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**MSc Thesis Project: Liquefied Natural Gas (LNG) as a Marine
Fuel and Impact on Energy Efficiency Design Index (EEDI)**

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To my Family

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Acronyms

A/E Auxiliary Engine

BOG Boil Off Gas

DNV-GL Der Norske Veritas – Germanischer Lloyd

ECA Emission Controlled Areas

EEDI Energy Efficiency Design Index

EIAPP Engine International Air Pollution Prevention

GHG Greenhouse Gases

HFO Heavy Fuel Oil

IACS International Association of Classification Societies

IGF International Code for Gas fuelled ships

IMO International Maritime Organization

LNG Liquefied Natural Gas

MARPOL International Convention for Prevention of Pollution at Sea

MCR Maximum Continuous Rating

SMCR Specified Maximum Continuous Rating

MDO Marine Diesel Oil

MGO Marine Gas Oil

M/E Main Engine

MEPC Marine Environment Protection Committee

PM Particulate Matter

PTI Power Take In

PTO Power Take Off

RPM Revolutions Per Minute

SFC Specific Fuel Consumption

SFOC Specific Fuel Oil Consumption

LRM Light Running Margin

BSR Barred Speed Range

I. Introduction and Aims of the Project

Around 90% of global trade is carried by sea, as the most economical and fuel efficient mode of cargo transportation. The total trade volume is increasing throughout the last century for the same reason and also the capacity of the vessels is coming bigger and bigger the last 20 years. On the other hand according to the Third Green House Gas study by the International Maritime Organization (IMO) in 2014, ships engaged in international trade in 1996 contributed about 1.8% of the total world's CO₂ emissions, which is approximated as 2.7% in 2007 and 2.2% in 2012. Given the present trend, this percentage could climb up two or two and a half times than it is today, by 2050.

In order to control this CO₂ emission from shipping, IMO has developed the first ever global CO₂ reduction index in the world, known as 'EEDI', Energy Efficiency Design Index. The purpose of the EEDI is to establish the minimum efficiency of new ships depending on ship type and size, provide a fair basis for comparison and to stipulate the development of more efficient ships in general. The basic formulation of EEDI is based on the ratio of total CO₂ emissions per ton-mile. As produced CO₂ depends on fuel consumption and fuel consumption then depends on the total power requirements of the vessel, eventually this EEDI formulation has certain impact on ship design parameters and hydrodynamics.

In this MSc Thesis, except the history and the details of the EEDI, a case study vessel (Aframax Tanker) is investigated in regards to the attained EEDI value and its relevance to the reference line. This vessel is a LNG fuelled vessel and the study will present:

- How this type of fuel affects the EEDI calculation formula
- Which are the advantages and the disadvantages of the LNG application onboard
- Which are the modification including hull, machinery and outfitting that you have to take into consideration
- Which are the other Eco-design applications onboard with examples in order to reduce the fuel oil consumption and also the EEDI
- Which is the modification cost and the payback period based on a real operation profile in Baltic Sea-ECA Area
- An alternative calculation of the EEDI based on a real operation profile and speed

II. Global Emissions

A. Greenhouse gases and their effect

Greenhouse gases (GHG) are gases located in the earth's atmosphere. They are responsible for Earth's habitable environment. Without them, Earth's surface would be subject to the sun's unfiltered radiation, creating extreme temperature conditions during daytime and night time alike.

Fortunately their existence acts as a partial blanket for the long wave radiation coming from earth's surface. This blanketing is known as the natural greenhouse effect. This is accomplished by their ability to absorb and re-emit sun radiation within the thermal infrared range. The most abundant greenhouse gases in Earth's atmosphere are:

- Water Vapour (H_2O)
- Carbon Dioxide (CO_2)
- Methane (CH_4)
- Nitrous Oxide (N_2O)
- Ozone (O_3)
- CFCs[27]

In order to understand the mechanics of greenhouse effect, on average, the energy received at the top of the Earth's atmosphere amounts to 175 Petawatts (PW) of which 31% is reflected by the clouds and from the surface. The rest 120 (PW) is absorbed by the atmosphere, land, ocean.[33] To Balance the absorbed incoming energy Earth must radiate the same amount of energy back to space. Because it is much colder than the sun, it radiates at much longer wavelengths, primarily in the infrared part of the spectrum. Much of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere and reradiated back to earth. This is re-radiation, which is similar to the greenhouses used for agricultural purposes, is called the greenhouse effect. (Figure 1).[27]

Not all greenhouse gases have the same contribution to the greenhouse effect. On clear skies it amounts for ~60% from water vapour (H_2O), ~25% from carbon dioxide (CO_2), ~8% from ozone (O_3) and the rest from all the remaining greenhouse gases. Clouds have a hand in greenhouse effect, but this phenomenon is not examined in this occasion.[33]

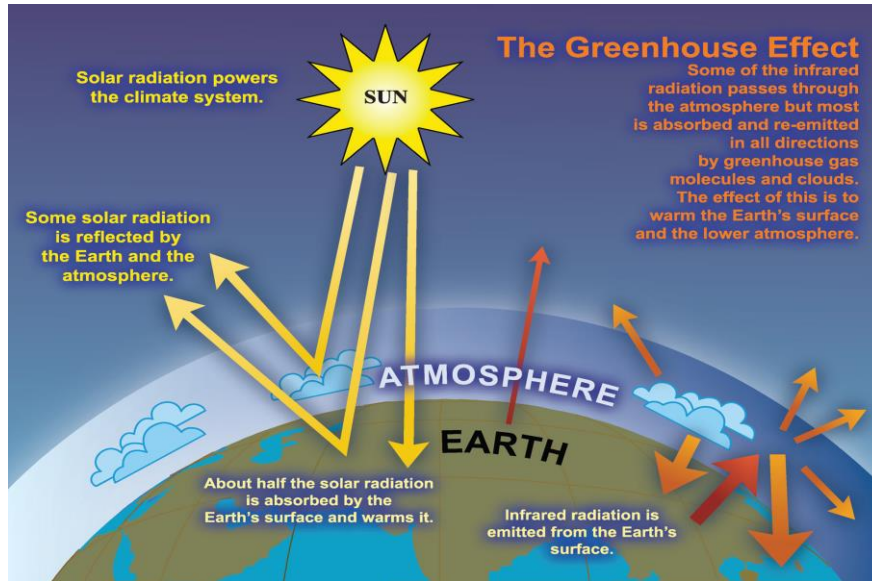


Figure 1 An idealised model of the natural greenhouse effect. [27]

This natural procedure ensures steady temperatures across Earth of average 15 degrees. Unfortunately over the last few years, when we are referring to greenhouse effect we are not referring to this natural procedure but to an infamous version of this, which has occurred due to manmade atmospheric pollution. This pollution has resulted to a rise of the global temperature, a phenomenon known as Global Warming.

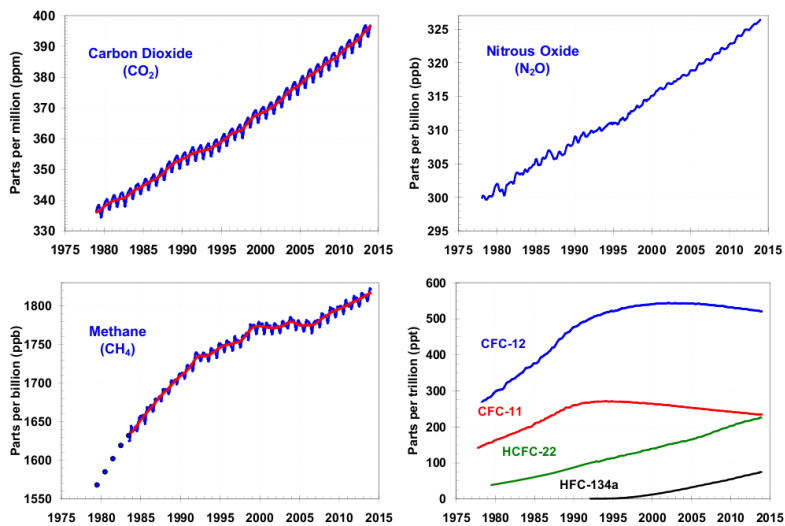


Figure 2 Greenhouse Gases Observations [27]

There are several components of the climate system, which affect atmospheric concentrations of greenhouse gases. Over the last century, deforestation, population growth and extensive use of fossil fuels have tampered with the balance of such

components, which led to an increase of greenhouse gases concentrations. This trend can be identified on Figure 2, and all gasses are measured in part per million/billion (ppm/b).

The Intergovernmental Panel on Climate Change (IPCC) suggests that a constant concentration of CO₂ alone at 550 ppm would lead to an average increase in Earth's temperature of ~3°C. Given the current CO₂ trajectory and in order to stabilize atmospheric CO₂ for this century, anthropogenic CO₂ emissions need to be reduced by 80%. [34]

Taking into account the aforementioned and CO₂ contributions to greenhouse effect, most greenhouse gasses emission reduction legislation is focused on the reduction of CO₂.

B. International Environmental Organizations

The first warnings regarding the greenhouse gases and their side effects came from the scientific community in the '60s. A prominent scientist amongst them, Roger Revelle, was one of the first to collect data of CO₂ concentrations and almost foresaw that the global post-World-War II economic expansion, driven by explosive population growth and fuelled mainly by coal and oil, was likely to produce an unprecedented and dangerous increase in the amount of CO₂ in the Earth's atmosphere. [35]

It took many years for the international community take seriously these heeds. Only in June 1988, United Nations Environment Programme (UNEP), an agency of the United Nations (UN), established the Intergovernmental Panel on Climate Change (IPCC). This panel in 1990 compiled their first assessment which confirmed, what independent scientists have been claiming all along. That is, the correlation between the greenhouse gases and the rise of the mean global temperature. These conclusions have led to the creation of the United Nation Framework Convention on Climate Change (UNFCCC), which was signed from all UN country members on the 1992 UN conference in Rio de Janeiro.

Following the creation of UNFCCC was the Kyoto Protocol. This protocol is an international agreement linked to the UNFCCC, which commits its parties by setting internationally binding emissions reduction targets. The Kyoto Protocol was adopted in Kyoto, Japan on 11 December 1997 and entered into force on the 16 February 2005. [36]

Except from binding emissions targets, the Kyoto Protocol also had conditions relevant to the reduction of ships' greenhouse gases emissions. In this respect the

International Maritime Organization (IMO), over the years, in collaboration with UNFCCC in working towards that goal.

C. Maritime Greenhouse Gases Emissions

A well-known study, in regards to the maritime greenhouse gases emissions, was conducted from IMO and it is known as the *Third GHG Study 2014*. According to this study the dominating source of emissions from shipping is originated mainly from ship's engines (Main and Auxiliary). Carbon dioxide (CO₂) is the most important GHG emitted from the exhaust gases from the aforementioned engines. Others emissions are considered insignificant and therefore not taken into account. [56]

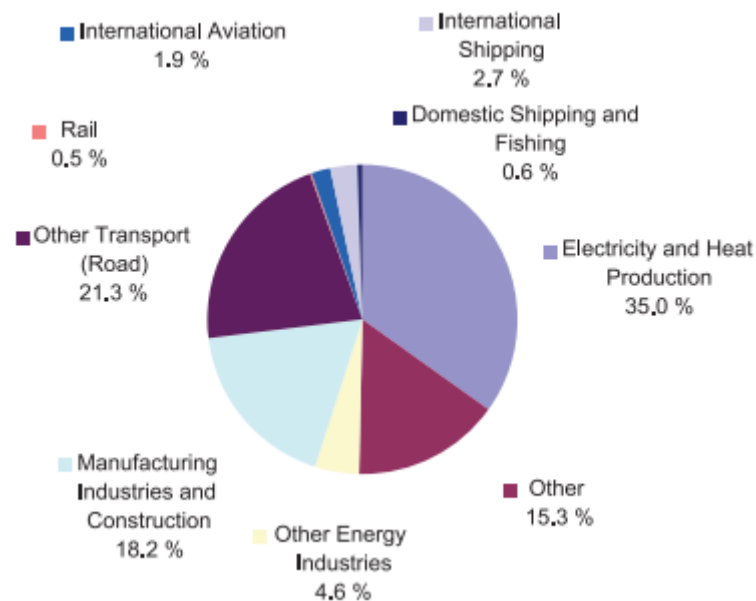


Figure 3 Emissions of CO₂ from shipping compared with global emissions (2007) [26]

In general, ships emissions are calculated by quantifying fuel consumption and thereafter multiplying that consumption by an emission factor. Furthermore the calculated emissions could be geographically distributed based on the available data of ship traffic.[56]

Seaborne transportation has been shown to be energy efficient in comparison to other modes of transportation, considering the emission in comparison to the generated work as it can be identified on Figure 4. Furthermore the total maritime CO₂ emissions are only accounting for 2.2% of the global emissions.

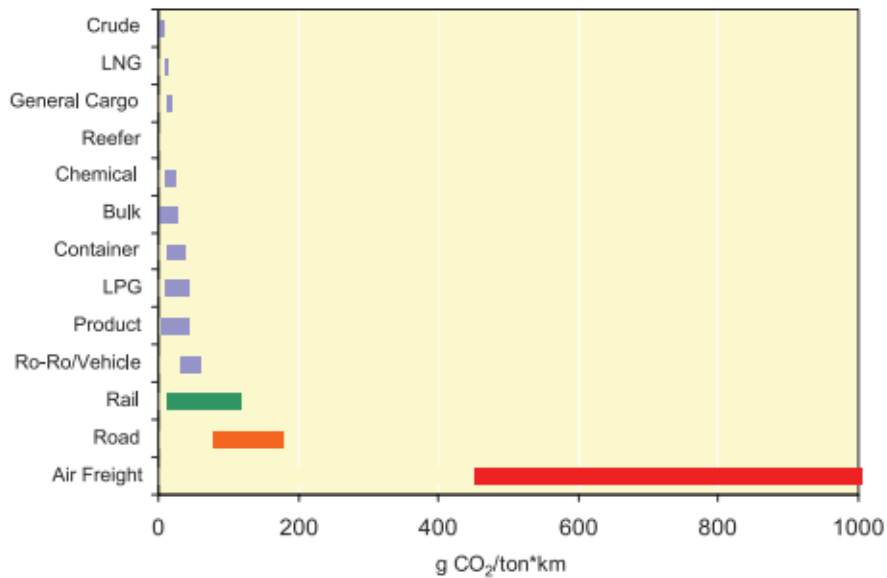


Figure 4 Typical range of CO₂ efficiencies compared to rail, road and air freight. [26]

Over the period 2007–2012, average annual fuel consumption ranged between approximately 247 million and 325 million tonnes of fuel consumed by all ships within this study, reflecting top-down and bottom-up methods respectively, depending on whether consumption was defined as fuel allocated to international voyages (top-down) or fuel used by ships engaged in international shipping (bottom-up), respectively. Correlated with fuel consumption, CO₂ emissions from shipping are estimated to range between approximately 739 million and 795 million tonnes per year in top-down results, and to range between approximately 915 million and 1135 million tonnes per year in bottom-up results.

This study estimates multi-year (2007–2012) average annual totals of 20.9 million and 11.3 million tonnes for NO_x (as NO₂) and SO_x (as SO₂) from all shipping. These results show that ships in 2050 will account for significantly higher percentage of the world’s anthropogenic CO₂ emission compared to the 2.2% today.[56]

In order to reduce CO₂ emissions there is a wide range of options. These options mainly depend on increasing the ship’s efficiency and reducing emission by changing ship design and ship operation. An overall assessment of these options can be found on Table 1.

	Saving of CO ₂ /tonne-mile	Combined	Combined
DESIGN (New ships)			
Concept, speed and capability	2% to 50% [†]		
Hull and superstructure	2% to 20%		
Power and propulsion systems	5% to 15%	10% to 50% [†]	
Low-carbon fuels	5% to 15%*		
Renewable energy	1% to 10%		25% to 75% [†]
Exhaust gas CO ₂ reduction	0%		
OPERATION (All ships)			
Fleet management, logistics & incentives	5% to 50% [†]		
Voyage optimization	1% to 10%	10% to 50% [†]	
Energy management	1% to 10%		

* CO₂ equivalent, based on the use of LNG.

† Reductions at this level would require reductions of operational speed.

Table 1 CO₂ Reductions Options[26]

D. Energy Efficient Design Index-EEDI

Under the CO₂ inclining phenomenon, IMO had to primarily reduce current ship's emissions. In order to do so Marine Environment Protection Committee (MEPC), a subcommittee of IMO, has introduced the Energy Efficiency Design Index (EEDI). Basically EEDI is a mathematical formula which represents the cost, in this instance the CO₂ emissions, divided by the gain which is the transportation ability of a ship.

$$EEDI = \frac{CO_2 \text{ emission}}{\text{transport work}}$$

Equation 1 EEDI simplified formula [29]

As explained in the previous chapter, taking under consideration the total gross of greenhouse gases emissions, CO₂ emissions are the only emissions considered for the marine industry. These originated from combustion of fuel on propulsion engines, auxiliary engines and boilers. If energy efficient, mechanical or electrical, technologies are incorporated on board the ship, their effects are deducted from the total CO₂ emissions.[29]

The transportation work is calculated by multiplying the ship's capacity (DWT), as designed, with the ship's design speed measured at the maximum design load condition and at 75% of the rated installed shaft power.[29]

The EEDI, in establishing a minimum energy efficiency requirement for new ships depends on ship type and size, provides a robust mechanism that may be used to

increase the energy efficiency of ships, stepwise, to keep pace with technical developments for many decades to come. It is a non-prescriptive mechanism that allows the choice of which technologies to use in a ship design to the stakeholders, as long as the required energy-efficiency level is attained, enabling the most cost-efficient solutions to be used.

Therefore, the primary goal of EEDI is to minimize the emitted CO₂ emissions, by improving the energy efficiency of the new vessels. For this reason in every new ship construction the EEDI is calculated and should have less than a reference point, or otherwise called Baseline (Figure 5). This Baseline represents the mean efficiency level of same type of ships build between 1999 and 2009.

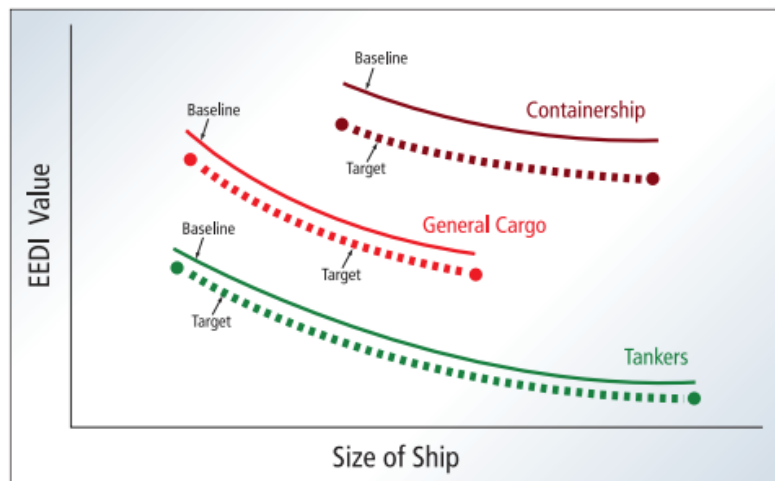


Figure 5 Examples of different ship type Baselines [29]

Based on the aforementioned baselines, IMO has set out a percentage decrease depended on ship type and size. The reduction of the EEDI value is time related and targets to a total of 30% reduction from the baseline value, which will be accomplished until 2025. More specifically new ships that are to be built between the 1st phase (2015-2019) of the project aim for 10% reduction from the baseline value, the 2nd phase (2020-2024) of the project aim for 20% reduction from the baseline and finally the 3rd phase (2025-) aim for 30% reduction from the EEDI baseline.

Reduction factors (in percentage) for the EEDI relative to the reference line for each ship type.					
	Size	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 onwards
Bulk Carriers	>20,000 Dwt	0%	10%	20%	30%
	10-20,000 Dwt	n/a	0-10%*	0-20%*	0-30%*
Gas tankers	>10,000 Dwt	0%	10%	20%	30%
	2-10,000 Dwt	n/a	0-10%*	0-20%*	0-30%*
Tanker and combination carriers	>20,000 Dwt	0%	10%	20%	30%
	4-20,000 Dwt	n/a	0-10%*	0-20%*	0-30%*
Container ships	>15,000 Dwt	0%	10%	20%	30%
	10-15,000 Dwt	n/a	0-10%*	0-20%*	0-30%*
General Cargo ships	>15,000 Dwt	0%	10%	15%	30%
	3-15,000 Dwt	n/a	0-10%*	0-15%*	0-30%*
Refrigerated cargo carriers	>5,000 Dwt	0%	10%	15%	30%
	3-5,000 Dwt	n/a	0-10%*	0-15%*	0-30%*

* The reduction factor is to be linearly interpolated between the two values depending on the vessel size. The lower value of the reduction factor is to be applied to the smaller ship size.

Table 2 Reduction Factors for the EEDI relative to the EEDI Reference line [29]

To sum up EEDI is trying to do the following:

- To demand a minimum level of efficiency.
- As the years progress, to increase the efficiency required.
- To motivate a continuous technological innovation to all the factors that influences the index.
- To separate the technical and designing tools from the operational and commercial tools for the reduction of the EEDI.
- And finally to make possible the comparison of the energy efficiency of different vessels of same type and size.

Therefore it can be claimed that EEDI is a guidance based on efficiency, which allows the designer or the shipyard to choose the most desired ways in order to accomplish their goals. In other words, they are free to choose between the most cost effective techniques, in order to achieve EEDI compliance and also to meet other environmental regulation coming into force in the future as shown in the below figure 6 such as NOx Tier III, Ballast Water Treatment and Fuel oil sulphur limit reduction-SOx.

