017 Update:

There are many studies investigating ship emission changes with biodiesel and biodiesel blends. BC emissions are reduced substantially when biodiesel replaces HFO and it is generally agreed to be as a result of the higher oxygen content of the biodiesel fuel (45, 46).

Many recent studies (since 2012) that utilized a variety of marine and non-marine diesel engines showed BC decreases of 30% - 90% when shifting from petroleum diesel to biodiesel or biodiesel blends (31, 47-54).

Of the studies of biodiesel emissions from marine engines one showed BC reductions within the range of the 2012 report (31), while one study showed that hydrogenation-derived renewable diesel (HDRD) had BC emissions 2 times higher than the ultra-low sulphur diesel (ULSD) at low RPM, and similar to ULSD at higher RPM (55). This study used a fuel that is manufactured using technology similar to that used in refining of oil and which produces a biodiesel with oxygen content similar to traditional petroleum-based diesel.

2017 Conclusion:

- *BC emission reductions unchanged since 2012*
- *Numerous new studies confirm 2012 results.*
- *Oxygen content of fuel is a significant driver of BC emissions reductions, and provides significant insights into the likely BC emissions from different fuels (e.g. HFO, distillate, different biodiesel sources).*

2.9.2 LNG

2012 Conclusion:

- *BC reductions of over 85%, and CO_2 reductions of 15 - 30% are possible with LNG fuel (baseline was low sulphur on-road diesel).*
- *Uptake of this fuel is, and will continue to be, dependent on traditional fuel costs, retrofit costs and implementation into new builds.*

2017 Update:

There are recent efforts in developing an LNG fueled fleet of ships, capitalizing on the NO_X, PM and CO_2 reductions of the fuel, and local availability (56).

From the emissions reduction perspective, the image of LNG as a clean fuel must be qualified with the emerging evidence of fugitive methane emissions of natural gas during extraction, transport and transfer and low-pressure 2 stroke and 4 stroke engines, which can alter the greenhouse gas balance of LNG (e.g. 57, 58). This is in addition to the CO_2 emissions of the lifecycle of the fuel.

2017 Conclusion

- *No changes since 2012 to BC emission reduction potential.*
- *No additional data available since 2012.*

2.9.3 Methanol – Dimethyl Ether (DME) (Ethanol – Diethyl Ether)

2012 Conclusion:

- *BC reductions of >95% are achievable with DME fuel.*
- *An energy content penalty (reduction) of ~10% exists for DME.*
- *Uptake of DME as a fuel is, and will continue to be dictated by traditional fuel costs, retrofits requirements, and global availability of fuel.*

2017 Update:

Reports from various sources continue to promote DME as a future fuel for many sectors, including shipping (59-61).

2017 Conclusion:

- *No changes since 2012 to BC emission reduction potential.*

2.9.4 Nuclear

2012 Conclusion:

- *>95% reductions in BC and CO_2 are possible.*
- *Significant barriers to implementation*

2017 Conclusion:

- *No changes since 2012 to BC emission reduction potential.*

Table 11 Summary of Alternative Fuels as an Abatement Option. (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks/ Limitations
Biodiesel – 100%	-5|nr|-11	50|nr|75	DE	IM	Fuel Availability
Biodiesel – 20% Blend	-1|nr|-3	10|nr|30	DE	IM	Fuel Availability
LNG	15|nr|30	85|nr|99	CF	IN	Engine/fuel storage retro-fit. Port supply of LNG. Fugitive emissions.
Methanol/DME	nr|-9|nr	nr|97|100	DE	MT	Fuel storage retrofit and onboard catalysis units required
Nuclear	nr|nr|95	nr|nr|95	NA	LT –> UN	Design, security and waste issues. CO_2 and BC emissions from fuel production/disposal

2.10 Exhaust Treatment

2.10.1 Electrostatic Precipitators (ESP)

2012 Conclusion:

- *60% - 80% reductions in BC possible with fuel penalty of at least 5%.*
- *Commercial availability for ships limited.*

2017 Update:

Three studies since 2012 have provided additional data on the potential reductions in BC emissions. These studies (62-64) present reduction rates from 15% to over 90%, which widens both the lower and upper bounds of potential reductions compared to the 2012 report. The study by Furugen, *et al.* (64) tested both HFO and MDO fuels showing BC reductions of approximately 60%.