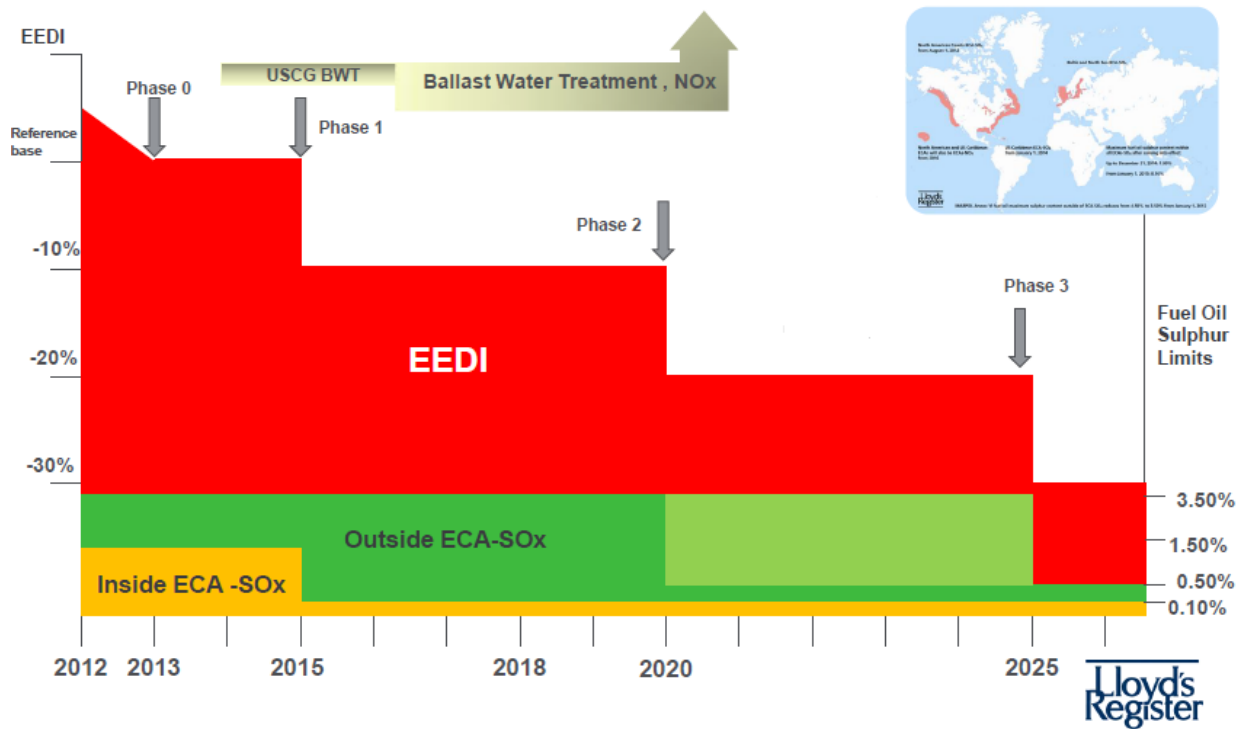


Figure 6 Environmental regulations coming into force [14]

III. EEDI IMO Legislation / Historical development.

After the Kyoto Protocol in 1997 the Secretariat of the International Maritime Organization (IMO) and the UNFCCC have frequently met in order to evaluate and reduce greenhouse gases emissions from the marine industry. Even though many studies had been conducted, a mention of an index to measure the CO₂ emissions hadn't been made until the 49th assembly of the Marine Environmental Protection Committee (MEPC) of IMO on August 2003. More specifically on the ANNEX 7, it stated that the “*IMO should take the lead in developing GHG limitation and reduction strategies and mechanisms for international shipping and that in doing so should cooperate with the Conference of the Parties to the UNFCCC*”.

Furthermore, it “*urges the MEPC to identify and develop the mechanism or mechanisms needed to achieve the limitation or reduction of GHG emissions from international shipping, and in doing so give priority to:*

- *The establishment of a GHG emission baseline;*
- *The development of a methodology to describe the GHG efficiency of a ship expressed as a GHG emission indexing for that ship. In the development of the methodology for **the GHG emission indexing scheme**, the MEPC should recognize that CO₂ is the main greenhouse gas emitted by ships;*
- *The development of Guidelines by which the GHG emission indexing scheme may be applied in practice. The Guidelines are to address such issues as verification; and*
- *The evaluation of technical, operational and market-based solutions;”[37]*

Following that 49th session of MEPC, IMO resolution A.963 (23) validated the aforementioned conclusions of the MEPC. But in order for IMO to actualize an index to reduce greenhouse gases many sessions of MEPC were required. They are summarized in the following sub-chapters.

A. MEPC 52nd Session on 11-15 October 2004

Following the A.963 (23) resolution the committee understands its role and in cooperation with its members will develop a methodology to describe GHG efficiency of a ship and develop guidelines, which may be applied in practice.

In addition some member states drafted preliminary Guidelines (MEPC 52/4/2, MEPC 52/4/9 and MEPC 52/4/5) for CO₂ indexing as a starting point for considerations related to the development of an indexing scheme. This would be a

voluntary mechanism to be used during a trial period. Furthermore it was agreed that “a CO₂ indexing scheme should be simple and easy to apply and should take into consideration matters related to construction and operation of the ship, and market-based incentives”. [38]

B. MEPC 53rd Session on 18-23 July 2005

The 53rd session was signified by the preliminary data acquired from the conducted trials of some member states. Based on this data, a Technical Workshop was held, whose main purpose was to further improve the draft Guidelines on GHG Indexing.

In this respect the committee issued MEPC 53-24 ANNEX 9 which included interim guidelines for ship CO₂ emission. These guidelines were to be used voluntarily from stakeholders during a trial period. Based on them, “when using the CO₂ index as performance indicator, the index should be given a perspective relative to absolute data and trend data:

- *The main indicator may be greenhouse gas emissions from energy use.*
- *Absolute data may be total tonnes of annual CO₂ emissions.*
- *The CO₂ index may represent the normalized data (CO₂ per tonne mile).*
- *Trend data may be the index value compared with previous years.*

Internal performance criteria and targets could be established as a benchmark for the CO₂ index.”[39]

C. MEPC 55th Session on 9-13 October 2006

In continuation of the work conducted by the previous sessions, this session primarily focused on a specific work plan and timetable for the development of the CO₂ index. It also recognized that CO₂ is the main greenhouse gas emitted by ships. The origin of the emitted CO₂ is a combustion by-product from the ship’s engines.

The work plan included further development of the CO₂ indexing scheme, requesting from its members to continue trials according to the interim guidelines issued on the previous session. Furthermore methodology for CO₂ emission baselines was to be considered in terms of efficiency.

D. MEPC 56th Session on 9-13 July 2007

This MEPC session called for an update in the 2000 IMO study on greenhouse gas emissions from ships. It gave out the basic outline that the new study should follow, as well as, a specific timetable. It was agreed that the study should cover the following:

- “Current inventories and future scenarios of emissions of GHGs and relevant substances from international shipping.
- Current and future emission reduction potential of GHGs and other relevant substances.
- Climate impacts of international shipping.”[40]

Furthermore it stated that the updated study should be submitted to the 59th MEPC session no later than 2010.

E. MEPC 57th Session on 31st March – 4th April 2008

At this session a CO₂ indexing formula made its first appearance. This formula was created by the Japanese delegation and was called “the framework for the CO₂ emissions index per unit shipping capacity”. The unit of that index was in CO₂ grams per ton mile and the basic format of the index formula as proposed from Japan, was as follows:

$$\text{Index} \left[\frac{g}{\text{ton} \times \text{mile}} \right] = \frac{\text{Fuel Consumption} \left[\frac{g}{kWh} \right] \times \text{Output of Main engine} [kW] \times (1 + k_2) \times \text{CO}_2 \text{ conversion} \left[\frac{gCO_2}{gFuel} \right]}{\text{DWT} [ton] \times \text{Maximum Speed} \left[\frac{n.mile}{h} \right] \times k_1}$$

k₁: Coefficient of decrease in propulsion efficiency in actual sea conditions.

K₂: Coefficient of contribution to CO₂ emissions from auxiliary machinery, reflecting output from auxiliary machinery, running time, and effects of limitations on CO₂ emissions from installation of facilities such as energy-conservation equipment.

[Equation 2 First format of CO₂ index as proposed from the Japanese delegation\[41\]](#)

Furthermore the committee proposed the creation of a Working Group on GHG emissions from ships. This Working Group was instructed to develop a CO₂ design index based on a regulatory framework with the following directions:

- *“Effective in contributing to the reduction of total global greenhouse gas emissions;*
- *binding and equally applicable to all flag States in order to avoid evasion;*
- *cost-effective;*
- *able to limit – or at least – effectively minimize competitive distortion;*
- *based on sustainable environmental development without penalizing global trade and growth;*
- *based on a goal-based approach and not prescribe specific methods;*
- *supportive of promoting and facilitating technical innovation and R&D in the entire shipping sector;*
- *accommodating to leading technologies in the field of energy efficiency;and*
- *practical, transparent, fraud free and easy to administer”[41]*

The findings of the Working Group were to be delivered by the following MEPC session.

F. First Intersessional Meeting of IMO’s Working Group on GHG emissions from ships on June 2008

The first working group on GHG emissions was conducted in order to elaborate and further evolve the 57th MEPC session conclusions. The meeting was attended by more than 210 delegates from all over the world.

This meeting was tasked with the development of a technical basis for reduction mechanisms that may form part of a future IMO regime to control GHG emissions from the international shipping. Their findings were reported to the 58th MEPC session. The meeting was split into four different subsections.

- Mandatory CO₂ Design Index
- Interim CO₂ operational index
- Best practices for voluntary implementation
- Economic instruments with GHG-reduction potential

In this respect after considering all delegations propositions and remarks in regards to the subject, the meeting further developed the mathematical formula that would be used for the calculation of the CO₂ design index. This index would contain a minimum level of fuel efficiency related to a baseline. As reference, the baseline will use the fuel efficiency of ships delivered between 1995 and 2005. This level though, would be reconsidered on the following MEPC sessions.[43]

Furthermore member states and observers were advised to test the robustness of the proposed draft formula by conducting simulations. The results of those tests would be submitted for review on the following MEPC session.

Regarding the index formula, the Danish delegation proposed the following:

$$\text{Attained design CO}_2 \text{ index} = \frac{\prod_{j=1}^M f_j \sum_{i=1}^{nME} C_{F ME_i} SFC_{ME_i} P_{ME_i} + \prod_{k=1}^L f_k \sum_{i=1}^{NAE} C_{F AE_i} SFC_{AE_i} P_{AE_i}}{\text{Capacity } V_{ref}}$$

Equation 3 Format of CO₂ index as proposed from the Danish delegation [44]

Even though both formulas proposed by the Japanese and Danish delegation were viable, it was agreed that the best solution would be a unified proposal with elements from both formulae. This would include the weather factor, f_w , as it was originally suggested from the Japanese delegation in the previous session.

$$\text{Attained design CO}_2 \text{ index} = \frac{\left(\prod_{j=1}^M f_j \right) \left(\sum_{i=1}^{nME} C_{F ME_i} SFC_{ME_i} P_{ME_i} \right) + \left(\prod_{k=1}^L f_k \right) \left(\sum_{i=1}^{NAE} C_{F AE_i} SFC_{AE_i} P_{AE_i} \right)}{\text{Capacity } V_{ref} \times f_w}$$

Equation 4 Format of CO₂ index as proposed from both delegations.[44]

In this respect the formula displayed on Equation 4 was the final formula proposed by this Intersessional meeting.

G. MEPC 58th Session on 6-10 October 2008

A significant number of amendment proposals by member states, forced this MEPC session to consider whether the future IMO GHG regime would be binding and equally applicable to all flag States or not.

Towards that direction many delegations spoke in favour of the common but differentiated responsibility (CBDR) principle under the UNFCCC and its Kyoto Protocol. They considered that the mandatory regime should be applicable only to countries listed in Annex I of the UNFCCC only.

In contrast, the opposition, stated that the GHG IMO regulatory framework should be applicable to all ships, irrespective of the flag they fly. Their main argument was

that, 75% of the world's merchant fleet fly the flag of countries not listed in Annex I to the UNFCCC. Therefore any regulatory regime would become meaningless and ineffective for the purpose of combating climate change.[45]

Furthermore, on this session, the United States delegation proposed an alteration to the index formula introduced in the First Intercessional Meeting of IMO's Working Group on GHG emissions. This change would consider also the factor of, innovative efficiency reduction technologies, modifying the index as follows:

$$\text{Attained design CO}_2 \text{ index} = \frac{\left(\sum_{i=1}^{NME} C_{FME_i} SFC_{ME_i} P_{ME_i} \right) + \left(\sum_{i=1}^{NAE} C_{FAE_i} SFC_{AE_i} P_{AE_i} \right) - \left(\sum_{eff=1}^{Neff} f_{eff} C_{F_{eff}} SFC_{eff} P_{eff} \right)}{\text{Capacity } V_{ref} \times f_w}$$

Equation 5 Format of CO₂ index as proposed from the United States delegation.[22]

Moreover, in concurring with the Brazilian proposal, the term “Design CO₂ Index” would change to the term known until today as “Energy Efficiency Design Index” or EEDI. In addition, the committee agreed to establish another Working Group on GHG instructing it to finalize the Energy Efficiency Design Index, including:

- A method of calculation.
- The regulatory text.
- A verification procedure.
- Any necessary associated guidelines.

H. Second Intercessional Meeting of IMO's Working Group on GHG emissions from ships on March 2009

The second Intercessional GHG working group, as instructed by the 58th MEPC committee, focused further to the implementation and the regulatory conditions of the EEDI and EEDI baselines. Their main concern, as before, was the increase of ships efficiency and the reduction of greenhouse gases from the marine industry.

The working group had to review a large amount of proposal in regards to the scope of implementation of EEDI and matters related to specific type of vessels. The general consensus was that EEDI should be able to “consider” the special circumstances under which some vessels are built and operate.

The main goal was to further evolve EEDI, through the experience already obtained over the last year's voluntary trials. The meeting issued a report with their findings and conclusions to the 59th MEPC session.

I. MEPC 59th Session on 13-17 July 2009

The 59th MEPC session continued working over the findings and conclusions of the second Intercessional GHG working group. The committee attempted to form an interim package of technical and operational measures for the reduction of greenhouse gases emitted from ships.

In regards to the Energy Efficiency Design Index, these interim measures included:

- The interim Guidelines on the method of calculation of the EEDI for new ships. (MEPC.1/Circ.681)
- The interim Guidelines for voluntary verification of EEDI. (MEPC.1/Circ.682) [46]

In addition this session “noted the progress made on EEDI baseline and agreed to invite Member Governments and observers to submit proposals and comments to the next session”. Finally, the EEDI formula was transformed to nearly the form that it is today:

$$EEDI = \frac{\left(\prod_{j=1}^M f_j \right) \left(\sum_{i=1}^{nME} P_{ME(i)} C_{FME(i)} SFC_{ME(i)} \right) + (P_{AE} C_{FAE} SFC_{AE} *) + \left(\left(\prod_{j=1}^M f_j \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} P_{AEeff(i)} \right) C_{FAE} SFC_{AE} \right) - \left(\sum_{i=1}^{neff} f_{eff(i)} P_{AEeff(i)} C_{FME} SFC_{ME} \right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

* If part of the Normal Maximum Sea Load is provided by shaft generators, SFC_{ME} may – for that part of the power – be used instead of SFC_{AE} .

Equation 6 Intermediate form of EEDI

J. MEPC 60th Session on 22-26 July 2010

Previous sessions have described that in order for EEDI to be effective as a greenhouse reducing measure, it should be mandatory to all ships, regardless of the flag they fly. In order to achieve that, this session of the committee proposed that EEDI should be part of the MARPOL Annex VI.

This suggestion met great objections from many member states. They opted for a new EEDI regulatory instrument, something which would be time consuming, postponing the whole project at the same time. MARPOL convention is the main international convention covering prevention of pollution of the marine environment from ships. In their view, CO₂ was not technically a “pollutant” and had no place in the MARPOL convention. Furthermore, maturity of the measures were considered, as well as some concerns related to EEDI application on specific ship types.

In order to solve all disagreements, the committee established a “*Working Group on Energy Efficiency for Ships*”. In regards to EEDI, this working group agreed on the following:

- The data to be used for the calculation of the EEDI baselines would be the existing database of existing ships in the Lloyd’s Register Fairplay database.
- To include EEDI as part to the MARPOL Annex VI. In this context, it reviewed and developed an interim text towards that direction, stating:
 - “*coverage of ship types and ship sizes for the EEDI;*
 - *target year for phases 1, 2 and 3 for the EEDI;*
 - *establishment of EEDI baseline(s);*
 - *reduction rate X from the baseline for phase 1 for the EEDI; and*
 - *coverage of ship sizes and implementation time for the SEEMP;”*
- The need for EEDI verification guidelines to support the regulatory framework.

Many delegations could not agree to some of the above and reserved their positions. [46]

K. MEPC 61st Session on 27 September – 1 October 2010

In this session, most discussions evolved around the implications of EEDI to the marine industry. More specifically, the apparent impacts of capacity building and speed reduction.

Given that ship capacity is denominator in the EEDI formula fraction, an increased capacity results to smaller EEDI values. This could affect the industry to turn to larger capacity building projects. In case this occurs, relevant capacity national legislations should be amended. Furthermore Maritime administration officers should be trained, to make sure those ships flying their flag, or foreign ships entering their port comply with the new requirements. Nevertheless, it stated that “*before the finalization of the EEDI regime an accurate assessment of the implications is not possible*”. [47]

Speed is another factor of the EEDI formula. It affects the index in a similar way as capacity. Many members believed that if a vessel travels under a certain speed, it would be unsafe. Therefore an IACS representative reasoned that it would be wise to provide a safeguard for such an eventuality.

Finally guidelines were issued in regards to:

- EEDI calculations.
- Survey and certification of EEDI.
- Draft guidelines for calculation of reference lines for use with the EEDI.[48]

L. MEPC 62nd Session on 11-15 July 2011

This MEPC session with resolution MEPC.203(62) amended the MARPOL ANNEX VI to include also the Energy Efficiency Design Index. In this respect making the EEDI regulations obligatory for all ships, independently of the flag they fly.

Resolution MEPC.203(62) gave specific guidelines as to:

- Survey, certification and means of control.
- Regulations on energy efficiency for ships.
- And finally the general form of the Certificate.

The introduction date of the regulations was set to the 1st of January 2013, and it had to apply to all ships of 400 gross tonnage and above. Furthermore a table was produced with the exact dates corresponding to all vessel types and capacities and the reduction factors for the EEDI relative to the EEDI reference line. (Table 2)[48]

As per previous sessions, many member states had their reservations in regard to these regulations. In order for the committee to satisfy them, it included a clause where the administration may waive the requirements of this regulation, until the 1st of January 2017. [49]

M. MEPC 63rd Session on 27 February – 2 March 2013.

Following to the resolution MEPC.203(62) of the 62nd MEPC session, this session was marked by the issuance of two following additional resolutions:

- “*2012 Guidelines on survey and certification of the EEDI.*” (Resolution MEPC.214(63))
- “*Guidelines for calculation of reference lines for use with the EEDI.*” (Resolution MEPC.215(63)) [50]

The first resolution would act as guidelines to interested parties (Administrations or organizations authorized by it) to conduct surveys in order to verify accordance with EEDI regulations. The second resolution would assist the same individuals to measure an average value for a defined group of ships. Based on that value, the verifier would be able to measure whether a specific vessel has reached the required score.

Additionally a specific schedule was drafted, in regards to the EEDI framework for the following MEPC sessions.

N. The following of the MEPC sessions until today.

The following MEPC sessions (64-68) proceeded as per drafted schedule in the previous session. The committee continued on the same pattern in regards to regulation considering mainly specific vessels that could be covered by the existing EEDI regulatory framework and making amendments as required.

In this respect, vessels in need of additional action could be considered vessels having alternative to mainstream propulsion systems or vessels that are not, until then, covered by the reference lines and reduction factors. Examples of such vessels could be turbine propulsion vessels or electric propulsion vessels for the former and passenger ships or Ro-Ro cargo ships for the latter.

Additionally the committee had to consider CO₂ reduction technologies which by the 63rd session were not yet fully materialized. Hence, no data was available at the time for investigation. Finally safety issues created by the new regulatory regime would have to be dealt with. An example could be the possibility of installation of an optimum propulsion system in terms of efficiency, but with insufficient power able to manoeuvre the vessel under adverse weather or other conditions.

Important resolutions in regards to the above:

- *Amendments to the 2012 guidelines on the method of calculation of the attained EEDI for new ships, (Resolution MEPC.224(64))[51]*
- *2013 Guidelines for calculation of reference lines for use with EEDI, (Resolution MEPC.231(65))*
- *2013 Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions, (Resolution MEPC.232(65))*
- *2013 Guidelines for calculation of reference lines for use with EEDI for cruise passenger ships having non-conventional propulsion, (Resolution MEPC.233(65))*
- *Amendments to 2012 guidelines on survey and certification of the EEDI, (Resolution MEPC.234(65))[52]*
- *2014 Guidelines on the method of calculation of the attained EEDI for new ships, (Resolution MEPC.245(66))[53]*

According to schedule all the above will have to be finalized until the 65th session and some of them to be adopted by the 66th MEPC session.

Finally on the 66th MEPC session with resolution MEPC.245(66) the EEDI formula took its final form. It was almost the same as the one proposed on the 59th MEPC session, except from the introduction of additional factors. These were, the cubic capacity correction factor (f_c), and the factor for general cargo ships equipped with cranes and other cargo related gear (f_l). Therefore the EEDI formula was further changed to:

EEDI =

$$\frac{\left(\prod_{j=1}^n f_j \right) \left(\sum_{i=1}^{nME} P_{ME(i)} C_{FME(i)} SFC_{ME(i)} \right) + (P_{AE} C_{FAE} SFC_{AE} *) + \left(\left(\prod_{j=1}^n f_j \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} P_{AEeff(i)} \right) C_{FAE} SFC_{AE} \right) - \left(\sum_{i=1}^{neff} f_{eff(i)} P_{AEeff(i)} C_{FME} SFC_{ME} ** \right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot V_{ref} \cdot f_w}$$

* If part of the Normal Maximum Sea Load is provided by shaft generators, SFC_{ME} may – for that part of the power – be used instead of SFC_{AE} .

** In case of $P_{PTI(i)} > 0$, the average weighted value of $(SFC_{ME} * C_{FME})$ and $(SFC_{AE} * C_{FAE})$ to be used for calculation of P_{eff}

Note: This formula may not be applicable to a ship having diesel-electric propulsion, turbine propulsion or hybrid propulsion system except for cruise passenger ships and LNG carriers.

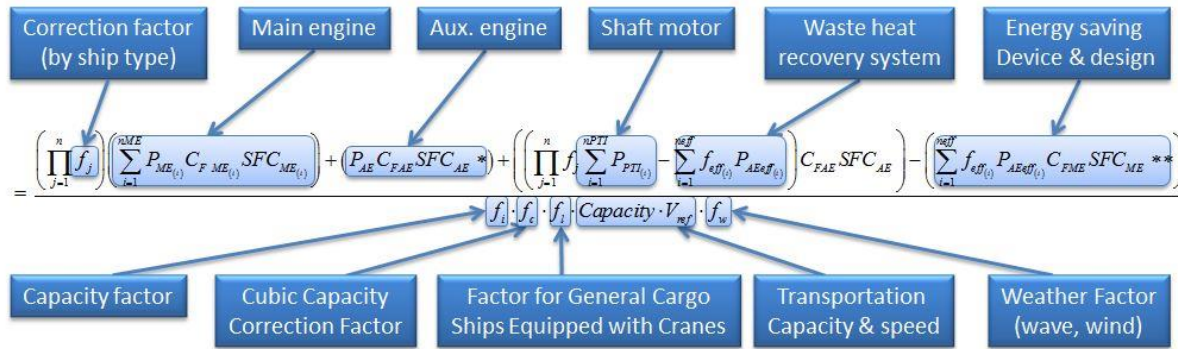
Equation 7 Final EEDI formula [53]

IV. EEDI Formula / Reference lines.

A. EEDI Formula, Description of Calculation Factors

The final Energy Efficiency Design Index (EEDI) formula as derived from the 66th MEPC session is as follows:

$$EEDI = \frac{CO_2 \text{ Emissions}(g / hr)}{DWT \times Speed(ton - knot)} = [g / ton - mile]$$



* If part of the Normal Maximum Sea Load is provided by shaft generators, SFC_{ME} may – for that part of the power – be used instead of SFC_{AE}

** In case of $P_{PTI(i)} > 0$, the average weighted value of $(SFC_{ME} * C_{FME})$ and $(SFC_{AE} * C_{FAE})$ to be used for calculation of P_{eff}

Equation 8 EEDI formula cut down and explained [32]

The EEDI formula, if cut down to its components (Equation 8), each component represents a certain factor or a system. In the following sector a brief summary and explanation of each factor is going to be presented. To avoid continuous referencing the following information has been extracted from “ANNEX 5 2014 Guidelines on the method of calculation of the attained EEDI for new ships, (Resolution MEPC.245(66))”. [32]

a. Conversion Factor (CF_{ME} and CF_{AE})

This is a conversion factor between fuel consumption and CO_2 emission for Main Engine and Aux Engine respectively. In other words, it is used to express the quantity of the emitted CO_2 from a given amount of fuel.

They are dependent on the carbon content of the fuel and their value for the most widely used marine fuels is as follows:

Type of fuel	Reference	Carbon content	C_F (t-CO ₂ /t-Fuel)
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
	Butane	0.8264	3.030
5 Liquefied Natural Gas (LNG)		0.7500	2.750

Table 3 Conversion Factor (CF) Table. [32]

On the EEDI calculation the values to be used are the ones, of the fuel used at the engine trials (Shop test) for the Engine International Air Pollution Prevention (EIAPP) certification.

b. Specific Fuel Consumption (SFC_{ME} and SFC_{AE})

This is the certified specific fuel oil consumption of (g/kWh) for the Main and Auxiliary Engines respectively.

For the calculation of the EEDI the values to be used, are the ones mentioned at the Engine International Air Pollution Prevention (EIAPP) certificate. In case of an unavailable EIAPP certificate then the values to be used are the ones provided by the engine manufacturer.

The general rule is that the SFC_{ME} is calculated at 75% of the Maximum Continuous Rating (MCR) of the Main Engine, and SFC_{AE} is calculated at the 50% of the Maximum Continuous Rating (MCR) of the Auxiliary engine.

c. Power (P_{ME} , P_{AE} , P_{PTO} and P_{PTI})

This is the power of Main Engines (ME), Auxiliary Engines (AE), Shaft Generator (PTO) and Shaft Motor (PTI) respectively.

For the power calculation of each machinery the following guide is to be used:

- P_{ME} is 75% of the Maximum Continuous Rating (MCR) of the Main Engine.
- P_{AE} is empirically calculated equal to:

➤ If the propulsion power is above 10.000 Kw then

$$P_{AE} = (0.025 \times MCR_{AE}) + 250$$

➤ If the propulsion power is below 10.000 Kw then

$$P_{AE} = (0.05 \times MCR_{AE})$$

- In case that shaft generator(s) is installed, P_{PTO} is the 75% of the rated electrical output power of each installed shaft generator.
- In case that motor generator(s) is installed, P_{PTI} is 75% of the rated power consumption of each shaft motor divided by the weighted average efficiency of the generators.

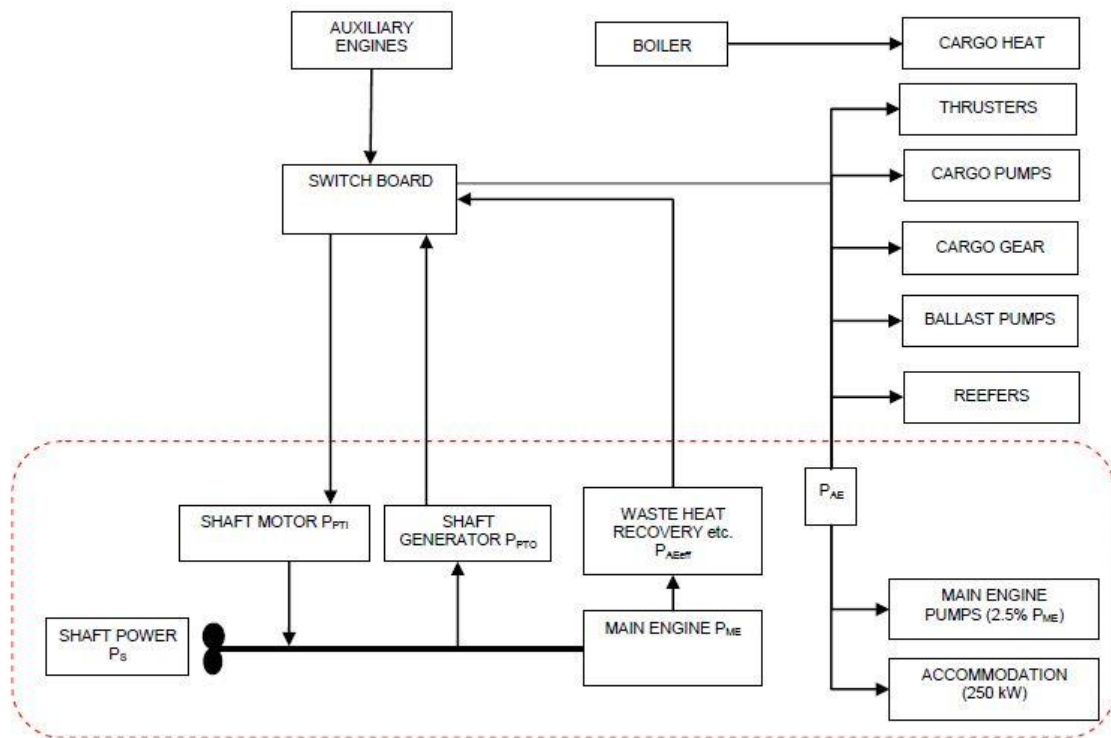


Figure 7 A Generic and Simplified Marine Power Plant [32]

d. Capacity

Capacity equals to the ships deadweight at the maximum summer load draught, as this is certified in the stability booklet. The above applies for bulk carriers, tankers, LPG carriers, LNG carriers, Ro-Ro vessels, Car Carriers, Ro-Pax ships, refrigerated cargo carriers and combination carriers.

For Container ships, the capacity is equal to 70% of the ship's deadweight.

e. Innovative Energy Saving Technologies (P_{eff} , P_{Aeff} and f_{eff})

The output of the innovative mechanical energy efficient technology for propulsion at 75% of main engine power is P_{eff} , while P_{Aeff} is the auxiliary power reduction due to innovative electrical energy efficient technology.

On the other hand f_{eff} is the availability factor of each innovative efficiency technology.

a. Speed (V_{ref})

V_{ref} is the ship speed, measured in nautical miles per hour (knots), on deep water in the maximum design load condition (Capacity) at the 75% of the engine(s) MCR and assuming the weather is calm with no wind, no waves and no current. The maximum design load condition shall be defined by the scantling draught with its associated trim, at which the ship is allowed to operate. This condition is obtained from the stability booklet approved by the classification society.

b. Correction Factors (f_w , f_i , f_c and f_l)

The f_w or weather factor is a non-dimensional coefficient indicating the decrease of speed in adverse weather conditions. The capacity factor (f_i) represents specific technical/regulatory capacity limitations while the cubic capacity correction factor (f_c) applies only to ships with specific cargoes, like LNG carriers or passenger ships. Finally f_l is the factor specific to general cargo ships equipped with cranes and other cargo-related gear.

B. Reference Lines (Baselines) Calculation

In this section, EEDI reference lines are going to be examined and calculated for the most common vessel types. To avoid continuous referencing, the following information has been extracted from “*ANNEX 14, 2013 Guidelines for calculation of reference lines for use with EEDI, (Resolution MEPC.231(65))*”. [52]

a. Definition of Reference Line

A reference line is defined as a curve representing an average index value fitted on a set of individual index values for a defined group of ships. One reference line has been developed for each ship type, ensuring in this way that data from comparable vessels has been included in the calculation of each reference line.

The reference line value is formulated in relation to capacity, and could be found by the following formula:

$$\text{Reference line value} = a (100\% \text{ deadweight})^{-c}$$

The “a” and “c” are parameters determined from the regression curve fit.

b. Data Source

The standard database delivering the primary input data for the reference line calculation is IHS Fairplay (IHSF) database. As it was agreed at the MEPC sessions, the ships that will provide the reference line would be existing ships of 400 GT and above delivered in the period from 1st January 1999 to 1st January 2009. The data to be used was:

- Ships’ capacity for the calculation of *Capacity*.
- Ships’ service speed for the calculation of reference speed V_{ref} .
- Ships’ total installed main power for the calculation of $MCR_{ME(i)}$.

In the occasion that some data entries for some ships are blank or zero (0), these specific entries should be removed from the reference line calculations.

c. Existing Ships’ Reference Line Calculation Methodology

In order to calculate the reference line, an estimated energy efficiency design index value for each ship contained in the set of ships should be calculated. Given the lack of data from the IHSF database the following assumptions had to be made.

- The conversion factor is constant for all engines $CF_{ME} = CF_{AE} = CF = 3.1144 \text{ g CO}_2/\text{g fuel}$
- The specific fuel consumption for all ship types is constant for all main engines, $SFC_{ME} = 190 \text{ g/kWh}$
- The specific fuel consumption for all ship types is constant for all auxiliary engines, $SFC_{AE} = 215 \text{ g/kWh}$
- $P_{ME(i)}$ is 75% of the total installed main power ($MCR_{ME(i)}$)
- P_{AE} is calculated according to chapter III A-c.
- No correction factors to be used except for f_{jRoRo} and f_{cRoPax}
- All innovative energy efficient technologies are excluded from the reference line calculation.

The velocity (V_{ref}) and Capacity used for the calculation of reference lines, are the velocity and capacity figures that appear on the IHSF database.

The equation used for calculating the estimated index value for each ship (Excluding containers and Ro-Ro cargo ships) is as follows:

$$\text{Estimated Index Value} = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{\text{Capacity} \cdot V_{ref}}$$

Equation 8 General Estimated Index Value for Reference Lines [54]

For containerships, it is taken into account only 70% of the capacity (DWT), in this respect the estimated index value is changed as follows:

$$\text{Estimated Index Value} = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{70\% \cdot \text{Capacity} \cdot V_{ref}}$$

Equation 9 Containership Estimated Index Value for Reference Lines [54]

Using the above methodology and taking under consideration the available data from IHS Fairplay it was calculated that the EEDI for each vessel type and 400GT and above. From these calculations the following table was produced of parameters for determination of reference lines (Table 4).

Ship type	Ship size	Parameters		R ²	Population	Excluded***
		a	c			
Bulk Carrier	≥400 GT	961.79	0.477	0.9289	2512	16
Gas tanker	≥400 GT	1120.00	0.456	0.9446	354	0
Tanker	≥400 GT	1218.80	0.488	0.9574	3655	14
Container ship	≥400 GT	186.52	0.200	0.6191	2406	32
General cargo ship	≥400 GT	107.48	0.216	0.3344	2086	47
Refrigerated cargo carrier	≥400 GT	227.01	0.244	0.5130	61	1
Combination carrier	≥400 GT	1219.00	0.488	0.9575	6**	0

Table 4 Parameters for determination of reference lines [54]

Further to the above table, please find below reference lines as these were created from the 62nd session of MEPC (MEPC 62/6/4).[54]

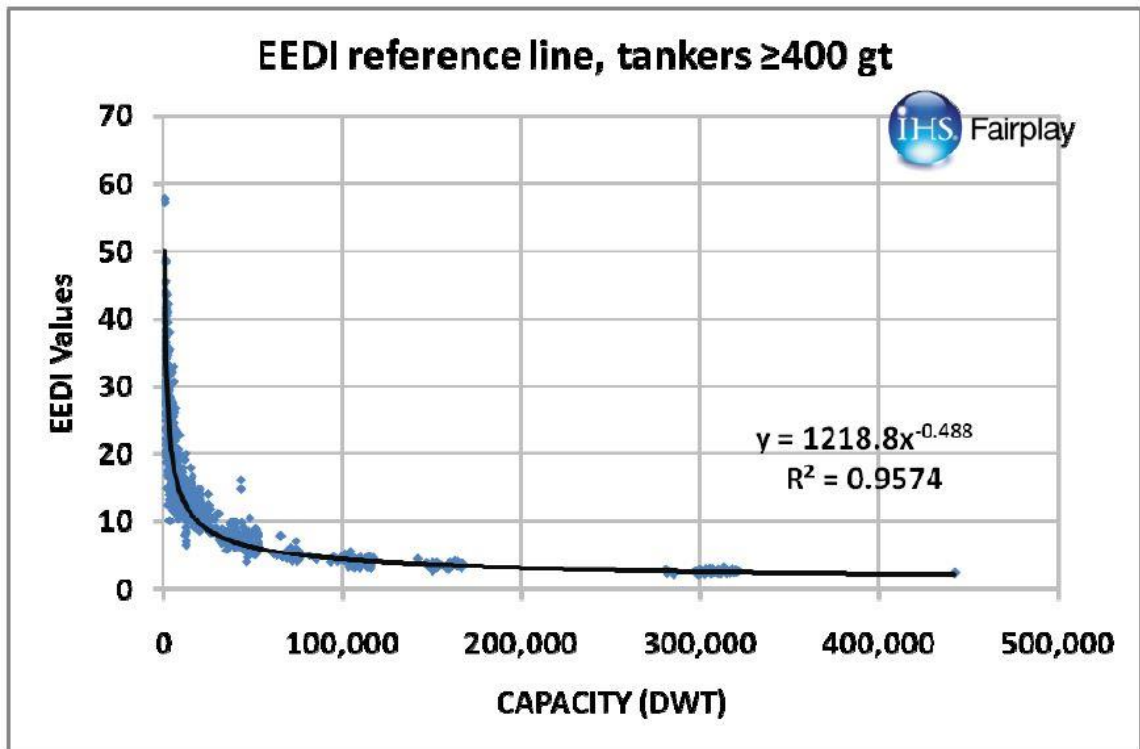


Figure 8 Tankers Reference Line [54]

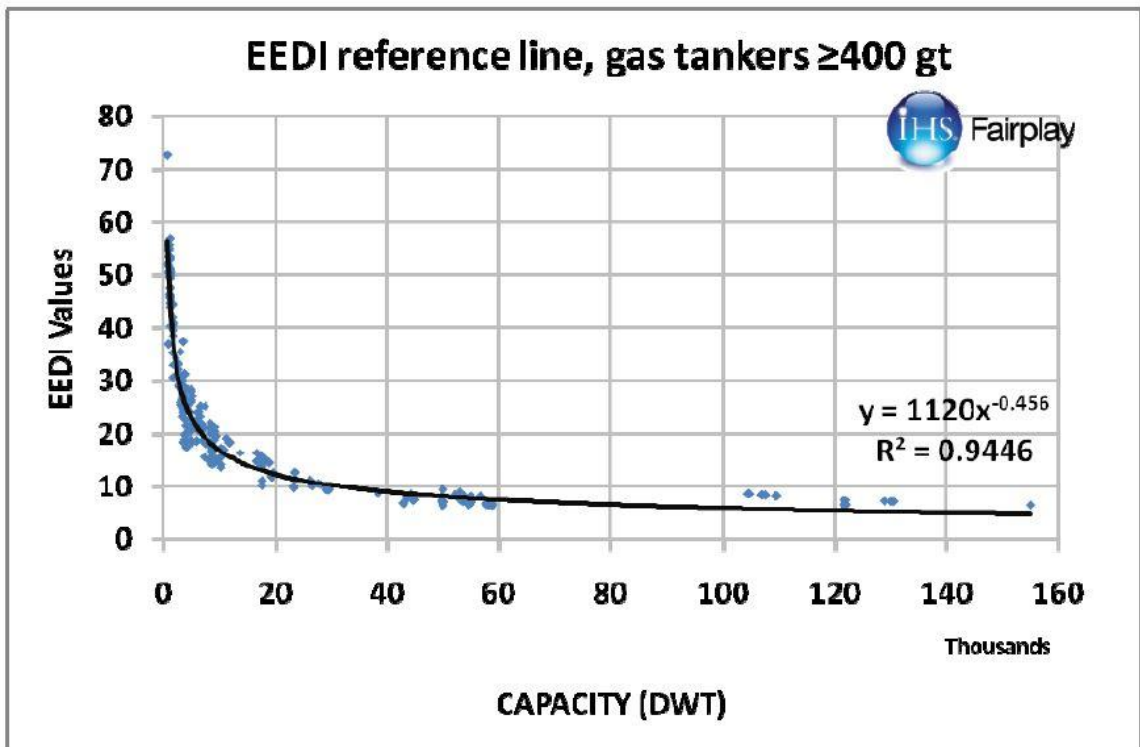


Figure 9 Gas Tanker Reference Line [54]

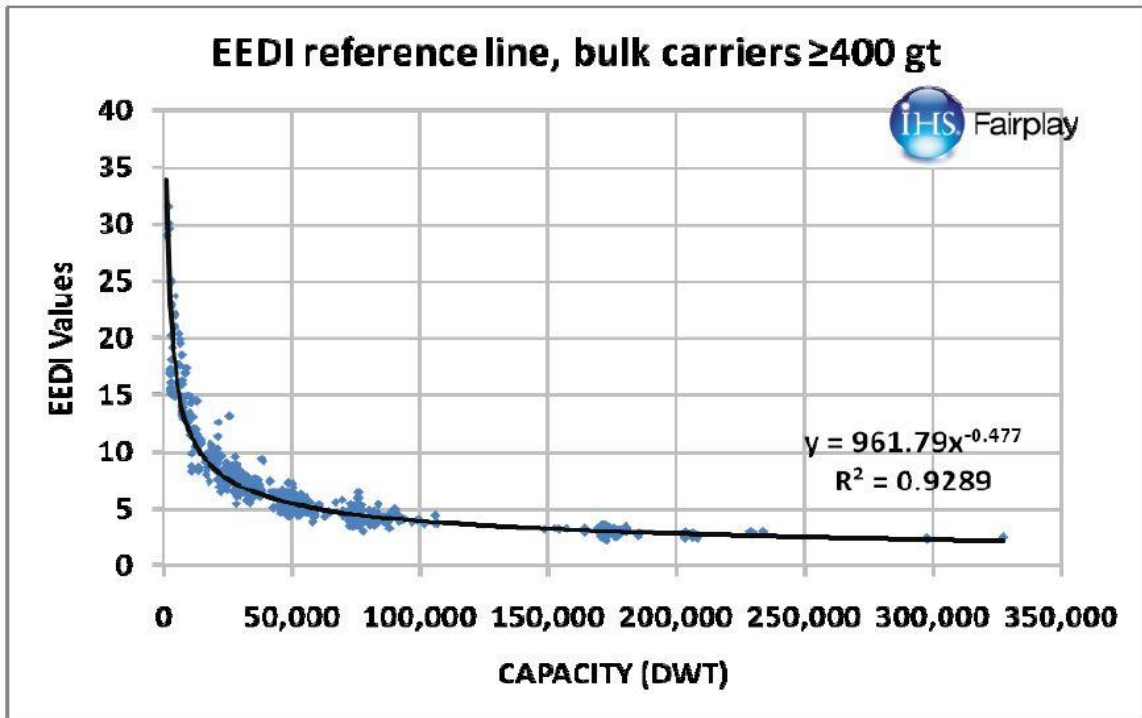


Figure 10 Bulk Carrier Reference Line [54]

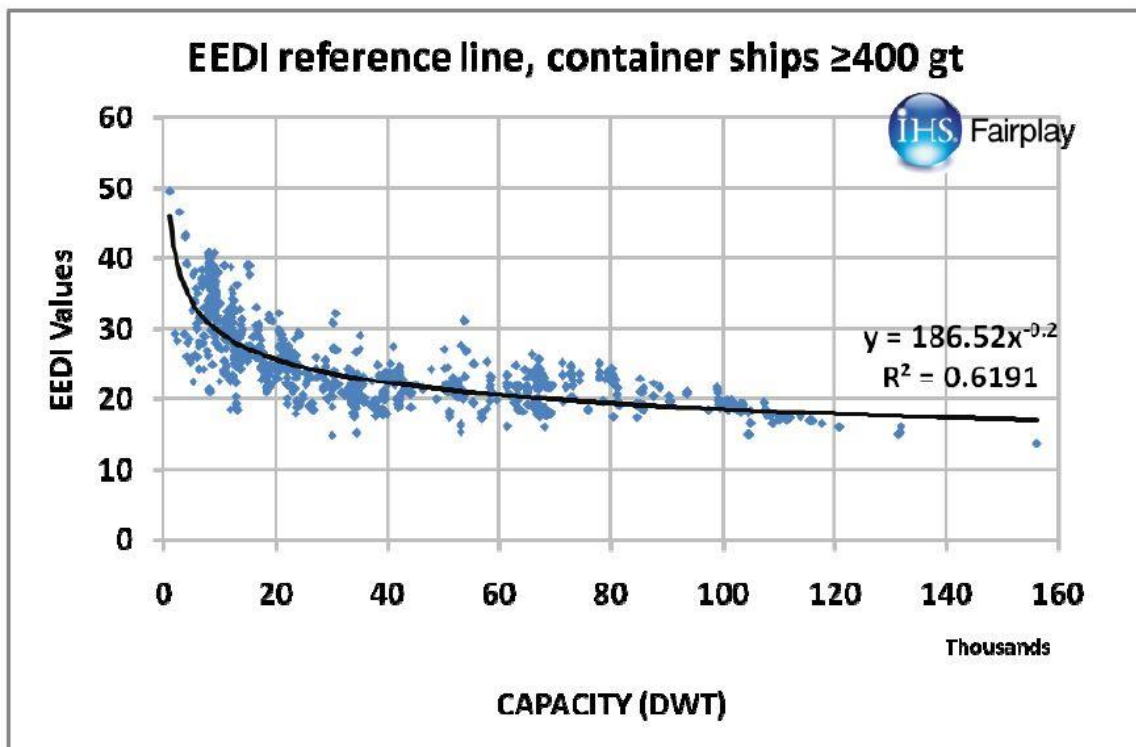


Figure 11 Containership Reference Line [54]