2017 Conclusion:

- *15% - 90% reductions in BC possible with fuel penalty of at least 5%.*
- *Commercial availability for ships limited.*

2.10.2 Diesel Particulate Filter (DPF)

2012 Conclusion:

- *70% - 99% reductions in BC possible with a fuel penalty of up to 6%.*
- *DPF technology for use on HFO is limited. Most units require use of low sulphur fuel.*

2017 Update:

Studies since 2012 on DFP technology show continued development for off-road heavy duty diesel engines (65, 66), DPFs for marine engines operating both distillate and residual fuels (44, 66, 67), and new sulphur resistant catalyst technologies for filtering HFO exhaust (68).

DPF technology is more efficient when applied to emissions from low sulphur fuels with studies prior to 2012, and more recent studies (67) showing BC reductions of ≥99%. In addition there are also numerous commercial suppliers of DPF technology (e.g. Hug Engineering, ETB). The investment and maintenance costs of such technology are beyond the scope of this report.

Investigations into the application of DPF technology on emissions from high sulphur fuels continues with improvements reported since 2012. The study by Maeda, *et al.* (44) reported BC reductions of 80% to 90% for a ship burning 0.8% sulphur MGO fuel. The study by Johansen (68) showed 80-90% reductions in BC from a cruise ship burning 1% sulphur HFO. As DPF technology for ships advances for higher sulphur fuels it is expected that filtration efficiencies will approach the upper limit of that reported here (i.e. 99%). In addition, global fuel sulphur limits will only require DPF development for operation on fuel with less than 0.5% fuel sulphur.

2017 Conclusion:

- *Most studies of DPF operation on exhaust from low sulphur fuels show BC reductions of ≥99%.*
- *BC emission reduction potential for DPFs on high sulphur fuels varies from 80 – 90%.*
- *Technology development for use of DPF on high sulphur fuels is advancing.*
- *DPFs for ships operating low sulfur fuels commercially available.*

2.10.3 Diesel Oxidation Catalysts (DOCs)

2012 Conclusion:

- *0% reductions in BC possible.*

2017 Conclusion:

- *No changes.*

2.10.4 Selective Catalytic Reduction (SCR)

2012 Conclusion:

- *0% to 35% reductions in BC possible.*

2017 Update:

The 2015 study of Lehtoranta, *et al.* (69) investigating PM reductions from HFO combustion with an SCR unit in place showed significant decreases in fine mode (<50nm) particles (factor of 10) but likely retention (no reduction) of particles >75nm (which are likely to be BC). Similar results were shown in Hallquist, *et al.* (70). This indicates that the SCR is capable of reducing volatile particles but it is uncertain that the technology is selective for BC. Lin (71) suggests that 15% reduction in BC emissions is possible when SCR retrofit is combined with integrated engine optimizations. More research, utilizing specific BC measurement is certainly warranted.

2017 Conclusion:

- *Recent studies suggest that particle reductions for SCR are limited to volatile particles, thus excluding BC reductions.*

- *The range of reported BC reductions using SCR is still 0% to 35% based on all reports. More study is certainly needed.*

2.10.5 Exhaust Gas Recirculation (EGR)

2012 Conclusion:

- *No BC reductions reported.*

2017 Conclusion:

- *No changes since 2012.*

2.10.6 Exhaust Gas Scrubbers (EGS)

2012 Conclusion:

- *50% to 70% BC reductions for scrubbing of high sulphur fuel exhaust.*
- *20% to 55% BC reductions for scrubbing of lower sulphur fuel exhaust.*
- *Up to 5% fuel penalty*

2017 Update:

Research on exhaust gas scrubbing for ship exhaust has continued since 2012 with numerous studies reporting on general scrubber development (72-75) and particle mass scrubbing efficacies ranging from 30% to >90% (76-78). All of these studies utilized fuel with sulphur concentrations >0.5%. A review article of particle removal by scrubbing technology (79), for the variety of exhaust scrubbing methods (wet scrubbers, venturi scrubbers, bubble towers and wet electrostatic scrubbers), confirmed particle mass removal rates of at least 85%.