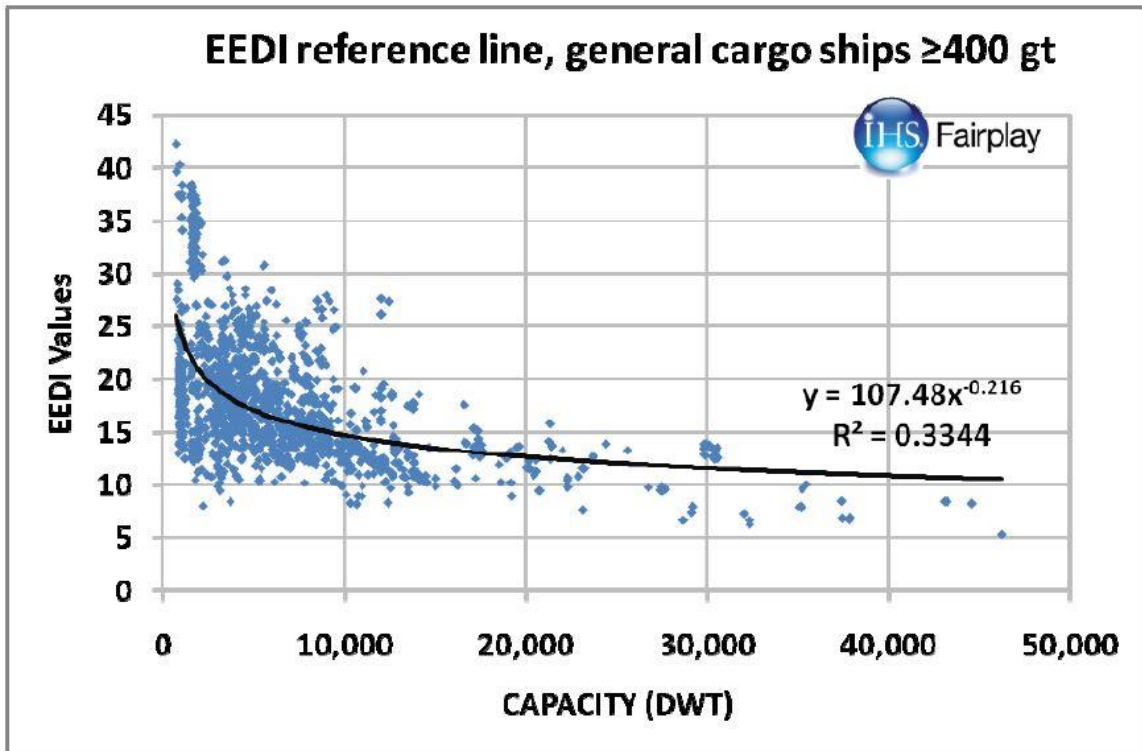


Figure 12 General Cargo Reference Line [54]

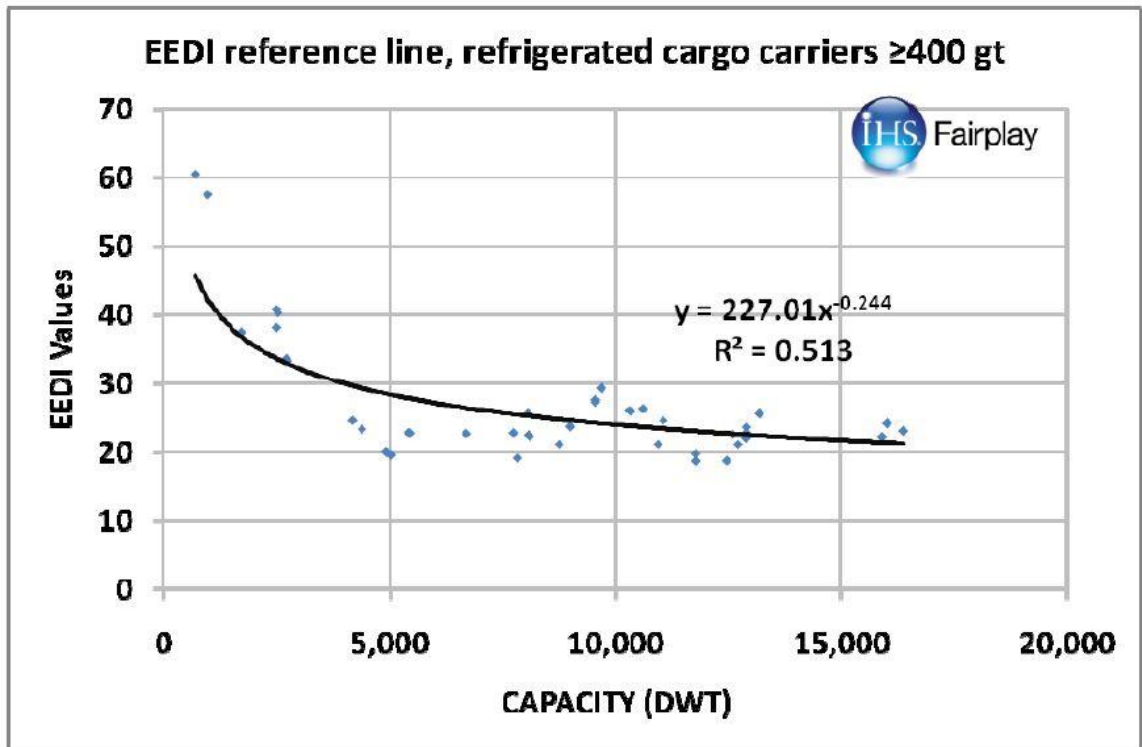


Figure 13 Refrigerated Cargo Reference Line [54]

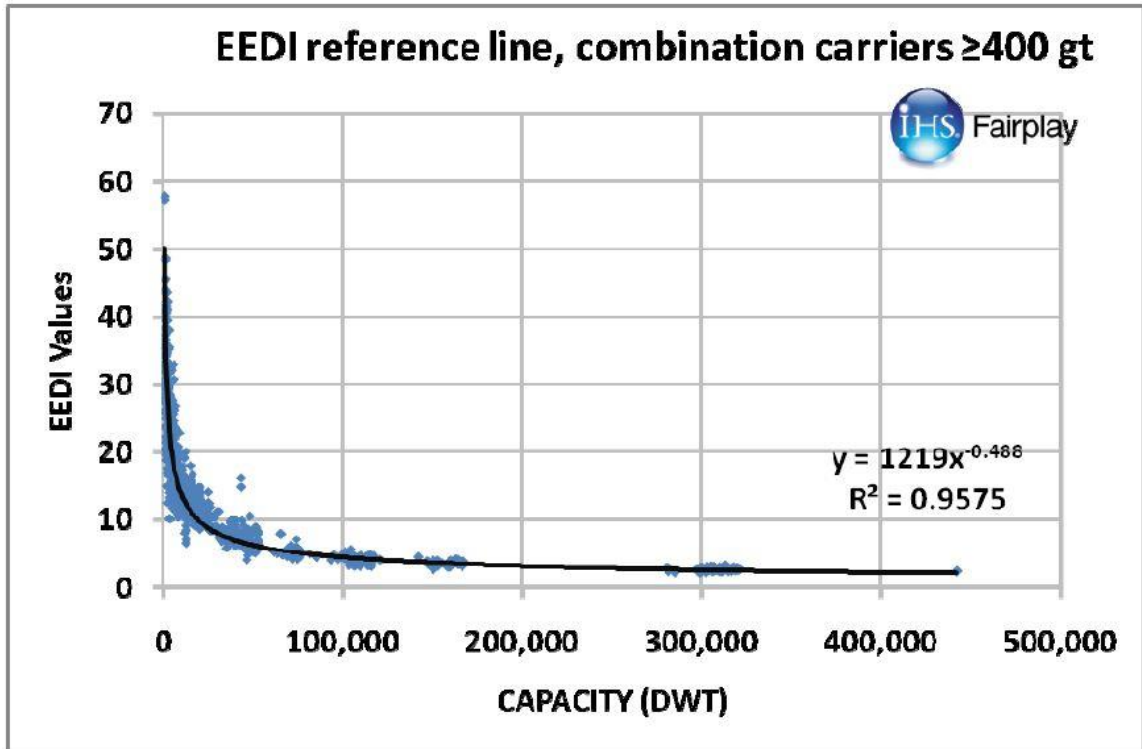


Figure 14 Combination Carriers Reference Line [54]

V. Eco-Design Vessels

Today's "ECO" ship design offers owners a package of improvements which combine to provide a ship with lower EEDI which is markedly less fuel-hungry than its predecessors, while carrying the same amount of cargo. The EEDI does not require any specific technologies, allowing the industry to determine how best to reach the efficiency standards. It achieves this through features which include a more efficient underwater form, possibly incorporating new bow designs that make the vessel less liable to speed loss in head seas, with the water flow around the after part helping to make the propeller more efficient. It might employ ducts or other devices to reduce the amount of propulsive power that is often wasted as the propeller pushes a vessel along.

A. Hull Form Optimization

Speed and draft flexibility are increasingly important parameters in the design of a new ship. Instead of optimizing the hull shape for a particular condition, the strategy is to optimize the design for the whole range of operational conditions. At design speed and draft, the optimized hull might have a slightly higher power demand than a conventional hull. However on all the other combinations of speed and draft the optimized hull is designed in total to have a lower power demand and thus less fuel consumption. Savings of up to 10% can be achieved when comparing a highly optimized hull to a conventional design on a yearly fuel consumption basis.[9] This figure depends on how often the ship is sailing at design and off-design conditions. The more spread in the operational profile, the higher potential for fuel saving.

Such optimized designs are achieved by way of systematic variation of the main dimensions of the vessel (Length, Breadth, Draught, Block coefficient) as well as other hull form parameters (Shape of the sectional area curve, Length of the parallel body, Waterline entrance angles, etc.).

The resistance of each version of the design is calculated with CFD for a speed and draft test matrix. After several iterations, the best "candidates" are selected for further investigations performing numerical propulsion tests. The finally selected hull forms (2 or even 3) are then model tested. [5]

Optimizing the hull shape reduces the overall resistance, so that in theory it is compatible with all other fuel saving measures. In addition to optimizing the hull form for a minimum resistance, the interaction between ship, propeller and the rudder is considered at the design stage by optimizing the wake field. This means that the propeller should be selected and optimized together with the final hull shape, and that flow improvement measures can be less efficient in the case of an optimized hull.

It is important to note that in order to improve an existing design it is possible to change part of the hull – for example the bow (figure 15). Conventional bulbous bows

are usually designed for one specific condition. Optimized design can reduce the wave making resistance in a wider combination of speed and draft – especially at low speed (manoeuvring condition) and low draft (ballast condition).[8,9]

An optimized bulbous bow may also perform better with regards to slamming loads. However, some wave piercing bows may give a larger number of slamming events, which implies that fatigue needs to be considered during the design of a new bulb. There are no special maintenance needs related to a different hull shape. All fuel savings based on hull form optimization directly improve EEDI, as long as the improvement is used to reduce the installed power by de-rating or selecting a smaller main engine. If, instead, the improvement is used to increase the speed, the gain in EEDI will only be approximately one-third of the power savings. This is due to the fact that on most vessels the power delivered to the propeller can be assumed to be proportional to the speed elevated to at least the 3rd power. $P_D = a \cdot V^b$ with a proportionality coefficient, and $b \geq 3$. [5]

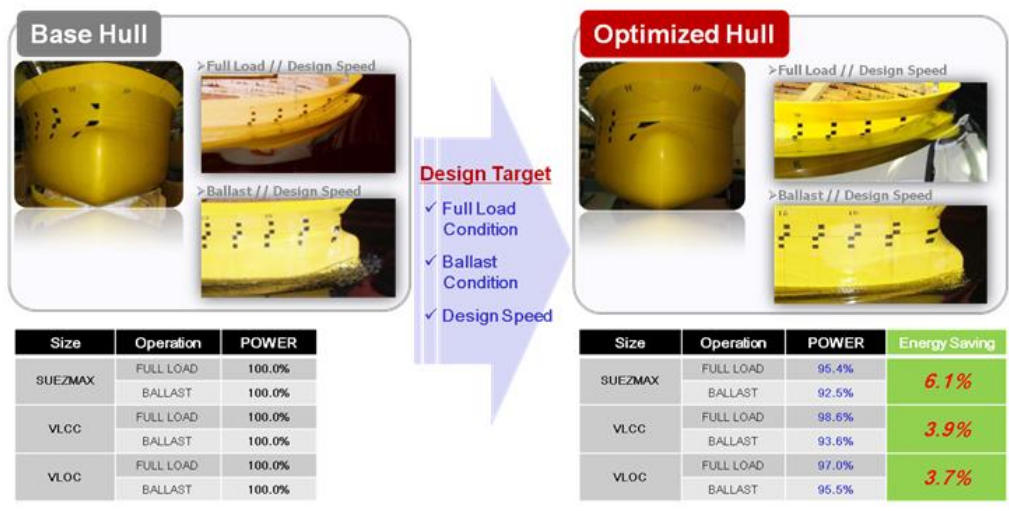


Figure 15 HHI vessels bow design optimization example [9]

B. Increased Propeller Diameter and Lower Number of Propeller Blades

Both these solutions have been proposed by MAN Diesel and they provide an efficiency gain but always paired with an engine modification, like an engine de-rating. According to these solutions, a larger diameter propeller results to higher propeller efficiency and lower optimum propeller speed. On the other hand, a lower number of propeller blades results to slightly higher propeller efficiency and increased optimum propeller speed (rpm). This difference may result to approximately 10% higher rpm. [23,24]

C. Duct Before the Propeller

A duct or nozzle is a ring with an air foil cross section. A ducted propeller, or propeller with nozzle, consists of a specially designed propeller fitted inside a duct. A pre-duct is a duct that is fitted just ahead of the propeller.

There are two main types of ducts. The decelerating ducted is used to improve cavitation and noise properties. The accelerating duct accelerates the flow through the propeller and generates thrust, depending on the vessel forward speed. The higher speed the less thrust and the more drag from the duct. This is why ducts are usually fitted on vessels with high propeller loading and low speeds, such as Tankers, Bulk carriers and Container vessels.

Pre-ducts are designed to modify the inflow to the propeller. Similarly to ducts, they can either reduce pressure pulses and induced aft body vibrations, or reduce flow losses in the wake field and thus reduce the necessary thrust to achieve a certain speed.

Such systems are not compatible with other measures located in front of the propeller. Because they modify the propeller slip stream, they are not compatible with Contra Rotating Propellers and also for twin screw ships. [5]



Figure 16 Duct before the propeller [5]

D. Replacement of the Propeller hub cup with fins

This innovation is delivered from Wartsila. The basic concept is to replace the conventional propeller hub cup with a modified one with fins. This retrofit will improve propulsive efficiency by weakening the hub vortex and by recovering kinetic energy from the rotating flow aft of the propeller blades.

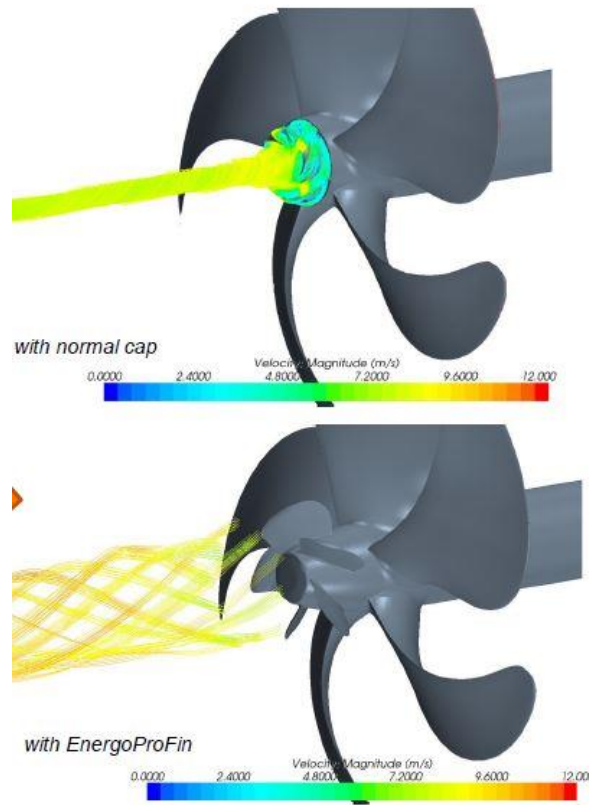


Figure 17 Example of the modified propeller hub cup[28]

It has been shown that the conventional propeller hub generates a negative thrust that is generated by the lower pressure behind the propeller hub. The modification reduces the pressure drag, resulting to a reduction of the negative thrust and therefore an increase of the propulsion thrust. This propulsion thrust is in turn translated into improved efficiency.

The efficiency gain from this application has been proven to be between 2-3%, depending on the type, size, speed and propeller diameter of the vessel.[5,28]

E. Reducing Operational Speed and Engine De-Rating

Since the rise of fuel costs, most companies in order to reduce operational costs have resorted to a temporary solution called ECO-SPEED. Basically this methodology reduces the operational speed of the vessel, resulting in this way to a less fuel consumption for the same voyage. On the other hand, the engine when built was not designed to work on that kind of RPM engine, providing in this way a margin for efficiency improvement.

In this respect by modifying some engine parts, like turbochargers, it was made possible to improve the efficiency at those low load levels of approximately 15-25%.

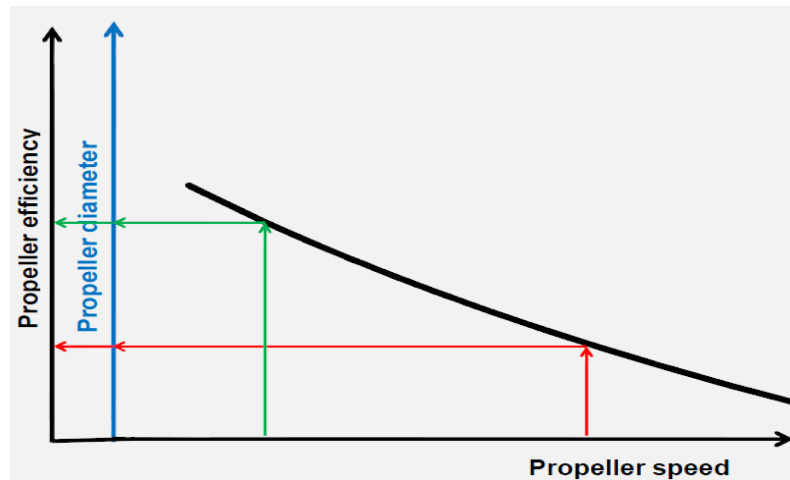


Figure 18 De-rating Efficiency Improvement [24]

The side-effect from such an installation could be a reduction to the attainable operating and top speed. The final gain in efficiency from this combined mechanical and operational solution could provide an additional 10-12% reduction in fuel costs. [5,23,24]

F. Main Engine De-rating

A vessel's engine and propeller are optimised and designed for a given operational and max. speed. If the operational speed of the vessel is generally lower than the one originally optimised for, it may be beneficial to consider de-rating of the main engine and propeller.

De-rating benefits

- Reduced SFOC at optimisation load
- New refurbished turbocharger(s)
- Increased overall propulsion efficiency with new bigger diameter propeller
- Less power demand for same vessel speed.[23,24]

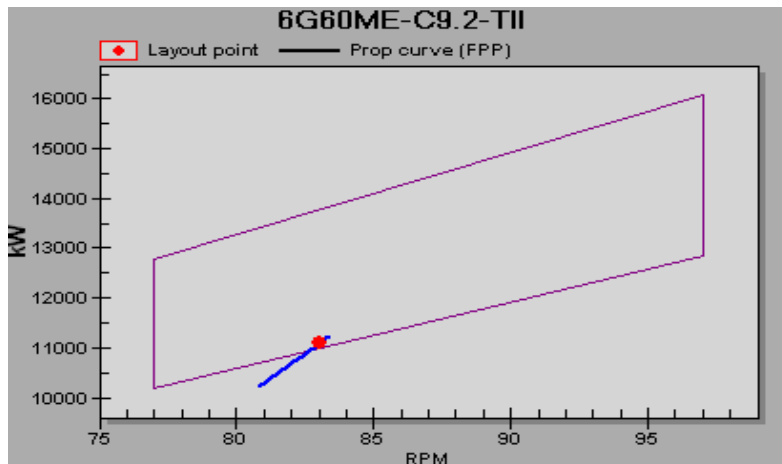


Figure 19 Engine layout and SMCR point[23]

Shipyards have to pay attention in the selection of LRM (Light Running Margin) when they choose a de-rated engine with lower rpm and bigger diameter propeller. MAN LRM recommendation, from 1st May 2015, is 4-10% that is applicable to all draughts at which the ship is intended to operate, whether ballast, design or scantling draught.

In brief, a ship should have a sufficient LRM such that:

- A safe and satisfactory ship speed can be maintained in heavy weather and/or with a fouled hull
- Ship accelerations needed for safe and efficient manoeuvring operations can be achieved
- The barred speed range (BSR) can be passed quickly, in seconds (which is often required also at zero ship speed, i.e. at bollard pull).[57]

G. Main Engine Optimization

The concept of engine de-rating is to fit the engine to run on a lower maximum continuous rating than its design maximum. A more optimized layout rating of the engine is selected by reducing the engine power and the appurtenant engine speed, leading to a reduction in the fuel oil consumption and possible increased propulsion efficiency.

One effective way of de-rating the engine with a good saving potential is to install the engine with one extra cylinder, without increasing the power. With high bunker costs this approach may have a favorable pay-back time.

A reduction of SFOC in the range of 1-4% may be expected when de-rating the engine, dependent of course on how much the engine is tuned down.

Depending on the intended operation range of the main engine, the engine may be SFOC-optimized in the following percentage SMCR (Specified Maximum Continuous Rating) ranges shown here below:

SFOC-optimised load ranges

High load	85-100% SMCR (standard-tuned engine)
Part load	50-85% SMCR
Low load	25-70% SMCR

Figure 20

The high-load range corresponds to a normal, standard-tuned engine of today. For part-load and low-load optimisation, the following engine tuning methods are available:

Engine tuning methods available

EGB	Exhaust Gas Bypass
VT	Variable Turbine Area or Turbine Geometry
ECT	Engine Control Tuning (only for ME/ME-C)

Figure 21

A reduction of SFOC in the range of 1-5% may be expected if for example low load optimization with EGB is applied to the engine. Below figure 22 shows SFOC curves for the whole optimization and tuning method options of a MAN B&W 6G60ME.[23,24]

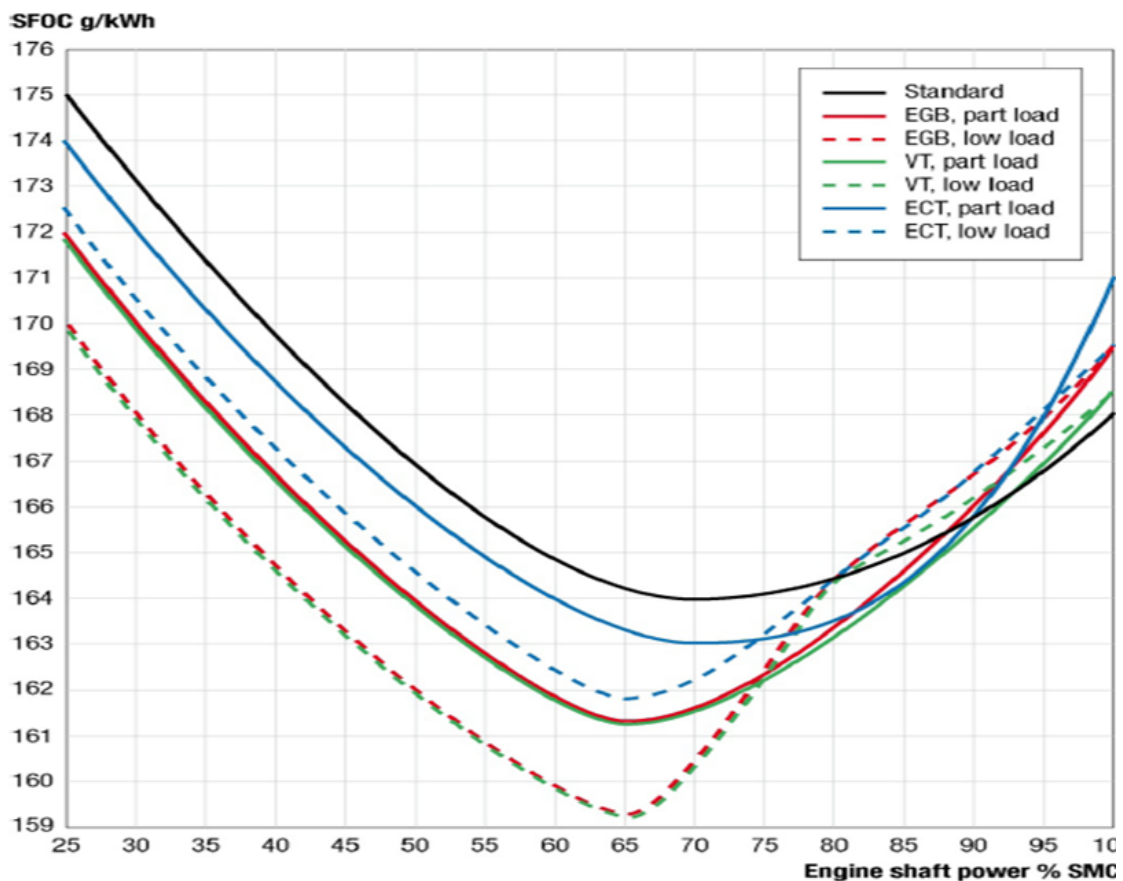


Figure 22 SFOC curves based on different optimization and tuning methods of a MAN B&W 6G60ME [24]

H. Rudder bulb(Costa Bulb)

The “original” propeller rudder transition bulb is the “Costa” bulb (figure 23). The “Costa” bulb is a bulb attached to the rudder directly behind the propeller boss. The bulb reduces the hub vortex losses and makes the wake field become more homogeneous. Often the bulb is integrated into a rudder with a modified profile.

The bulb itself has been measured to reduce power needs by up to 4%, although 3% is a more conservative figure. In connection with a modified rudder profile (full spade rudder), this figure can increase to up to 6%. [5]

One disadvantage caused by the rudder bulb is that during a dry-dock, it’s impossible to dismantle the propeller without dismounting the rudder blade. No special maintenance is however foreseen.

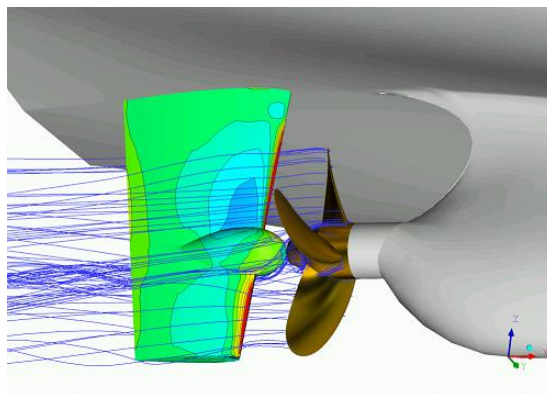


Figure 23 Costa bulb rudder[5]

I. Antifouling Coatings

The working principle of fuel saving with antifouling coating is to reduce the friction resistance component by maintaining a hull surface as smooth as possible. In addition to preventing hull fouling, some coatings are designed to gradually smooth down the paint roughness by the action of sea water.

As such there is a distinction to be made between the coatings that prevent the development of added resistance, and the coating that in addition can reduce the friction resistance. For the first case, the coatings are designed to maintain the added resistance due to fouling under a certain level between two dry dockings. For the second case, the coating designed to reduce hull surface friction are documenting in average 4% power savings compared to a hull coated with a high quality SPC.

In both cases, the performance of the antifouling coating depends on:

1. The operational profile of the vessel, as fouling has different developing rates in different parts of the world, mostly due to water temperature.
2. The speed of the vessel, as some fouling can be naturally eliminated with a sufficient speed, especially for SPC coatings.
3. The quality of the coating application on the hull[5]

Fuel savings can be measured at model scale with rotating cylinders experiments where the torque is measured and compared to a reference surface. However there are no scaling laws to extrapolate the obtained results to full scale. Another method is to tow a plate with different coating in a towing tank and use the ITTC guidelines to scale up the results. At full scale, very accurate performance monitoring system is needed to measure the effect of the antifouling, and a comparable reference case is needed: possibly a sister vessel with the same operational profile, or the same vessel at the same dry docking interval.[5]

There are three main types of antifouling systems available on the market: Biocidal Antifouling, Foul Release Coatings and Hard Coatings.

-Biocidal Antifouling is based on biocides that act as a repellent to the potential fouling organisms in the sea water. Biocidal Antifouling has a binder system that will polish in the water to expose new amounts of poison, called Self Polishing Copolymers (SPC). Only the highest quality products will be capable of fouling control for a long time. Some products may exhibit an increase in polishing rate with time resulting in polish through to the anticorrosion primers and increased fouling as a consequence.

-Foul release coating such as Silicon and Fluoropolymer systems prevent fouling by minimizing adhesion to the surface and do not contain any poison. These coating systems are dependent on certain minimum speeds for the fouling to release and the coatings are more subjected to mechanical damage and roughening than traditional antifouling coatings.

-Hard coating is typically epoxy coating similar to the anticorrosive primers. The fouling control is based on hull cleaning.[5]

All coating paints are subject to the IMO International Convention on the Control of Harmful Anti-fouling Systems on Ships. Most high quality coatings are designed to work efficiently for 60 months. Over this duration, there is no guarantee that the antifouling system will work well.

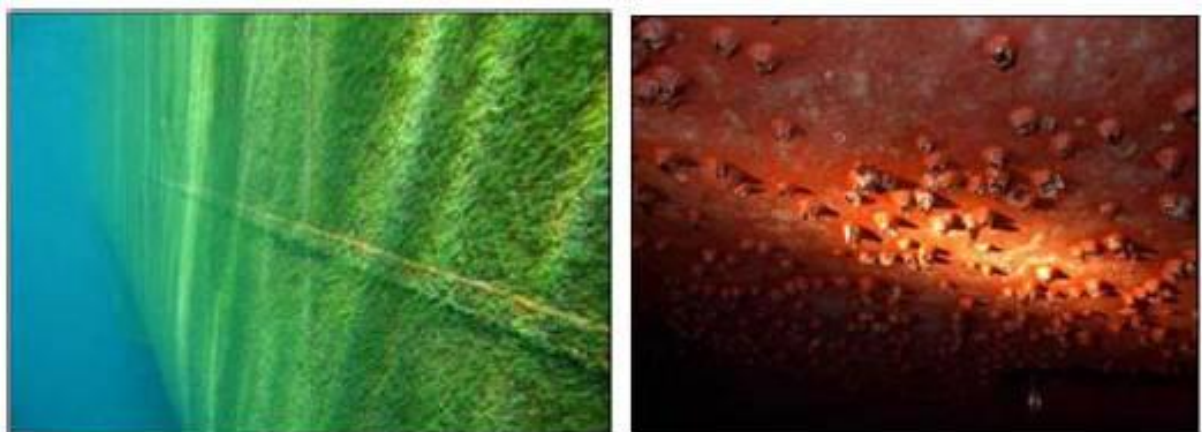


Figure 24 Hull fouling [8]

J. ECO-Vessels Study Examples

Below figure and tables are examples regarding eco-design modification and EEDI reduction for an Aframax tanker (figure 25-table 5) and a VLCC (table 6).

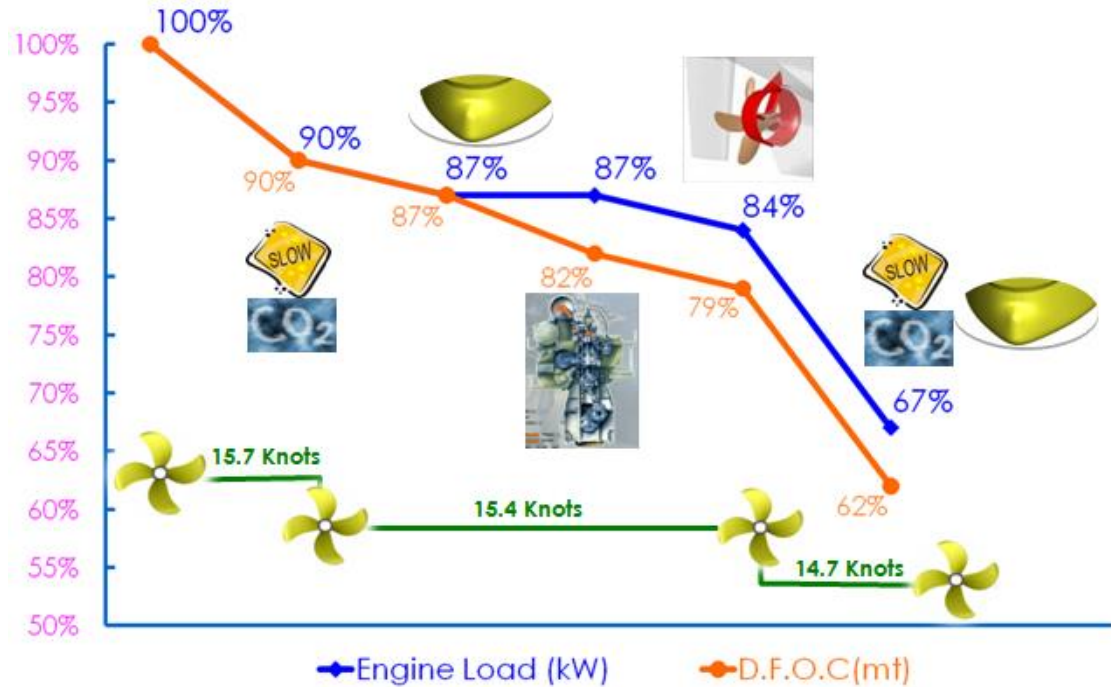


Figure 25 HHI Aframax tanker Design improvements[8]

		Aframax Tanker (2008)	Aframax Tanker (2011)	ECO Aframax Tanker (2014)	Remark
LOA x B x D x Td x Ts	(m)	250x44x21x13.6x14.7	250x44x21x13.6x14.7	252x45x21.2x13.6x15.1	
Deadweight at Td / Ts	(mt)	101,400 / 112,200	101,700 / 112,500	100,000 / 115,000	
Cargo capacity	(m ³)	127,800	127,800	129,500	
Main Engine		7S60MC-C8	7S60ME-C8.2	6G60ME-C9.2	
Nominal Rating	(kW x rpm)	16,660 x 105	16,660 x 105	16,080 x 97	
MCR	(kW x rpm)	16,660 x 105	14,000 x 90	11,080 x 83	
NCR	(kW x rpm)	14,994 x 101.4	12,600 x 86.9	9,972 x 80.1	
SFOC at MCR/NCR	(g/kWh)	174.0 / 171.9	168.4 / 166.2	162.2 / 160.0	
DFOC at NCR	(mt/day)	61.9	50.3	38.3	
Service Speed at Td	(knots)	15.7	15.4	14.7	15% S.M.
DFOC at 14.7 knots	(mt/day)	47.3	42.9	38.3	
Energy Saving Device		-	Preswirl duct	Preswirl duct	
EEDI(ATT./REQ.)		4.14 / 3.94 (105.1%)	3.49 / 4.18 (83.7%)	2.79 / 4.13 (67.6%)	

Table 5 HHI Aframax design improvements table [8]

Green Ship EEDI Reduce Plan: Example of DSME

VLCC

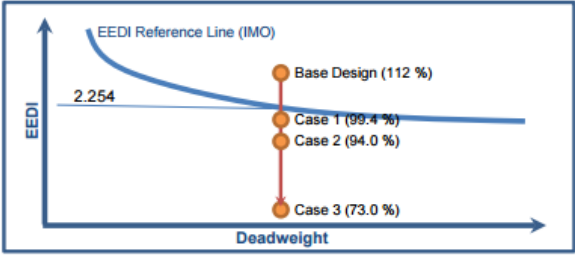
Dimension (Lbp x B x D x Td x Ts x Cb)
 320 x 60 x 30.5 x 21 x 22.5 x 0.82

DWT (Ts) : 319,600 MT

Vs (Serv.) : 16.2 → 15.9 Kts

DFOC : 101.6 → 94.9 MT/day

Case 3) LFS design to be developed further



Parameter	Base Design	Improved (Case 1)	Improved (Case 2)	Improved (Case 3)
Applied Economies	7S80MC-C8.2	←	←	7S80ME-C8.2-GI
	N/A(derated)	10 % derated	10 % derated	10 % Derated
	PSS	PSS	PSS + WHRS(1200kW)	PSS + LFS*
	Prop Dia. 10.0 m	←	←	←
MCR (kW) x RPM	29,260 kW x 78.0	26,330 kW x 75.3	←	←
EEDI speed (knots)	15.9	15.5	←	←
SFOC at 75% MCR (g/kWh)	168.1	166.1	168.1	141.2
CO2 Emission (g/h)	12,075,373	10,757,969	10,166,380	8,182,817
EEDI (g/ton-mile)	2.515	2.241	2.115	1.646
EEDI/Reference line (%)	112 %	99.4 %	94.0 %	73.0 %

* LFS ; LNG Fueled Ship

Table 6 DSME VLCC design improvements table[10]

VI. Liquefied Natural Gas (LNG)

A. What is the LNG?

Liquefied natural gas (LNG) is natural gas that has been converted into liquid state. The liquefaction process involves removing some components, such as dust, helium, acid gases, water and heavy hydrocarbons. The natural gas is then cooled down to approximately $-163\text{ }^{\circ}\text{C}$ ($-261\text{ }^{\circ}\text{F}$) at close to atmospheric pressure converting it to liquid. By doing so the volume is reduced about 600 times than in its gaseous form making it easier for storage and shipment in special cryogenic sea vessels to receiving terminals all over the world.

Natural gas is a fossil fuel where the main ingredient is methane (CH_4), a gas which is composed of one carbon atom and four hydrogen atoms. Natural gas is formed from the decaying remains of pre-historic plants and animals. These decaying remains are organic material and when exposed to heat and pressure over thousands of years some changes into coal, oil and natural gas. Unlike coal and oil, natural gas is clean burning and emits lower levels of harmful chemicals into the air. Natural gas is colorless, shapeless, and odorless in its pure form but an odorant called mercaptan that smells like “rotten eggs” is added to the gas before it is delivered to users for safety reasons to detect any harmful leaks.

COMBINATION OF CHEMICALS IN NATURAL GAS

Chemical	Formula	Percentage
Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulphide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	trace

Table 7 Natural gas chemicals [12]

LNG's density is between 430 kg/m^3 and 470 kg/m^3 , depending on its temperature, pressure and composition. The energy content based on the lower heating value (LHV) of LNG is about $48,6\text{ MJ/kg}$ which is higher than the energy content of MGO with a LHV of $42,6\text{ MJ/kg}$. [12]

B. LNG as a Ship Fuel

Natural gas is best known as an energy source for cooking, heating and generating electricity. Compressed natural gas (CNG) has been used as a fuel for cars,

trucks and buses because natural gas burns cleaner than gasoline and diesel releasing lower emissions of harmful pollutants.

LNG has been used as a marine fuel for many years, but mainly as the BOG in LNG carriers before the year 2000. The first ship running on LNG was the passenger ferry “Gultra”, launched 2001 in Norway. LNG has proven its safety and technical feasibility as a fuel for ships in more than 150 LNG fuelled ships in operation today. Because of new more stringent environmental regulations within Emission Control Areas (ECA) the use of LNG as a ship fuel has been growing, especially in Europe. As of April 2015, 200 new LNG fuelled ships are being built and it is estimated that about 1000 LNG fuelled ships will be in operation in the year 2020 (figure 26). [4,7,13]

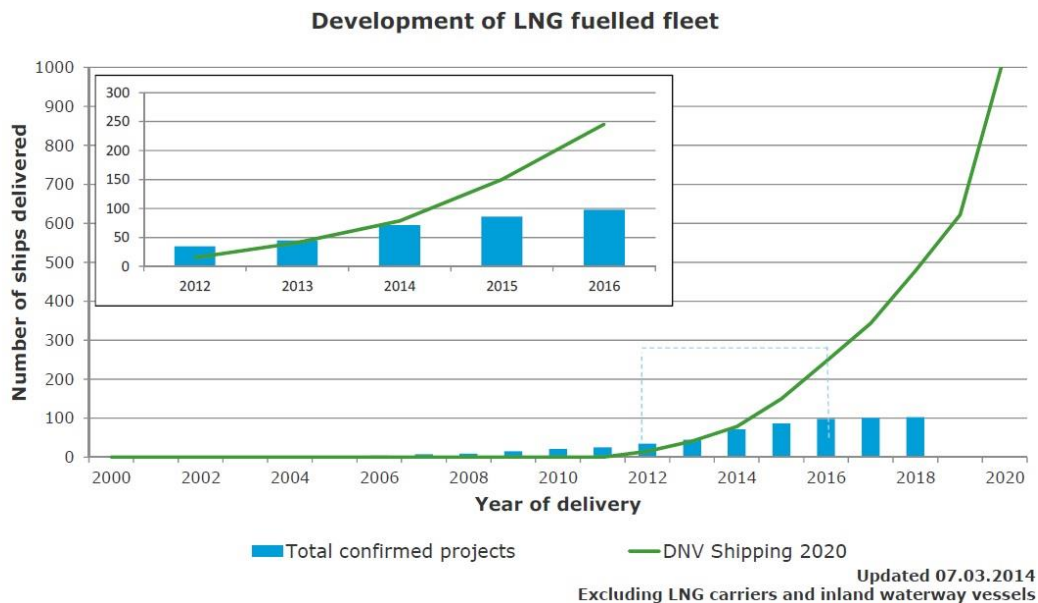


Figure 26 Development of LNG fuelled fleet [19]

C. Gas Injected Engine Technology

The main engines today running on LNG as an energy source are dual-fuel engines and lean burn single gas engines. Dual-fuel engines are mainly supplied by Wärtsilä and MAN Diesel whereas Mitsubishi and Rolls-Royce are the other suppliers of gas engines.

The lean burn gas engines run only on gas. Lean burn means that the air-fuel ratio is high which leads to lower combustion temperatures resulting in lower NOx formation. It works according to the Otto cycle where combustion occurs with a spark plug ignition. The injection of gas is at low pressure.

This engine is designed to ensure high efficiency and low emission but it does not have the flexibility to run also on fuel oil.

Dual-fuel engines run either on LNG in gas mode or on conventional oil in diesel mode. They can be designed either as four stroke (low pressure) engines or as two stroke (high pressure) engines (MAN ME-GI) or as two stroke (low pressure) engines (WARTSILA X-DF). The Dual-fuel low pressure engines work according to the Otto cycle in gas mode but a small amount of diesel fuel, less than 1% of the total fuel used, is injected into the combustion chamber (instead of a spark plug) igniting the lean air mixture. The gas is injected at low pressure. Figure 27 shows this process.

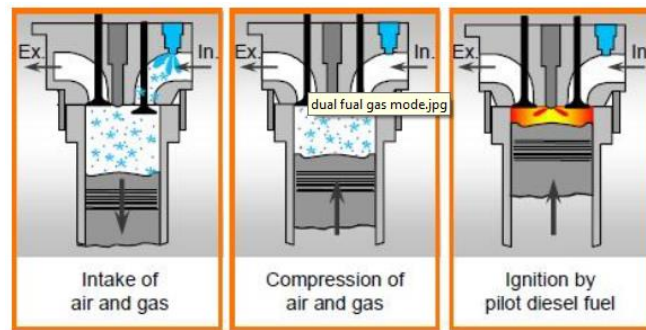


Figure 27[4]

The dual-fuel two stroke engines differ in a way that the gas is injected at a high pressure (about 300 bar) together with pilot diesel oil. First the fuel oil ignites and then the gas by the burning fuel oil. Dual-fuel engines work according to the normal diesel cycle in the diesel mode. Air is compressed raising the temperature to the ignition temperature of the fuel and ignites when the fuel is injected. Figure 28 shows this process.

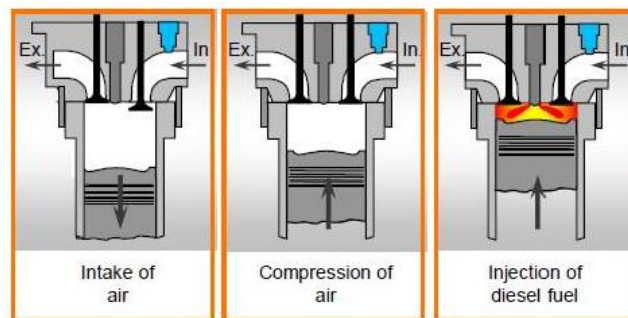


Figure 28[4]

Dual-fuel engines can switch from gas mode to diesel mode on the go at any engine load without any complications and it takes under a second. However transferring from diesel mode to gas mode is a gradual process and the effect on the engines speed and load is minimal. Dual-fuel engines in gas mode have lower load acceptance than in diesel mode and therefore the engines automatically change to diesel mode if they have been running on engine loads below 15% for three minutes. In alarm situations such as gas system failure the engines switch automatically to

diesel operation. The efficiency of the dual-fuel engines in gas mode can be about 48.5%. [4,19]

The dual-fuel engines are preferred for ship propulsion where there is limited supply of LNG infrastructure. The main benefit of dual-fuel engines is the fuel flexibility, to be able to run either on LNG or conventional oil depending on the operational pattern (ECA Areas), economic factors and the fuel availability. With two systems, dual-fuel engines can achieve full redundancy by using diesel oil as a back-up fuel in case of gas system failure as well as during longer voyages and bad weather where more energy is needed.