Studies investigating the removal of BC explicitly were limited with one study (29) showing BC reductions of 20-40% for a PURESOx scrubber (www.alfalaval.com) at 1.9% fuel sulphur concentration and BC reductions of approximately 30% from an in-service container vessel with a Tier 0 engine operating on HFO (<3%). A study by Lieke*, et al.* (80) showed that scrubbers operating on SSD engines significantly alter soot structure. BC aggregate collapse and internal mixing of organic matter and sulphates were observed after scrubbing indicating the significant interaction between the BC component of the exhaust and the scrubbing mechanisms. This study utilized fuel with 0.5% to 0.75% sulphur.

Three studies focused on the development of wet electrostatic scrubbers (74, 76, 79), showing better fine particle removal than traditional sea-water scrubbing, which could translate into improved BC removal capability.

2017 Conclusion:

- *The lower limit of BC removal rates with scrubbers using high sulphur fuel is downgraded to 20%, with some new studies suggesting that reductions of roughly 30% might be expected.*
- *Additional studies since 2012 show particle mass removal of at least 85% however BC removal cannot be easily inferred from these studies.*
- *BC reductions for high sulphur fuel are adjusted to be 45% based the mid range of reported studies.*
- *The addition of BC measurements to scrubbers research is necessary.*

Table 12 Summary of Exhaust Treatments as an Abatement Option. (nr: not reported)

Abatement Measure	⇓CO_2 % LOW|MID|HIGH	⇓BC % LOW|MID|HIGH	Technology Maturity	Uptake Time	Remarks/ Limitations
Electrostatic Precipitators	-5|nr|nr	15|nr|90	OS	IN	Size, Commercial availability for ships
Diesel Particulate Filters – Low Sulphur Fuel	-1|-4|-6	≥99	CF	IM	Commercial availability for ships.
Diesel Particulate Filters – High Sulphur Fuel	-1|-4|-6	80|85|90	CF	IN	Limited availability for ships.
Diesel Oxidation Catalysts	nr|nr|nr	nr|0|nr	CF	IN	Often combined with DPF
Selective Catalytic Reductions	nr|nr|nr	0|nr|35	CM	IM	
Exhaust Gas Recirculation	nr|nr|nr	nr|0|nr	CF	IN	May increase BC Soot build up reported
Scrubbers – High Sulphur	-1.5|-3|-5	20|45|70	CM	IM	Unit cost. Fuel S regulation motivation.
Scrubbers – Low Sulphur	-1.5|-3|-5	20|37.5|55	CM	IM	Unit cost. Fuel S regulation motivation.

2.11 Fuel Switching – Which Fuel Properties Alter BC Emissions?

As the review in section 2.7 shows, there is significant variability in BC response to a shift from HFO to a lower sulphur fuel. As previously mentioned, the sulphur content is a very coarse proxy for fuel quality and as such, reviewing what fuel quality parameters may lead to changes in BC emissions is necessary. For example, low sulphur fuels can be produced from blending of residual fuels or from distillation, producing fuels with very different levels of sulphur, ash, heavy metals, and polyaromatic hydrocarbons (81).

It is apparent from the review of data in section 2.8.1 that BC emissions are cut dramatically as the oxygen content of the fuel increases. For biodiesel produced from hydrogenation process, the oxygen content is close to zero, and as shown in the study of Betha*, et al.* (55), the BC emissions do not drop, unlike the emissions from traditional esterification processes. This indicates that parameters within the fuel, such as oxygen content, can have a significant influence on BC emissions.

For petroleum-based fuels, that contain very little molecular oxygen, the complexity of the hydrocarbon, particularly the content and complexity of the poly-aromatic hydrocarbons, is known to affect combustion (42). Poly-aromatic hydrocarbon content is known to directly correlate to BC emissions from gasoline and aircraft engines (82-84) however data for marine engines is sparse. Poly-aromatic content of fuel alters speed of combustion (which is often summarized as an aromaticity index), and is accounted for in the timing of fuel injection. When engines are operated outside of their tuned parameters, combustion can become inefficient leading to higher emissions. However, within an ideally tuned engine, the hydrocarbon complexity still leads to BC formation, evidenced by non-zero BC emissions even under optimum real world operating conditions. What is currently unknown is if subtle differences in the properties of the fuel can lead to alterations in the BC emissions large enough to be measured. For example in the study of Johnson*, et al.* (29) "*a predictive equation for fuel and load effects on BC EFs was not found in the data, suggesting that further research might explore the influence of in-cylinder combustion phenomena and or other fuel parameters such as total aromatic content on BC EFs". While* Miller (85) suggests that "*prediction of BC emissions will likely require a deeper analysis of the chemistry of the fuels, especially aromatics, and the associated combustion processes*".