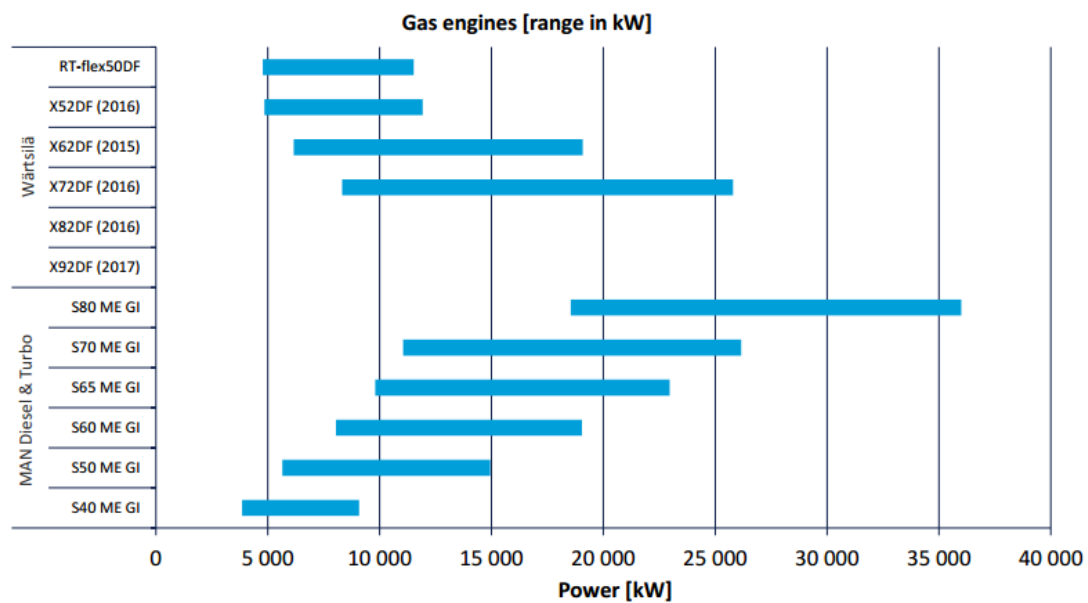


Figure 29 2-Stroke Gas engines are available over a wide range of power output [4]

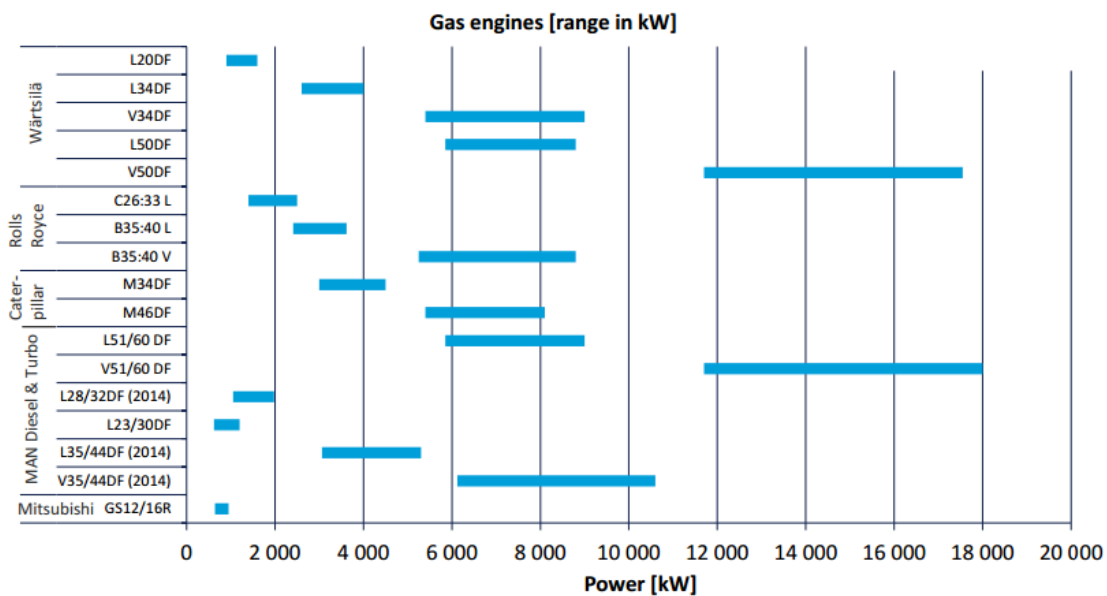


Figure 30 4-Stroke Gas engines are available over a wide range of power output [4]

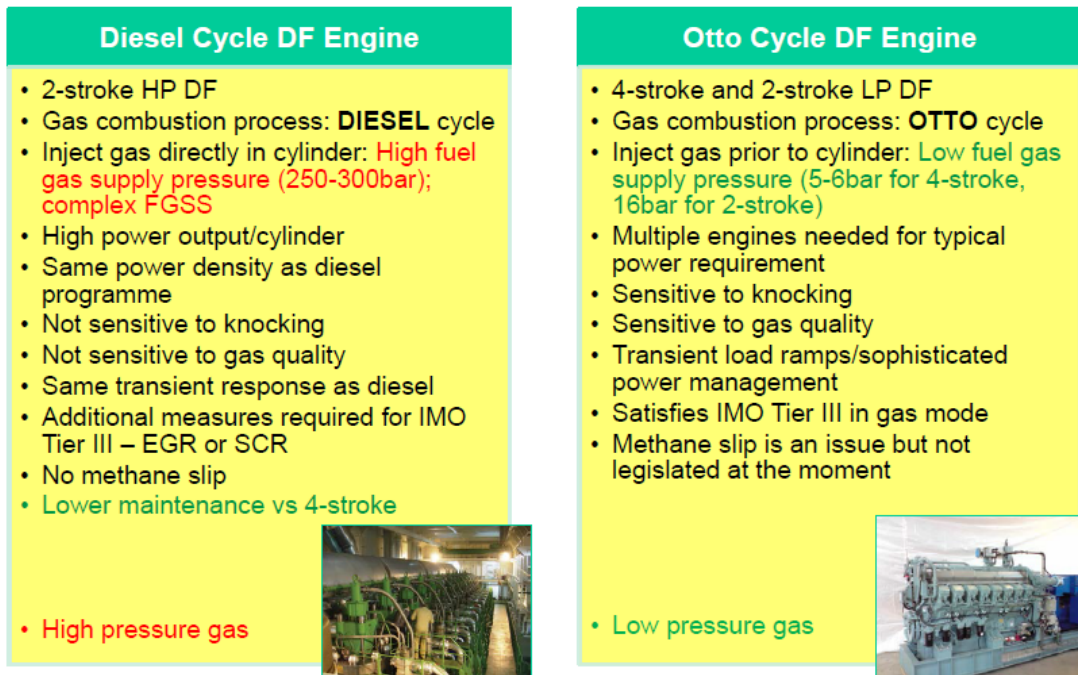


Figure 31 Diesel and Otto cycle comparison tables [25]

D. Storage Tanks Onboard Ships

According to the current IMO- IGC code, the LNG tanks onboard ships using LNG as a fuel have to be independent tanks type A, B or C. These tanks are self-supporting and are not a part of the ship's hull structure. [2]

Type "A" tanks are prismatic tanks which are adjustable to the ship's hull making them space efficient. The pressure within the tanks may not exceed 0,7 bar and therefore a complex fuel system with a compressor is needed. The tanks need a full secondary barrier to ensure safety because the construction material used is not crack propagation resistant. Below Figure 32 shows the structure of a type "A" tank.

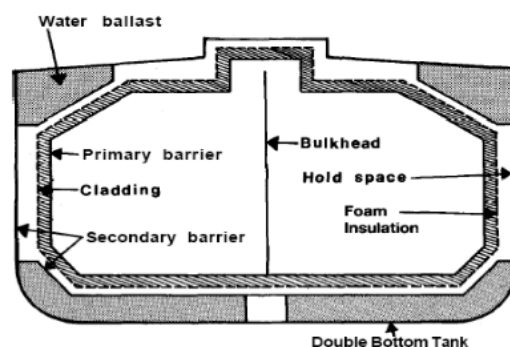


Figure 32 Type A tank [3]

The most common Type “B” tanks are the spherical (Moss type) tanks, see below Figure 33. This design only requires partial secondary barrier. This type of tank is mainly used in LNG carriers.



Figure 33 Type B tank [3]

Type “C” tanks are spherical or cylindrical (pressure tanks) with more than 4 bar design pressure. The cylindrical tanks can be placed vertical or horizontal. Because of the low design stress no secondary barrier is required. The advantage of the type “C” tanks are that the pressure increase due to BOG within the tanks is not a problem because they are designed for high pressure which also allows high loading rates. The disadvantage of these types of tanks is the space demand required onboard the ships because of the tanks shape. Figure 34 below shows a type “C” cylindrical tank.

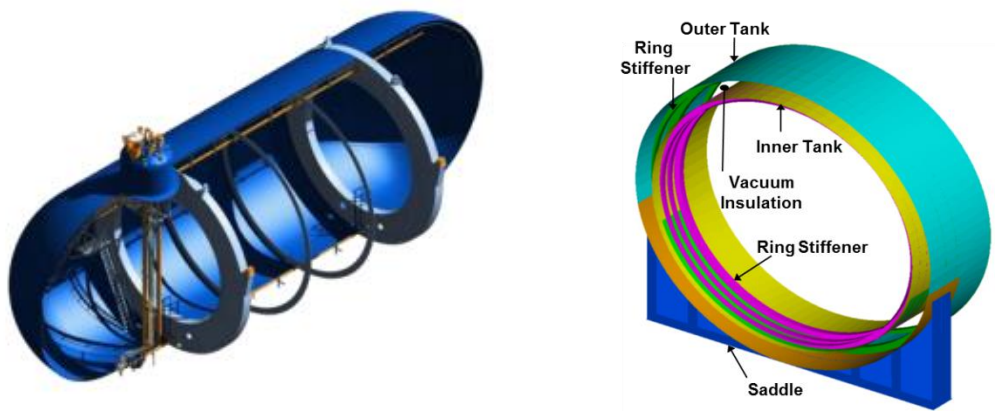


Figure 34 Type C tank [3]

To minimize sloshing the sphere is the preferable shape of LNG tanks. Cylinders with semi spherical ends comes next and then prismatic shapes. Type “C” tanks are the preferred solution for ships with LNG propulsion. The tanks have proven to be reliable and safe and they are easy to manufacture and install on deck or below

deck. The tank design is under development with the focus to increase space efficiency. The maximum filling ratio of LNG tanks are 95%. [2,3,4]

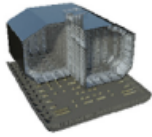

Tank type	Prismatic tank	Spherical tank	Cylindrical tank		Tank truck
					
IMO type	B	B or C	C		
Heat insulation	External		External	Vacuum	Vacuum
Max. pressure	0.7 bar	1 bar	10 Bar		10 Bar
Space efficiency	High	Low	Medium		Low/Medium
Gas delivery	Pumping Out		Pressure Built-Up Type		
Design cost	High	Medium	Low	Low	-
BOG treatment	Necessary		Not Necessary		
Suitable cap.	>5,000m ³	>5,000m ³	30-1,000m ³	30-1,000m ³	<100m ³
Cost	High	High	Medium	Medium	Low/Medium

Table 8 LNG tanks comparison table [6]

E. Special Class Requirements for a LNG fuelled ship

The gas engine, LNG tanks and gas fuel systems are designed according to the requirements set out in the DNV-GL class rules for gas-fuelled engine installations and IMO's Interim Guidelines on safety for natural gas-fuelled engine installations in ships, as summarized in the following.

Redundancy: The propulsion and fuel supply system must be so designed that the remaining power for propulsion and power generation after any gas leakage with following safety actions is in accordance with the requirements for remaining power and main functions after a single failure. Both MAN B&W and WARTSILA dual fuel engines have full fuel flexibility, meaning that the fuel oil is also a back-up fuel for the LNG.

Engine room and piping: The engine room is designed as an inherently gas safe machinery space. This implies that the engine room is considered gas safe under all conditions, normal as well as abnormal conditions. All gas supply piping within the machinery space boundaries must be enclosed in a gas tight enclosure, i.e. double wall piping or ducting. Gas fuel piping must not be led through accommodation spaces, service spaces or control stations. Gas pipes passing through enclosed spaces in the ship must be enclosed in a duct. This duct must be mechanically under-pressure ventilated. Gas piping must not be located less than 760 mm from the ship's side. An arrangement for purging gas bunkering lines and supply lines with nitrogen must be installed. The double piping between the forward tank room and the engine room is fitted in the double bottom, with the required distance from side and bottom. Gas supply lines passing through enclosed spaces must be completely enclosed by a

double pipe or duct. The arrangement and installation of the high-pressure gas piping must provide the necessary flexibility for the gas supply piping to accommodate the oscillating movements of the engine, without running the risk of fatigue problems. The length and configuration of the branch lines are important factors in this regard.

Storage tanks and tank room: The tank room boundaries must be gas tight. The tank room must not be located adjacent to machinery spaces of category A. If the separation is by means of a cofferdam, then additional insulation to class A-60 standard must be fitted. Access to the tank room is as far as practicable to be independent and direct from open deck. The storage tank used for liquefied gas must be an independent tank designed in accordance with the DNV-GL Rules for Classification of Ships, which is in accordance with the IMO International Gas Carrier Code (IGC Code). The tank is to be either an IMO type A, B or C tank. For our project, a type C tank is used. Pressure relief valves must be fitted. The outlet from the pressure relief valves must be located at least $B/3$ or 6 m, whichever is greater, above the weather deck and 6 m above the working area and gangways. It must be possible to empty, inert and purge bunker tanks and associated gas piping systems. Gas in a liquid state with a maximum acceptable working pressure of 10 bar can be stored in enclosed spaces. The gas storage tank(s) must be located as close as possible to the centerline and:

- Minimum, the lesser of $B/5$ and 11.5 m from the ship side
- Minimum, the lesser of $B/15$ and 2 m from the bottom plating
- Not less than 760 mm from the shell plating

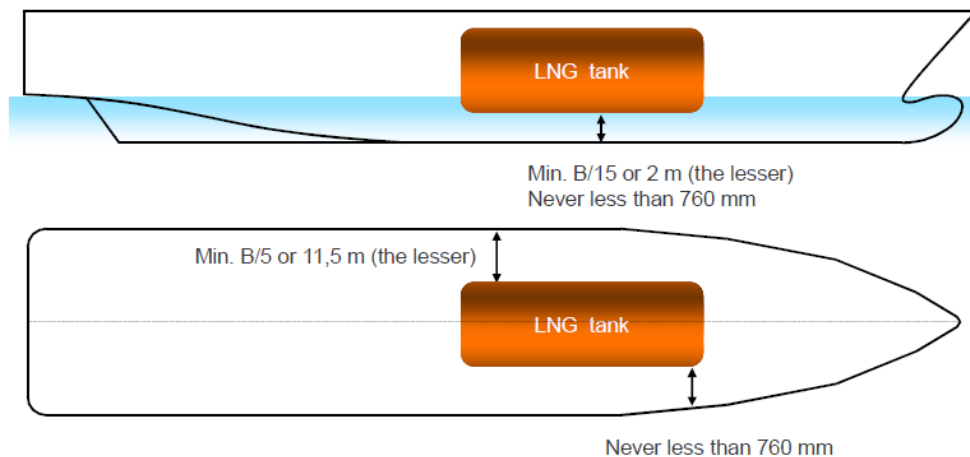


Figure 35 Tank location onboard [3]

For vessels other than passenger vessels, a tank location closer than $B/5$ from the ship side may be accepted and approved by the Class, on a case by case basis. The storage tank and associated valves and piping must be located in a space designed to act as a secondary barrier in case of a liquid gas leakage. Alternatively, pressure relief venting to a safe location (mast) can be provided. The space must be capable of containing leakage and be isolated thermally, so that the surrounding hull is not exposed to unacceptable cooling in the event of a liquid gas leakage. This secondary barrier space is called “tank room” in other parts of this chapter. When the tank is double-walled and the outer tank shell is made of cold resistant material, a tank room

could be arranged as a box fully welded to the outer shell of the tank, covering all tank connections and valves, but not necessarily all of the outer tank shell.

Ships fuelled only with LNG need to have at a minimum two separate LNG tanks, each with its own separate tank space. Ships with dual-fuel LNG propulsion only need one LNG tank.[2,3,4,10,11,19]

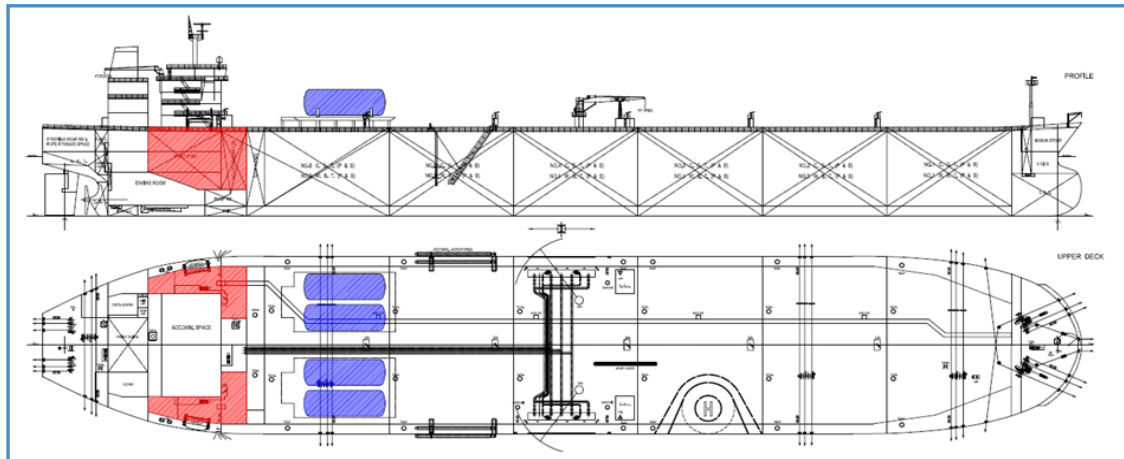


Figure 36 A typical Tanker arrangement with 4 Type C LNG tanks on deck (RED: Fuel oil tanks, Blue: LNG Tanks) [9]

Other class requirements and design modification:

- Structural reinforcement to be applied under the LNG tanks
- Increase capacity of D/Gs onboard
- LNG fuel tanks shall be provided with platforms of steel open grating construction with handrails.
- FGS (Fuel Gas Supply) room to be provided on upper deck
- Dry powder room/N₂ Generator to be provided on upper deck
- Wheelhouse front windows shall be A-0 class
- A-60 windows in ECR
- GVU (Gas Valve Unit) for each gas fueled engine
 - Double block and bleed valves
 - Enclosed GVU room with ventilation
- ESD (Emergency Shut Down) system
- Fire Extinguishing System
- LNG manifold area:
 - Dry powder system
 - Water curtain (manifold area-hull side of the vessel)
- LNG fuel tank:
 - Fixed Sea Water spray system
 - Dry powder system
- FGS room:
 - High pressure CO₂ system
 - Dry powder system
 - Sea Water from fire main line
 - Portable fire extinguisher

- Fire/Gas detection system
Smoke detectors, thermal detectors and gas detectors shall be provided in the following areas:
 - FGS room
 - Dry powder/N₂ generator room
- Fire/general alarm system
The manually operated call points for fire alarm shall be provided as follows:
 - FGS room
 - Dry powder/N₂ generator room
- Rearrangement of piping and equipment on deck
- Other equipment such as FGS room davit, ventilation fans, lighting system etc.[2,3,30]

F. Safety Issues with LNG

LNG operations have an excellent safety record with LNG vessels in operation for 50 years and LNG as a marine fuel since the year 2001. [4]

In liquid state LNG is not explosive and in case of a spill it would evaporate quickly because in gaseous form it is lighter than air. The risks of LNG depend on its state at the moment of release. LNG spills over water are very different to LNG spills over land. Below Figure 37 displays the hazards resulting from a spill over water.

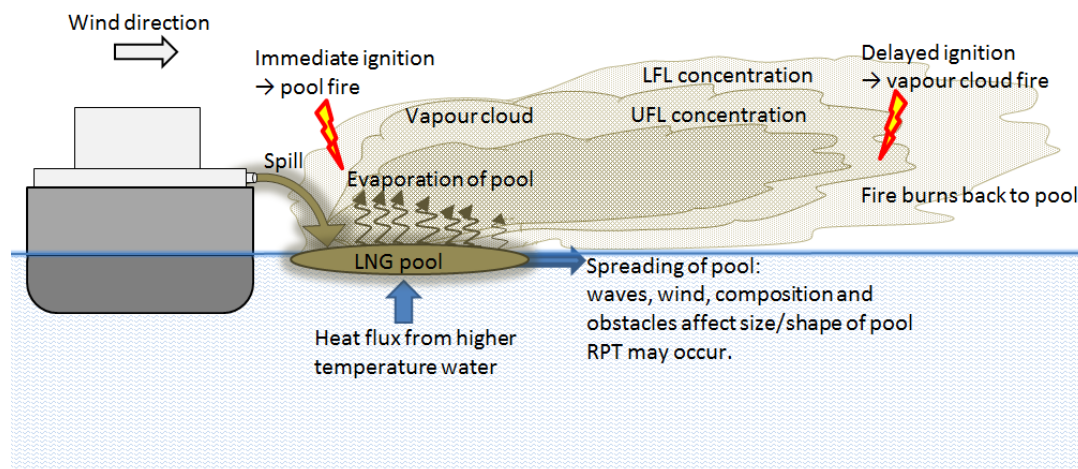


Figure 37[12]

During normal ship operations the likelihood of a LNG spill is very low because of the required safety systems onboard. Storage, transport and the use of LNG involves specific safety risks that have to be identified and assessed for each case scenario, in relation to the probability of it occurring and the severity in case it does, to ensure sufficient safety levels. The main risk outcomes and safety concerns with the release of LNG are:

- **Cryogenic damage**

Because of LNG's low temperature at -163 °C it is considered a cryogenic liquid. Damage such as metal embrittlement, cracking and structural failure can be caused to the ship or infrastructure materials that cannot handle contact to such cold temperatures. Special steels exist that do not suffer from a LNG spill and can be applied to sensitive areas such as LNG loading areas/bunkering station. [7]

- **Crew injuries**

Serious injuries to personnel in the immediate area if they come in contact with cryogenic liquids. Skin contact with LNG results in effects similar to thermal burns and with exposure to sensitive areas, such as eyes, tissue can be damaged on contact. Prolonged contact with skin can result in frostbite and prolonged breathing of very cold air can damage lung tissue. Special crew training with relevant certification is required for LNG fuelled vessels in order to eliminate such problems and human errors during operation.[7]

- **Operational and Training Requirements for onboard Personnel**

Recognizing this is new technology and personnel are well versed in the diesel world, crews have to be brought up to speed on the gas side. The IMO Human Element, Training and Watchkeeping (HTW) Sub-Committee developed interim guidance on training for seafarers on ships using gases or other low-flashpoint fuels. This interim guidance provides training for different types of seafarers. All seafarers serving on board ships subject to the IGF Code should receive appropriate ship and equipment specific familiarization. The guidelines provide additional basic and advanced training on the risks and emergency procedures associated with fuels addressed in the IGF Code. Basic and advanced training should be given by qualified personnel experienced in the handling and characteristics of fuels addressed in the IGF Code.[22]

- **Asphyxiation**

A large release of LNG close to people or a spill in enclosed non ventilated spaces could cause asphyxiation if there becomes large concentrations of natural gas in air resulting in a deficiency of oxygen. [12]

- **Pool fire**

If there is an immediate ignition of a LNG spill a pool of fire occurs. Once the pool of liquid starts to evaporate, the mixture of air and LNG vapor over the pool will burn on ignition when the LNG vapor is within the flammable range of 5-15% mixture with air. As the pool of LNG continues to evaporate it provides fuel to the fire. With concentration less than 5%, the lower flammability limit (LFL), the LNG vapor would not burn because there is not enough natural gas as fuel and with concentration higher than 15%, the upper flammability limit (UFL), there is insufficient oxygen to support combustion. Some experts believe that pool fires on

water pose the greatest LNG hazard and would most likely result from events like collision where metal on metal provides an ignition source. [12]

- **Vapor cloud fire**

If there is a delayed ignition of the LNG vapor after a spill a vapor cloud fire occurs. Then a vapor cloud within the flammable range of 5-15% mixture with air is ignited away from the initial LNG spill causing a fire. The fire can burn back to the source of the LNG spill as a “fire ball” (burning fast) or as a “flash fire” (burning slow). Since these LNG fires generate fairly low pressures they are unlikely to cause pressure damages.

- **Explosions**

LNG in liquid state is not explosive. If a confined fuel-air cloud forms in spaces like the ship’s hull or tank a damaging overpressure can emerge from a vapor cloud fire. With high degree of confinement, a strong mixture with air and a large source of ignition there is a potential for an explosion. [7]

- **Rapid phase transition (RPT)**

If LNG at high pressure (higher than atmospheric pressure, cold LNG) comes in contact with much warmer water RPT can occur. The liquid transforms quickly into gas resulting in explosive boiling and similar is to an explosion, shock waves and over pressure can be formed. No combustion is involved.[12]

- **Venting**

Every LNG tank installation must have a ventilation arrangement where the exit of the vent is at least 10m from any possible ignition source. This is usually accomplished by fitting a mast type vent above, or near, the storage tank. Often leads from filling line over pressurization relief valves are led to this mast. Unless the vent mast can drain readily back to the LNG storage tank, the liquid dumped in the base of the mast will vaporize often pistoning remaining liquid to the top.[7]

G. LNG Bunkering of Ships

LNG Bunkering of ships would be in port or offshore using feeder vessels. The main bunkering methods used are: straight from and Truck-to-Ship, Terminal-to-Ship via pipeline, Ship-to-Ship and Portable tanks, see below Figure 38

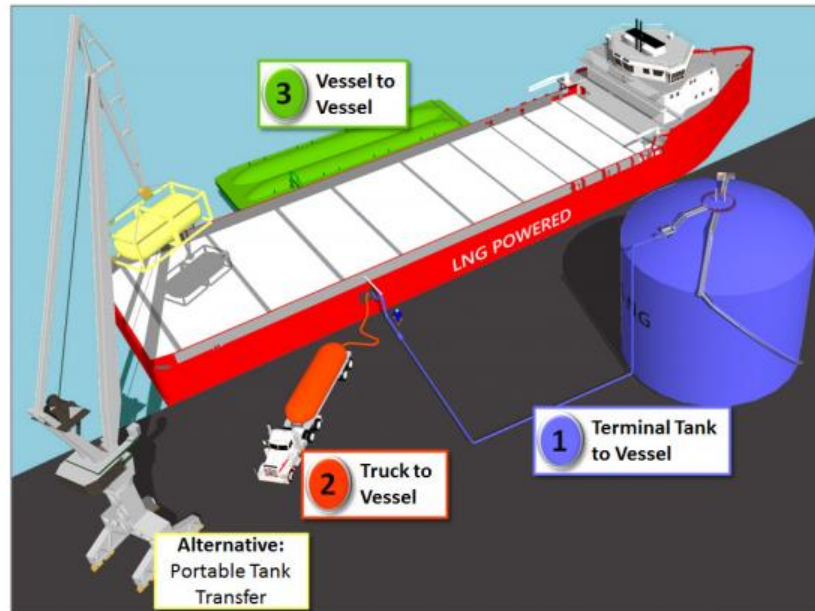


Figure 38 LNG Bunkering methods [16]

- 1. Shore/Pipeline-to-Ship (PTS):** LNG is transferred from a fixed storage tank on land through a cryogenic pipeline with a flexible end piece or hose to a vessel moored to a nearby dock or jetty. These facilities have scalable onsite storage such that designs could be capable of performing bunkering of larger volumes than TTS or with portable tanks.
- 2. Truck-to-Ship (TTS):** is the most common method used to support the LNG-fueled ship network, to date. It is the transfer of LNG from a truck's storage tank to a vessel moored to the dock or jetty. Typically, this is undertaken by connecting a flexible hose designed for cryogenic LNG service. A typical LNG tank truck can carry 13,000 gallons (abt.47m³) of LNG and transfer a complete load in approximately one hour.
- 3. Ship-to-Ship (STS):** It is the transfer of LNG from one vessel or barge, with LNG as cargo, to another vessel for use as fuel. STS offers a wide range of flexibility in location bunkering, and flexibility on quantity and transfer rate. There are two types of STS bunkering operations, one is performed at the port, and the other is carried out at sea.
- 4. Portable tanks:** They can be used as portable fuel storage. They can be driven or lifted on and off a vessel for refueling. The quantity transferred is flexible and dependent on the number of portable tanks transferred. A 40-foot (FEU) (ISO-scale) intermodal portable tank can hold approximately 13,000 gallons (abt. 47m³) of LNG.

All these bunkering methods can be used parallel, as complementary solutions during peak LNG demand and when serving different ship types. [1,12,16]

H. LNG Bunkering Station Onboard

The LNG bunkering station must be located so that sufficient natural ventilation is provided. Stainless steel drip trays must be fitted below liquid gas bunkering connections and where leakages may occur. The drip trays should be drained over the ship's side by a pipe that preferably leads down near the sea. The surrounding hull or deck structures must not be exposed to unacceptable cooling in case of leakage of liquid gas. The bunkering system must be so arranged that no gas is discharged to the air during filling of the storage tanks. A manually operated stop valve and a remote operated shutdown valve in series, or a combined manually operated and remote valve must be fitted in every bunkering line close to the shore connecting point. It must be possible to release the remotely operated valve in the control location for bunkering operations and/or another safe location. Means must be provided for draining the liquid from the bunkering pipes at bunkering completion. Bunkering lines must be arranged for inerting and gas freeing. Water curtain shall be provided at ship side. The bunkering pipes must be gas-free during operation of the vessel. In addition to the above requirements, the rules contain specific requirements to ventilation, gas detection and fire protection of tank area, engine room and bunkering station. [1,4,15,16]

A typical bunkering operation onboard a LNG-fuelled vessel follows four distinct stages:

- 1. General**
- 2. Pre –filling**
- 3. Filling**
- 4. Post-filling**

In the first step, there is a general exchange of information and communication with the parties involved in the bunkering. In the pre-filling step, the bunkering lines are made ready for LNG. They need to be cooled down and cannot contain any moisture or oxygen. The low temperature of LNG would cause damage when in contact with warmer lines and cause pressure peak as LNG expands to gas in the contact. As gas is flammable under certain oxygen levels, oxygen must be removed from the lines to render them safe. Consequently, in this step there is a pre – cooling of shore –side lines and pump (in some cases pressure differential is used instead of pumps), connection of bunker hose to the ship (bunkering station), oxygen and water are removed from the ship's lines (inerting , with nitrogen), nitrogen is then pushed out from the line using natural gas (purging).

Bunkering is finalized with the post-filling step in which valves are closed and what is left of LNG in the bunkering line is forced into the ship's tank, using the pressure in the lines. At this point, the lines are full of natural gas, which is removed with nitrogen (inerting), for safety reasons. The bunker hose is disconnected and the bunker operation is finished.[15,16]

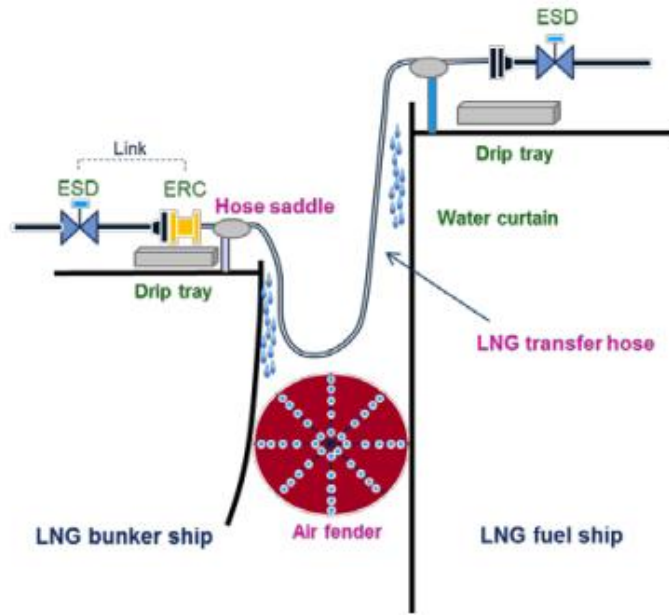


Figure 39 LNG Bunkering STS arrangement [16]

I. LNG Bunkering Infrastructure

The North European countries are currently focusing on small-scale distribution and operation of LNG, with small LNG terminals. Small scale infrastructures have been established in Norway since the year 2000.

There is a limited liquefaction capacity in Northern Europe. Ten liquefaction plants exist today, in Northern Europe and more plants are planned and proposed over the next five years. The European and Eurasian countries import LNG mainly from Qatar, 48% of the total LNG imported in the year 2011. Current and planned LNG infrastructures worldwide and in Northern Europe are shown in below Figure 40-41 and table 8.

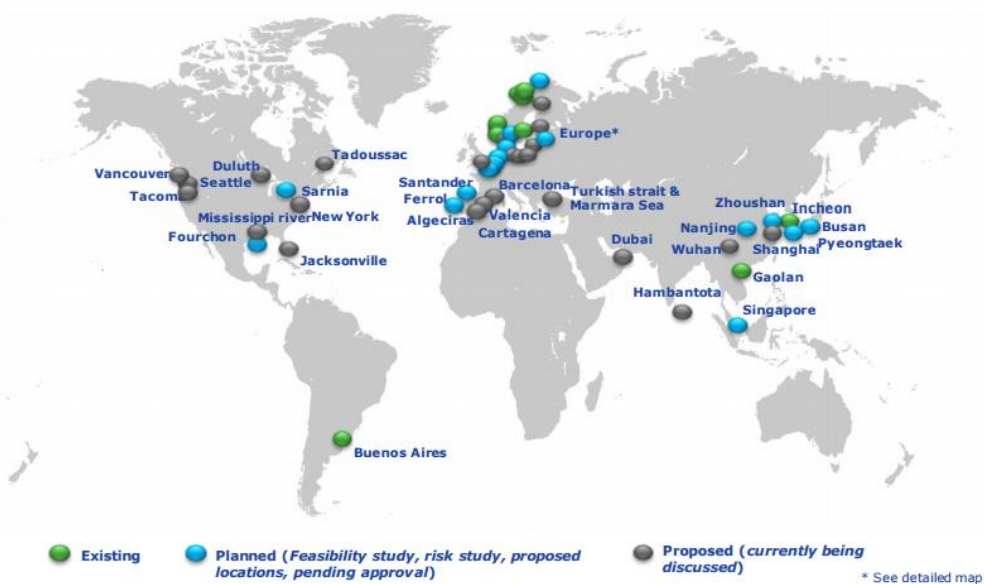


Figure 40 LNG Bunkering grib by 2020 worldwide [13]

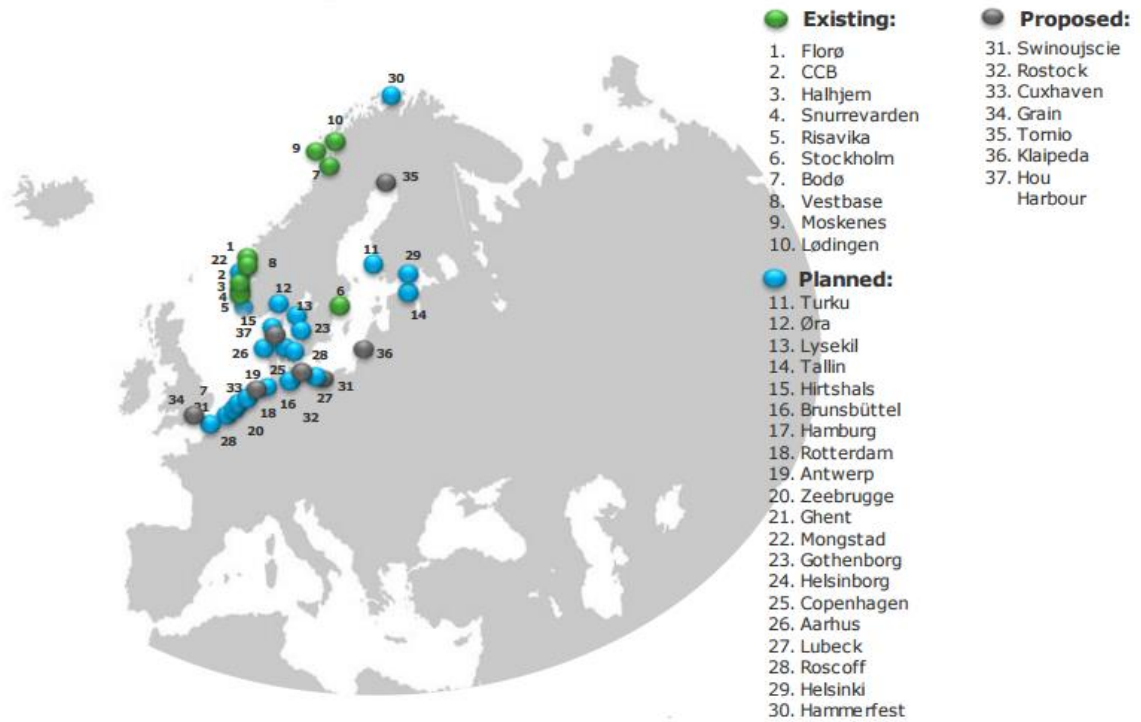


Figure 41 LNG Bunkering grib in Europe by 2020 [13]

Global LNG bunkering infrastructure	Existing	Planned <i>(feasibility study, risk study, proposed locations, pending approval)</i>	Proposed <i>(currently being discussed)</i>
Baltic and North Sea ECA	Florø, CCB, Halhjem, Snurrevarden, Risavika, Stockholm, Bodø, Vestbase, Moskenes, Lødingen	Øra, Lysekil, Tallin, Hirtshals, Brunsbüttel, Hamburg, Rotterdam, Antwerp, Zeebrugge, Ghent, Turku, Mongstad, Gothenborg, Helsinborg, Copenhagen, Aarhus, Lubeck, Roscoff, Helsinki, Hammerfest	Swinoujscie, Rostock, Cuxhaven, Grain, Tomio, Klaipeda, Hou Harbour
North American ECA and US Caribbean ECA		Fourchon	Tacoma, New York, Jacksonville, Seattle, Mississippi river
Canada and the Great Lakes		Samia	Tadoussac, Port of Duluth, Vancouver
South America	Buenos Aires		
Mediterranean Sea		Ferrol, Santander	Turkish Strait and Marmara Sea, Valencia, Barcelona, Cartagena, Algeciras,
Asia Pacific	Incheon, Gaolan (Zhuhai)	Busan, Pyeongtaek, Singapore, Zoushan, Nanjing	Wuhan, Shanghai, Shangdong, Hambantota, west coast of India
Middle East			Dubai

Table 8 LNG bunkering stations summary table [13]

Global LNG bunker demand by 2020

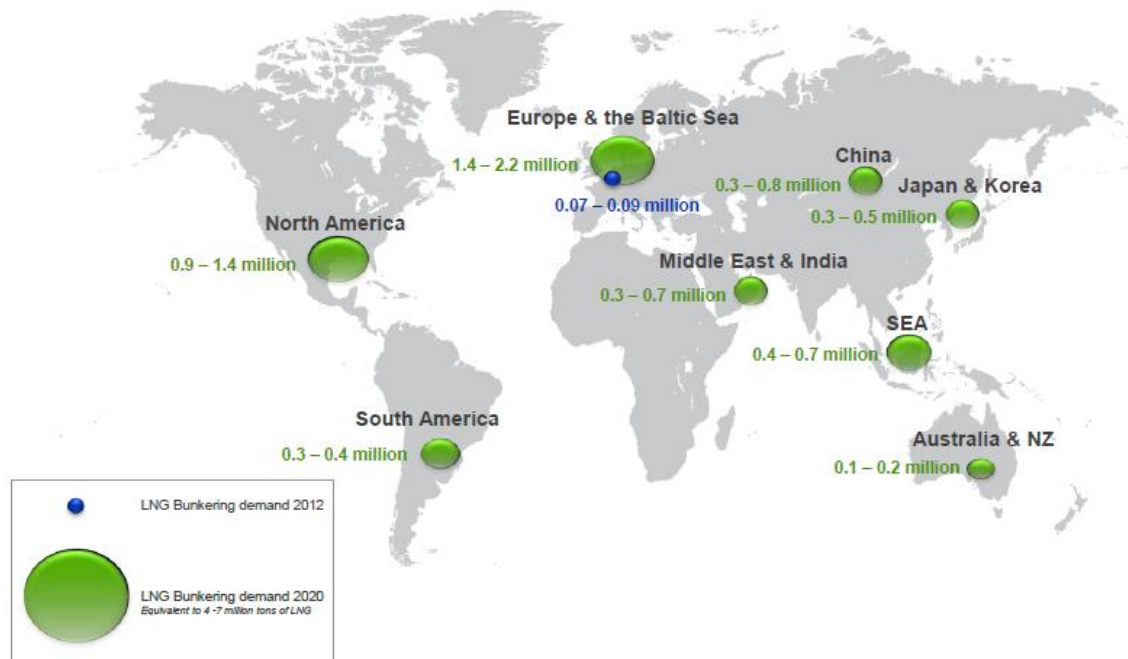


Figure 42 LNG bunkering demand 2020 [13]

It is estimated that large import terminals will be established by 2020 in France, Finland, Germany and Poland. Additional terminals are expected in the Mediterranean Sea due to increased demand of LNG.

A LNG import terminals usually includes offloading berths and ports, LNG storage tanks and where there are gas grid vaporizers (needed, to convert LNG back to gas) and a pipeline linked to the local gas grid.[12,13,15,16]

K. Main Benefits of Using LNG as a Fuel

Switching to LNG as a ship fuel has some benefits both environmental and economic. These benefits can act as drivers for ship owners to switch to LNG as a fuel. In this chapter the main benefits are described and other influencing factors that could lead to a switch to LNG propulsion.

a. Emission reduction

The main environmental pollutants that ships emit are CO₂, SO_x, NO_x and PM:

- **Carbon dioxide (CO₂)** is a greenhouse gas that contributes to global warming and a reduction of CO₂ from ship propulsion is only possible by burning less oil or switching to alternative fuels.
- **Sulphur oxide (SO_x)** combines with water and forms “Acid rain” that can be harmful to aquatic animals, plants and infrastructure.

- **Nitrogen oxide (NO_x)** also forms “Acid rain” when combined with water. This pollutant can be harmful to humans where it can damage the lungs and cause asthma and heart disease. NO_x contributes greatly to smog and ozone formation.
- **Particulate matter (PM)** is the soot that comes from the ships exhaust. It can cause respiratory problems and cancer. PM can also cause metal corrosion on ships. The smaller particles (2µm-10µm) can be transported with wind over large distances. [7,13]

Using LNG as a fuel for ships offers great environmental advantages in emission of these four pollutants compared to conventional fuels, see below Figure 43.

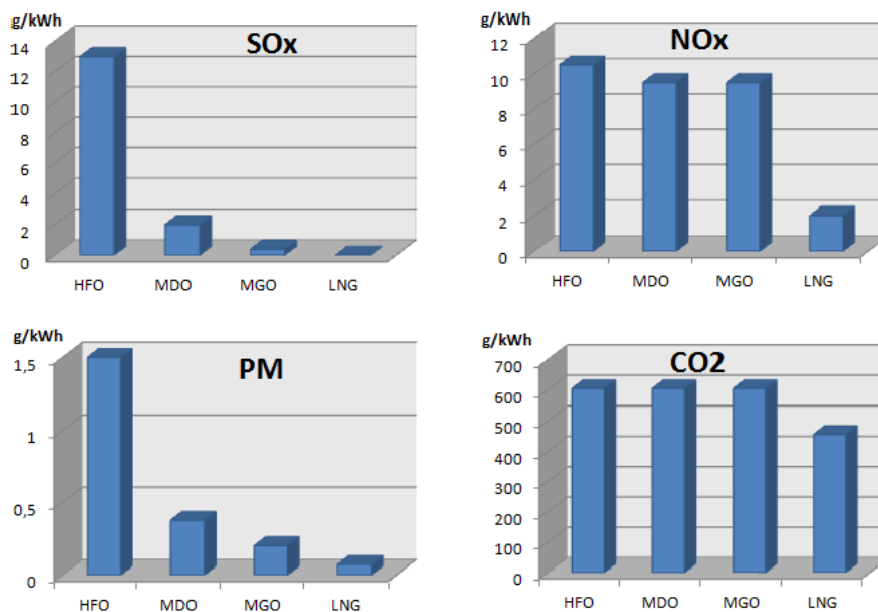


Figure 43 Emission comparison for different fuel types [19]

LNG as a fuel has very low concentration of SO_x since it is removed from the fuel when liquefied. PM emission is almost nothing, NO_x is reduced by 85-90% in Otto Cycle (sp Tier III compliance with new WARTSIA X-DF engine) and CO₂ by 25-30% compared to conventional oil because of the low carbon to hydrogen ratio of LNG (table 9). In countries where a carbon tax has been imposed on fuels a reduction in CO₂ emission can be of economic interest.

Emission component	Emission reduction with LNG as fuel	Comments
SO _x	100%	Complies with ECA and global sulphur cap
NO _x , Low pressure engines (Otto cycle)	85%	Complies ECA 2016 Tier III regulations
NO _x , High pressure engines (Diesel cycle)	40%	Need EGR/SCR to comply with ECA 2016 Tier III regulations
CO ₂	25-30%	Benefit for the EEDI requirement, no other regulations (yet)
Particulate matter	95-100%	No regulations (yet)

Table 9 Emission reduction with LNG as fuel [23]

b. Lower Fuel Cost

Switching to LNG as a fuel can have economic benefits because LNG is expected to cost less than MGO and HFO, see below Figure 44.