Despite the depth of knowledge in the petroleum industry on fuel refining and quality, it is apparent that the influence of fuel composition on combustion and subsequent BC emissions is still in a crude state (42, 81, 86, 87). This is particularly so for large marine engines. The recent efforts by the IMO and EUROMOT (30) to provide a standardized measurement protocol, including detailed fuel quality analysis is an important step towards understanding BC emissions and their connection to fuel quality. However, it is unlikely that the connections between each fuel quality parameter and BC emissions will be found with any certainty until a dedicated and carefully designed experiment is performed that controls for each variable.

In the review of data in section 2.7 there were two different types of "higher quality" fuels used. Distillate fuels (MDO, MGO, ULSD) will contain less sulphur, ash, and heavy hydrocarbons. Various residual oils (LS-HFO, LFO) often contain the higher levels of sulphur, ash, heavy metal and higher boiling point hydrocarbons. However some residual fuels can have low sulphur content, allowing for fuel blending producing low sulphur fuels that meet IMO or national emission control area requirements.

The study Zetterdahl*, et al.* (28) looked into BC emissions from a switch from high sulphur residual to a low sulphur residual and showed no net change in BC emissions. Data within the study of EUROMOT (30) showed significantly larger BC emissions for a low sulphur residual (0.008%) compared to distillate with higher fuel sulphur levels (up to 0.58%). An additional study (44) showed BC reductions of 35% to 65% when switching from HFO to a high sulphur distillate, further highlighting that the distillate nature of the fuel is more important than sulphur content. These results suggest that BC reductions result from the switch from a residual to a distillate fuel, rather than a switch from a high sulphur residual to a low sulphur residual fuel. It is likely that the distillation process produces a fuel with less complicated hydrocarbons, allowing for cleaner combustion. Reduced levels of impurities such as ash and heavy metals may also contribute.

For all studies reviewed in section 2.7 the fuel analysis parameters were tabulated with the intention of assessing the BC emission changes for correlations. Unfortunately the fuel analysis results were inconsistently reported and did not allow for comprehensive comparisons.

As Figure 1 and tTable 13 show, a number of studies show variability within experiments that indicates that both engine and fuel parameters are significantly influencing the emissions. Significantly, the data of EUROMOT (30) show larger and more consistent BC reductions for a fuel switch on 2-stroke engines than for 4-stroke engines.

When considering the aggregation of all data it is apparent that BC emissions reductions, on average, do result from a switch from a HFO to a distillate, or higher quality fuel.

2017 Conclusion

- *Fuel sulphur content is a very coarse proxy for fuel quality.*

- *BC reductions correlate to increasing molecular O_2 content of the fuel.*
- *Both engine and fuel parameters have a large influence on BC emissions*
- *Recent studies suggest that BC emissions reductions result from a switch from residual to distillate fuels.*
- *It is likely that the distillation process produces a fuel with less complicated hydrocarbons, allowing for cleaner combustion.*
- *Recent studies show that a switch from high sulphur residual fuel to low sulphur residual fuel does not result in any BC emissions reductions.*
- *Analysis of fuel quality is poorly reported, making correlations to BC emissions changes difficult. Standard measurement protocols should be followed (30).*

Table 13 Summary of BC reductions from fuel switching. All "fuel 2" fuels are distillates unless specified as otherwise.

Study	BC Measure	HFO Details (%)		Fuel 2 Details (%)		Fractional BC Change	Load	Engine	Comments
(88)	EC	3.90	HFO	0.02	MGO	-0.33	0.75	4-S, MSD, In Service	
(88)	EC	3.90	HFO	0.02	MGO	-0.35	0.50	4-S, MSD, In Service	
(88)	EC	3.90	HFO	0.02	MGO	0.44	0.25	4-S, MSD, In Service	
(89)	EC	2.17	HFO	0.1	MGO	-0.62	0.10	4-S, MSD, Test Bed	
(89)	EC	2.17	HFO	0.1	MGO	-0.46	0.75	4-S, MSD, Test Bed	
(89)	EC	2.17	HFO	0.1	MGO	-0.20	0.25	4-S, MSD, Test Bed	
(89)	EC	2.17	HFO	0.1	MGO	-0.34	0.10	4-S, MSD, Test Bed	
(89)	BC	2.17	HFO	0.1	MGO	-0.80	1.00	4-S, MSD, Test Bed	
(89)	BC	2.17	HFO	0.1	MGO	-0.87	0.75	4-S, MSD, Test Bed	
(89)	BC	2.17	HFO	0.1	MGO	-0.81	0.25	4-S, MSD, Test Bed	
(89)	BC	2.17	HFO	0.1	MGO	-0.74	0.10	4-S, MSD, Test Bed	
(43)	FSN	0.89	HFO	0.05	LFO	-0.52	1.00	4-S, Wärtsilä Vasa 4R32 LN	***Data flagged for this reference*** *Study used two independent methods to measure BC that showed opposite trends.*
(43)	FSN	0.89	HFO	0.05	LFO	-0.09	0.75	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	0.89	HFO	0.05	LFO	-0.10	0.50	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	0.89	HFO	0.05	LFO	-0.20	0.25	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	0.89	HFO	0.05	LFO	-0.40	0.10	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	2.42	HFO	0.05	LFO	-0.33	1.00	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	2.42	HFO	0.05	LFO	-0.55	0.75	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	2.42	HFO	0.05	LFO	-0.67	0.50	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	2.42	HFO	0.05	LFO	-0.94	0.25	4-S, Wärtsilä Vasa 4R32 LN	
(43)	FSN	2.42	HFO	0.05	LFO	-0.88	0.10	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	0.89	HFO	0.05	LFO	1.36	1.00	4-S, Wärtsilä Vasa 4R32 LN	

(43)	EC	0.89	HFO	0.05	LFO	2.66	0.75	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	0.89	HFO	0.05	LFO	1.35	0.50	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	0.89	HFO	0.05	LFO	-0.15	0.25	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	0.89	HFO	0.05	LFO	-0.17	0.10	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	2.42	HFO	0.05	LFO	0.86	1.00	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	2.42	HFO	0.05	LFO	0.34	0.75	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	2.42	HFO	0.05	LFO	-0.19	0.50	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	2.42	HFO	0.05	LFO	-0.41	0.25	4-S, Wärtsilä Vasa 4R32 LN	
(43)	EC	2.42	HFO	0.05	LFO	-0.44	0.10	4-S, Wärtsilä Vasa 4R32 LN	
(90)	FSN	0.83	HFO	0.1	LFO	-0.69	1.00	4-S, MSD, Propulsion Mode	
(90)	FSN	0.83	HFO	0.1	LFO	-0.84	0.75	4-S, MSD, Propulsion Mode	
(90)	FSN	0.83	HFO	0.1	LFO	0.60	0.50	4-S, MSD, Propulsion Mode	
(90)	FSN	0.83	HFO	0.1	LFO	0.01	0.25	4-S, MSD, Propulsion Mode	
(90)	FSN	0.83	HFO	0.1	LFO	0.00	1.00	4-S, MSD, Generator Mode	
(90)	FSN	0.83	HFO	0.1	LFO	0.26	0.75	4-S, MSD, Generator Mode	
(90)	FSN	0.83	HFO	0.1	LFO	0.36	0.50	4-S, MSD, Generator Mode	
(90)	FSN	0.83	HFO	0.1	LFO	0.06	0.25	4-S, MSD, Generator Mode	
(25)	EC	2.70	HFO	0.001	ULSD	1.80	0.75	4-S, MSD, Test Bed	***Data flagged for this reference*** *"The fuel injection nozzle was designed for operation with a heavy fuel oil, and therefore, the spray characteristics are not optimal for distillate oils"*
(25)	EC	2.70	HFO	0.001	ULSD	1.57	0.50	4-S, MSD, Test Bed	
(25)	EC	2.70	HFO	0.001	ULSD	-0.80	0.25	4-S, MSD, Test Bed	
(25)	EC	2.70	HFO	0.001	ULSD	-0.98	0.10	4-S, MSD, Test Bed	
(91)	BC	1.60	HFO	0.001	ULSD	-0.26	0.50	4-S, MSD, Test bed	*"Statistically Insignificant". Average load*
(91)	BC	1.60	HFO	0.001	ULSD	0.40	1.00	4-S, MSD, Test bed	
(91)	BC	1.60	HFO	0.001	ULSD	0.30	0.75	4-S, MSD, Test bed	
(91)	BC	1.60	HFO	0.001	ULSD	-1.20	0.50	4-S, MSD, Test bed	
(91)	BC	1.60	HFO	0.001	ULSD	-1.80	0.25	4-S, MSD, Test bed	
(26)	BC	0.01	LS HFO	0.005	MGO	-0.60	1.00	2-S, MSD, In Service	
(26)	BC	0.01	LS HFO	0.005	MGO	0.00	0.75	2-S, MSD, In Service	
(26)	BC	0.01	LS HFO	0.005	MGO	0.00	0.50	2-S, MSD, In Service	
(26)	BC	0.01	LS HFO	0.005	MGO	0.25	0.25	2-S, MSD, In Service	
(26)	BC	0.01	LS HFO	0.005	MGO	-0.50	0.10	2-S, MSD, In Service	
(27)	EC	1.00	HFO	0.0008	LFO	-0.63	0.75	4-S, MSD (Wärtsilä Vasa 4R32)	*Authors suggest that results are incorrect due to engine tuning and measurement bias. Also suggest that if results are correct that it may be the difference in HFO fuel properties and blending that lead to*

									different BC emissions.
(92)	EC	1.60	HFO	0.0008	ULSD	-0.07	0.50	4-S, MSD, Test Bed	*"Statistically Insignificant". Average load*
(93)	EC	1.00	HFO	0.1	MGO	-0.65	0.50	4-S, MSD, In Service	*Average Load*
(93)	EC	0.50	HFO	0.1	MGO	-0.17	0.50	4-S, MSD, In Service	*Average Load*
(28)	EC	0.48	HFO	0.0092	LS-resid	0.00	0.85	2-S, SSD, In Service	*Low sulphur fuel BC emissions were presented with ranges that straddled the single HFO BC emission data point.*
(94)	EC	2.50	HFO	0.1	Resid Blend	0.66	0.75	4-S, MSD (Wärtsilä Vasa 4R32)	
(94)	EC	2.50	HFO	0.1	Resid Blend	0.1	0.25	4-S, MSD (Wärtsilä Vasa 4R32)	
(29)	EC	0.90	HFO	0.3	MGO	-0.67	0.60	2-S, MAN B&W ML0241	
(29)	EC	0.90	HFO	0.3	MGO	-0.20	0.40	2-S, MAN B&W ML0241	
(29)	EC	0.90	HFO	0.3	MGO	0.38	0.20	2-S, MAN B&W ML0241	
(29)	EC	0.90	HFO	0.3	MGO	-0.18	0.10	2-S, MAN B&W ML0241	
(29)	EC	0.10	LS HFO	0.1	MGO	-0.55	1.00	2-S, MAN B&W 6L48	
(29)	EC	0.10	LS HFO	0.0	MGO	0.00	0.75	2-S, MAN B&W 6L48	
(29)	EC	0.10	LS HFO	0.1	MGO	0.00	0.50	2-S, MAN B&W 6L48	
(29)	EC	0.10	LS HFO	0.1	MGO	0.00	0.25	2-S, MAN B&W 6L48	
(29)	EC	0.10	LS HFO	0.1	MGO	0.05	0.10	2-S, MAN B&W 6L48	
(29)	EC	2.40	HFO	0.17	MGO	-0.61	0.25	2-S, Hyundai B&W 11k98ME7	
(44)	EC	2.29	HFO	0.8	MDO	-0.35	0.75	2-S, MAN B&W 6L50MC	
(44)	EC	2.29	HFO	0.8	MDO	-0.75	0.50	2-S, MAN B&W 6L50MC	
(44)	EC	2.29	HFO	0.8	MDO	-0.36	0.25	2-S, MAN B&W 6L50MC	
(30)	FSN	>0. 75	HFO	<0.1	MDO	-0.62	1.00	4-S, SSD, Various	*Average of numerous experiments on a variety of engines.*
(30)	FSN	>0. 75	HFO	<0.1	MDO	-0.41	0.75	4-S, SSD, Various	
(30)	FSN	>0. 75	HFO	<0.1	MDO	-0.30	0.50	4-S, SSD, Various	
(30)	FSN	>0. 75	HFO	<0.1	MDO	-0.71	0.25	4-S, SSD, Various	
(30)	FSN	2.29	HFO	0.08	MDO	-0.63	1.00	2-S, SSD, Various	
(30)	FSN	2.29	HFO	0.08	MDO	-0.79	0.75	2-S, SSD, Various	
(30)	FSN	2.29	HFO	0.08	MDO	-0.76	0.50	2-S, SSD, Various	
(30)	FSN	2.29	HFO	0.08	MDO	-0.76	0.25	2-S, SSD, Various	

2.12 Post 2020 – 0.5% Global Fuel Sulphur Cap

Some subtle shifts in BC abatement potential may result from the shift to the 0.5% fuel sulphur cap mandated for 2020 by the IMO.

- Development of DPF technology will only need to advance to a level to be able to operate on 0.5% fuel sulphur, rather than sulphur levels in excess of 2%.

- Sea water scrubbing technology appears to utilize the hygroscopic nature of sulphuric acid emissions coating BC to remove a greater fraction of BC than for low sulphur fuel. The 2012 report showed 20% to 60% less BC removal for lower sulphur fuel.

- BC reductions of 33% will likely result from a shift from residual to distillate fuels. Blending of HFO and low sulphur residual fuels to produce a 0.5% sulphur compliant fuel will likely not lead to BC emissions reductions, as suggested for a switch from HFO to distillates. The results from section 2.7 and 2.11 suggest that residual blending will have a variable effect on BC emissions and likely will lead to no net change or increases in BC emissions.

3 Summary

Since the 2012 BC abatement technology report (1) additional BC emissions measurements have been reported for electrostatic precipitators, diesel particulate filters, sea water scrubbers and fuel switching (HFO-distillate, HFO-biodiesel). Abatement potential remains unchanged for all technologies except HFO-distillate fuel switch and electrostatic precipitators. Technology maturity has advanced for Water-in-Fuel-Emulsion and diesel particulate filters. Abatement potential and technology maturity remain unchanged since the 2012 report.

Many new studies on the BC emissions changes with a switch from HFO to distillate fuels were available. It was identified that the BC emission potential of different fuels is a complicated mix of fuel and engine properties and more attention must be paid to these parameters to provide higher resolution for correlations between BC emissions and fuel changes. When re-analysing all of the 2012 report studies and all subsequent studies, a more certain average BC emissions reduction was found. The average and median BC reduction potential was 33% and 34% respectively, indicating that the results are not heavily influenced by major outlying results.

Finally, it is concluded that the most favourable BC abatement options are unchanged from the 2012 report. The six technologies are primarily ranked based on their BC abatement, secondarily ranked by their concomitant abatement of CO_2, SO_X and NO_X and tertiary ranked by technology maturity and availability (see the 2012 report for the ranking calculations). The first section of Table 14 presents these six technologies in order of BC emissions reductions potential. The remaining sections of Table 14 summarize all other abatement options based on "alternative fuel" and "operations/design" categories.

Table 14 Summary of BC abatement options.

BC Reduction Strategies	***BC Reduction***	***Drawbacks***
Top Rated Reduction Strategies From This Review		
LNG	93.5%	New engine investment
DPF – Low Sulphur Fuel	≥99%	Economic Incentives
DPF – High Sulphur Fuel	85%	Technology Maturity
WiFE	70%	Technology maturity
Scrubbers – High Sulphur Fuel	45%	Retrofit + Cost
Scrubbers - Low Sulphur Fuel	37.5%	Retrofit + Cost
HFO – Distillate	33%	Increased fuel costs
Slow Steaming – De-Rating	15%	Complex fleet dynamics
Alternative Fuel Strategies		
Biodiesel – 100%	50-75%	
Biodiesel Blend – 20%	10-30%	
Methanol – DME	97%	

Nuclear	95%	
Engine Options		
Slide Valves	10 – 50%	
Exhaust Treatment		
Electrostatic Precipitators	10 – 90%	
Selective Catalytic Reduction	0 – 30%	
Operational/Design Strategies		
EEDI Achieved with SEEMP and following design strategies:	10%/20%/30%	For newbuild ships after 2015/2020/2025
Ballast Water and Trim	1-5%	
Propeller Optimization	3-20%	
Construction Weight	5%	
Air Lubrication	3.5-15%	
Aerodynamics	3-4%	
Hull Coatings	2-9%	
Hull Cleaning	3-10%	
Wind – Flettner Rotors	3.6-12.4%	
Solar	5-17%	
Weather Routing	2-10%	
Autopilot Upgrades	0.5-4%	

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