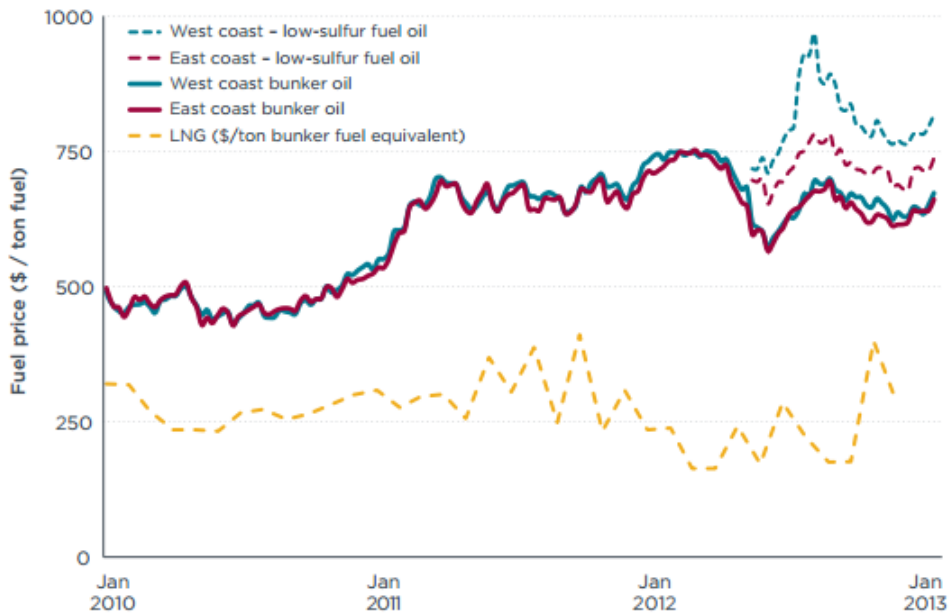


Figure 44 Fuel prices [16]

Fuel prices should always be compared based on energy content instead of mass because more energy is in one tonne of LNG than in one tonne of MGO and HFO. Today there are great variations of LNG prices depending on geographic regions. North America has the lowest natural gas price because of increased gas supply due to the growth of shale gas availability. Future fuel prices are always hard to predict, but experts assume that oil prices will remain high in the coming years and as oil resources decline prices will rise. As of now proven natural gas reserves have higher R/P-ratios than oil and are increasing at a faster rate. With shale gas increasing the world's natural gas supply the price advantage of LNG compared to conventional oil is expected to be maintained in the future.[16]

L. Main Disadvantages of LNG as a Fuel

The main disadvantages and possible obstacles for ship owners to switch to LNG as a ship fuel are explained in this chapter.

a. High Investment Cost

To be able to use LNG as a fuel the ships need purpose-built or modified engines, a system of special LNG fuel tanks, a vaporizer and a double insulated piping because of LNG properties and for safety reasons. The investment cost of a new built LNG fuelled ship is estimated to be about 20-25% more than of a conventional fuelled ship. The added investment cost will vary significantly between ship types and the cost it is expected to decrease in the future as more LNG fuelled ships are constructed.

The cost of converting a ship is more expensive than the added investment cost imposed on a new ship running on LNG propulsion. The equipment cost of converting an existing engine can be similar to buying a new engine, but the installation can be easier and cheaper. The largest expense of a conversion is installing the LNG tanks, piping, safety system and ship modifications. This cost can be five times the cost of the engine conversion or engine replacement. The total additional cost for LNG powered ships, compare to HFO/MGO, with a storage tank cost of 300 USD/GJ, is for the coast ships 708 USD/Kw, ocean-going 1450 USD/Kw and 770 USD/Kw for container vessel. The actual cost can vary between the ship type, size and configuration.[7,12]

An approximate installation cost and payback period calculation, based on an operation profile in Baltic Sea-ECA area can be found in Chapter VII.

b. More Space Demand

LNG tanks and fuel system require more space onboard ships compared to conventional oil. LNG has lower energy density compared to MGO (table 10).

ENERGY DENSITY RATIO FOR MGO AND LNG			
Fuel	Lower Heating Value MJ/kg	Density kg/m ³	Energy Density MJ/m ³
MGO	42,6	836	35.614
LNG	48,6	440	21.384
- LNG/MGO energy density ratio for given volume = 1,6			

Table 10 Energy density comparison [13]

This means that LNG needs about 1,6 times the volume compared to MGO to give the same amount of energy. The total volume needed for the tank and the tank room is expected to be about 2,5 to 4,0 times more than for conventional oil.

c. Methane Slip from Engine

With gas and dual-fuel engines running on Otto cycle process (low pressure engines-WARTSILA X-DF) in gas mode some methane slip of 1-2% occurs, i.e. uncombusted methane (CH₄) slips through the engine, especially at low engine loads. The GHG effect of methane is stronger than of CO₂, that is because methane is much more powerful than CO₂ as a greenhouse gas. i.e. one kg of methane released to the air corresponds to 21-25 kg of CO₂. But the volume of the methane slip from the engine is so small that the effect is limited and the total reduction of CO₂ by using LNG as a fuel compared to conventional oil would still be within 20-25%.

Methane emissions of 4-8 g/kWh for spark-ignited and low pressure dual-fuel Engines are reported from manufacturers. Methane slip does not occur in diesel-cycle mode, but only in Otto-cycle mode (dual-fuel as well as spark-ignited) and is generally higher at lower engine loads.

Even so the methane slip from gas engines has to be minimized and engine manufactures are working on overcoming this problem in order to guarantee the GHG reduction potential of LNG. If not it could become a concern for ship owners in countries where taxes are set on GHG emission. [6,13,58]

VII. EEDI Case Study

A case study vessel (Aframax Tanker) is investigated in regards to the attained EEDI value and its relevance to the reference line for different types of fuel and an alternative EEDI calculation based on a real operation profile.

A. Case Study EEDI Calculation based on Fuel Mode

For this case study, the particulars of a typical Aframax tanker have been used in order to calculate the energy efficiency design index and compare it to the baseline of the specific ship type [20, 21, 30, 55]. These particulars are:

Built Year:	2016
Shipyard:	DSME
Length Overall L_{OA} :	249.90 m
Length Water Line L_{WL} :	246.40 m
Length Between Perpendiculars L_{BP} :	242.20 m
Breadth B:	44.00 m
Depth D:	21.20 m
Draught Moulded T:	15.00 m
Capacity DWT:	112700 mt
Displacement Δ :	132939 mt
Fuel Type Used:	HFO, MDO, MGO
Fuel oil Tanks	2450 m ³
MDO/MGO Tanks	800 m ³
Speed V_{ref} :	14.5 knots
Installed Power M/E MCR_{ME} :	11820 Kw
Specific Fuel Consumption SFC_{ME} :	165,2 g/kWh
Number of installed M/Es:	1
M/E type:	HHI-MAN B&W 6G60ME
Installed Power A/E MCR_{AE} :	875 Kw
Specific Fuel Consumption SFC_{AE} :	205 g/kWh
Number of installed A/Es:	3
A/E type:	HiMSEN 7H17/28
Shaft Generator (P_{PTO}):	0
Shaft Motor (P_{PTI}):	0
Innovative Energy Saving Technologies (P_{eff} , P_{Aeff}):	0
Correction Factor f_j :	1
Correction Factor f_w :	1
Correction Factor f_i :	1
Correction Factor f_{eff} :	1

a. Case Study EEDI Reference Line Value Calculation

To calculate the value on the reference line graph of this specific vessel's size and type the instructions of chapter III should be followed. According to them the following formula is being used:

$$\text{Reference line value} = a (100\% \text{ deadweight})^{-c}$$

Where, the “a” and “c” are parameters determined from the regression curve fit, and are available in the contents of the Table 4 of page 29. Based on that table the “a” and “c” values for Tankers are “1218.8” and “0.488” accordingly. In this respect and including the deadweight of our Case Study Aframax Tanker (DWT=112,700mt) the reference line value of our vessel should be:

$$\text{Reference Line Value} = 1218.8 * (112,700)^{-0.488}$$

$$\text{Reference Line Value} = 4.178$$

Therefore the max EEDI value for the capacity of the case study vessel is 4.178 equal to the EEDI Phase 0.

EEDI Phases as follows:

	PHASE 0(2013)	PHASE 1(2015)	PHASE 2(2020)	PHASE 3(2025)
EEDI Req.	4,174	3,756	3,339	2,921

b. EEDI Calculation(MGO Mode)

The EEDI formula, given that the correction factors are all equal to 1, the existence of only one main engine and the unavailability of energy efficient applications (P_{PTO} , P_{PTI} , P_{eff} , P_{Aeff}), is converted to a more simplified version as follows:

$$EEDI = \frac{(P_{ME} \cdot C_{FME} \cdot SFC_{ME}) + (P_{AE} \cdot C_{FAE} \cdot SFC_{AE})}{Capacity \cdot V_{ref}}$$

The P_{ME} equals to the 75% of the installed power and the P_{AE} for vessels with propulsion of above 10,000 Kw equal to $((0.025 \cdot MCR_{AE}) + 250)$ therefore transforming the equation to:

$$EEDI = \frac{(0.75 \cdot MCR_{ME} \cdot C_{FME} \cdot SFC_{ME}) + ((0.025 \cdot MCR_{AE}) + 250) \cdot C_{FAE} \cdot SFC_{AE}}{Capacity \cdot V_{ref}}$$

Knowing from below table the required values, it is therefore easy to calculate the EEDI value for this case study ship:

DWT	112700	tons
V	14,5	Kts
M/E	11820	kW
M/E sfoc @ 75%MCR	165,2	g/kWh
D/G	545	kW
D/G sfoc	205	g/kWh
Cf(MGO)	3,206	ton CO ₂ /ton fuel

$$EEDI = \frac{(0.75 * 11820 * 3.206 * 165,2) + ((0.025 * 11820) + 250)3,206 * 205}{112700 * 14.5}$$

$$EEDI = 3.092$$

	PHASE 0(2013)	PHASE 1(2015)	PHASE 2(2020)	PHASE 3(2025)
EEDI Req.	4,174	3,756	3,339	2,921
EEDI Compliance	Satisfied	Satisfied	Satisfied	Not Satisfied

c. EEDI Calculation (HFO Mode)

The EEDI formula, given that the correction factors are all equal to 1, the existence of only one main engine and the unavailability of energy efficient applications (P_{PTO} , P_{PTI} , P_{eff} , P_{Aeff}), is converted to a more simplified version as follows:

$$EEDI = \frac{(P_{ME} \cdot C_{FME} \cdot SFC_{ME}) + (P_{AE} \cdot C_{FAE} \cdot SFC_{AE})}{Capacity \cdot V_{ref}}$$

The P_{ME} equals to the 75% of the installed power and the P_{AE} for vessels with propulsion of above 10,000 Kw equal to $((0.025 \cdot MCR_{AE}) + 250)$ therefore transforming the equation to:

$$EEDI = \frac{(0.75 \cdot MCR_{ME} \cdot C_{FME} \cdot SFC_{ME}) + ((0.025 \cdot MCR_{AE}) + 250) \cdot C_{FAE} \cdot SFC_{AE}}{Capacity \cdot V_{ref}}$$

Knowing from below table the Conversion factors, it is therefore easy to calculate the EEDI value for this case study ship:

DWT	112700	tons
V	14,5	kts
M/E	11820	kW
M/E sfoc @ 75%MCR	175,1	g/kWh
D/G	545	kW
D/G sfoc	215	g/kWh
Cf(HFO)	3,114	ton CO ₂ /ton fuel

$$EEDI = \frac{(0.75 * 11820 * 3.114 * 175,1) + ((0.025 * 11820) + 250)3,114 * 215}{112700 * 14.5}$$

$$EEDI = 3.179$$

	PHASE 0(2013)	PHASE 1(2015)	PHASE 2(2020)	PHASE 3(2025)
EEDI Req.	4,174	3,756	3,339	2,921
EEDI Compliance	Satisfied	Satisfied	Satisfied	Not Satisfied

B. Case Study EEDI Calculation based on LNG Mode

For this case study, the particulars of a LNG fuelled Aframax tanker have been used in order to calculate the energy efficiency design index and compare it to the baseline of the specific ship type [20,21,30,55]. These particulars are:

Built Year:	2016
Shipyard:	DSME
Length Overall L _{OA} :	249.90 m
Length Water Line L _{WL} :	246.40 m
Length Between Perpendiculars L _{BP} :	242.20 m
Breadth B:	44.00 m
Depth D:	21.20 m
Draught Moulded T:	15.00 m
Capacity DWT:	111200 mt
Displacement Δ:	132939 mt
Fuel Type Used:	HFO, MDO, MGO, LNG
Fuel oil Tanks	2450 m ³
MDO/MGO Tanks	800 m ³
LNG Tank Volume	2600 m ³
Speed V _{ref} :	14.5 knots
Installed Power M/E MCR _{ME} :	11820 Kw

Specific LNG Consumption SFC_{ME} :	132.1 g/kWh
Specific Fuel(Pilot) Consumption SFC_{ME} :	7.1 g/kWh
Number of installed M/Es:	1
M/E type:	HHI-MAN B&W 6G60ME-GI
Installed Power A/E MCR_{AE} :	1170 Kw
Specific LNG Consumption SFC_{AE} :	186 g/kWh
Specific Fuel(Pilot) Consumption SFC_{AE} :	4.8 g/kWh
Number of installed A/Es:	3
A/E type:	HHI-WARTSILA 8L20DF
Shaft Generator (P_{PTO}):	0
Shaft Motor (P_{PTI}):	0
Innovative Energy Saving Technologies (P_{eff} , P_{Aeff}):	0
Correction Factor f_j :	1
Correction Factor f_w :	1
Correction Factor f_i :	1
Correction Factor f_{eff} :	1

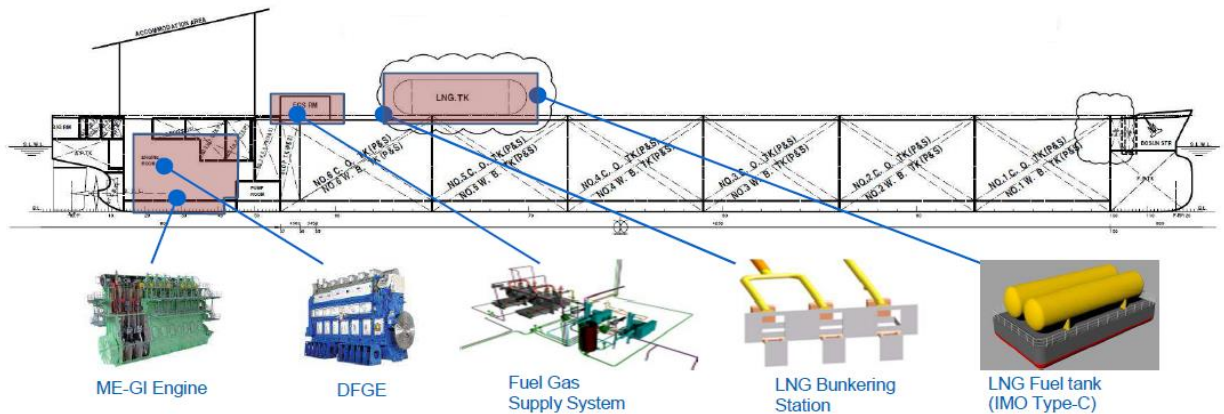


Figure 45 LNG fuel tank position on deck[8]

a. Case Study EEDI Reference Line Value Calculation

To calculate the value on the reference line graph of this specific vessel's size and type the instructions of chapter III should be followed. According to them the following formula is being used:

$$\text{Reference line value} = a (100\% \text{ deadweight})^{-c}$$

Where, the "a" and "c" are parameters determined from the regression curve fit, and are available in the contents of the Table of page 9. Based on that table the "a" and "c" values for Tankers are "1218.8" and "0.488" accordingly. In this respect and including the deadweight of our Case Study LNG Fuelled Aframax Tanker (DWT=111,200 mt) the reference line value of our vessel should be:

$$\text{Reference Line Value} = 1218.8 \cdot (111,200)^{-0.488}$$

$$\text{Reference Line Value} = 4.201$$

Therefore the max EEDI value for the capacity of the case study vessel is 4.201 equal to the EEDI Phase 0.

EEDI Phases as follows:

	PHASE 0(2013)	PHASE 1(2015)	PHASE 2(2020)	PHASE 3(2025)
EEDI Req.	4,201	3,781	3,361	2,941

b. EEDI Calculation (LNG Mode)

The EEDI formula, given that the correction factors are all equal to 1, the existence of only one main engine and the unavailability of energy efficient applications (P_{PTO} , P_{PTI} , P_{eff} , P_{Aeff}), is converted to a more simplified version as follows:

$$EEDI = \frac{(P_{ME} \cdot C_{FME} \cdot SFC_{ME}) + (P_{AE} \cdot C_{FAE} \cdot SFC_{AE})}{Capacity \cdot V_{ref}}$$

The P_{ME} equals to the 75% of the installed power and the P_{AE} for vessels with propulsion of above 10,000 kW equal to $((0.025 \cdot MCR_{AE}) + 250)$ therefore transforming the equation to:

$$EEDI = \frac{(0.75 \cdot MCR_{ME} \cdot C_{FME} \cdot SFC_{ME}) + ((0.025 \cdot MCR_{AE}) + 250) \cdot C_{FAE} \cdot SFC_{AE}}{Capacity \cdot V_{ref}}$$

Knowing from below table the Conversion factors, it is therefore easy to calculate the EEDI value for this case study ship:

DWT	111200	tons	
V	14,5	Kts	
M/E	11820	kW	
M/E sfc LNG @ 75%MCR	132.1	g/kWh	95%
M/E sfoc F.O @ 75%MCR	7.1	g/kWh	5% pilot fuel
D/G	545	kW	
D/G sfc LNG	186	g/kWh	95%
D/G sfoc F.O.	4,8	g/kWh	5% pilot fuel
Cf(MGO)	3,206	ton CO ₂ /ton fuel	
Cf(LNG)	2,75	ton CO ₂ /ton fuel	

$$EEDI = \frac{(0.75 \cdot 11820 \cdot 2.75 \cdot 132.1 \cdot 0.95 + 0.75 \cdot 11820 \cdot 7.1 \cdot 3.206 \cdot 0.05) + (545 \cdot 2.75 \cdot 186 \cdot 0.95 + 545 \cdot 3.206 \cdot 4.8 \cdot 0.05)}{111200 \cdot 14.5}$$

$$EEDI = 2.07$$

	PHASE 0(2013)	PHASE 1(2015)	PHASE 2(2020)	PHASE 3(2025)
EEDI Req.	4,201	3,781	3,361	2,941
EEDI Compliance	Satisfied	Satisfied	Satisfied	Satisfied

The use of LNG as the vessels primary fuel results to lower EEDI values. For example at the case study vessel's 14.5 knots reference speed, the MGO EEDI value is 3.066 while the LNG EEDI value is 2.07. This translates to 32% reduction in the case study vessel EEDI value which means that the case study vessel meets all EEDI phases and this happens only with LNG as primary fuel.

C. An Alternative EEDI Calculation Based on the Operation Profile at Design Speed

In this chapter we will calculate the EEDI with an alternative method in order to see how the operation profile of the specific ship can change the EEDI value. For this case study, the above particulars of a typical Aframax tanker and a LNG fuelled Aframax tanker have been used in order to calculate the energy efficiency design index based on the below year basis operation profile in ECA Area and compare it to original EEDI calculation of the specific ship type.

<u>OPERATION</u>	<u>%</u>	<u>DAYS</u>
LOADING	11	41,25
DISCHARGING	23	85
LADEN	25	90,8
BALLAST	29	105,85
WAITING LOADING	9	33,35
WAITING DISCHARGING	2	6,9

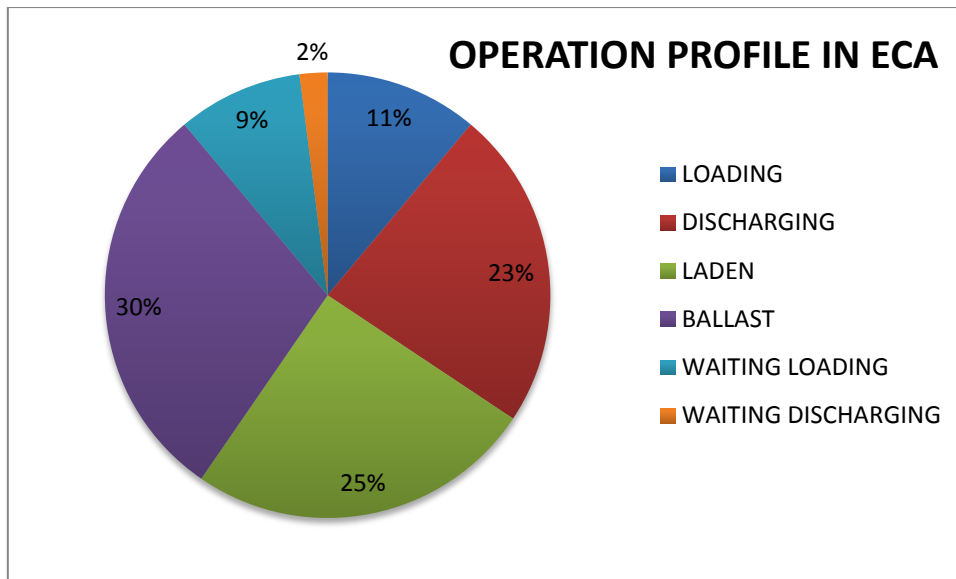


Figure 46 Operation profile chart

a. MGO Mode

$$EEDI = \frac{((0.75 * 11820 * 3.206 * 164) + ((0.025 * 11820) + 250)3,206 * 200) * 196.6 + ((0.025 * 11820) + 250)3,206 * 200) * 166.5}{112700 * 14.5 * 90.8}$$

$$EEDI_{MGO} = 7,032$$

b. HFO Mode

$$EEDI = \frac{((0.75 * 11820 * 3.114 * 172.4) + ((0.025 * 11820) + 250)3,114 * 210) * 196.6 + ((0.025 * 11820) + 250)3,114 * 210) * 166.5}{112700 * 14.5 * 90.8}$$

$$EEDI_{HFO} = 7,208$$

c. LNG Mode

$$EEDI = \frac{((0.75 * 11820 * 2.75 * 132.1 * 0.95 + 0.75 * 11820 * 7.1 * 3.206 * 0.05) + (545 * 2.75 * 186 * 0.95 + 545 * 3.206 * 4.8 * 0.05)) * 196.6 + ((545 * 2.75 * 186 * 0.95 + 545 * 3.206 * 4.8 * 0.05) * 166.5)}{111200 * 14.5 * 90.8}$$

$$EEDI_{LNG} = 4,78$$

FUEL	EEDI att.	EEDI oper.	%
HFO	3,143	7,208	129,335
MGO	3,066	7,032	129,354
LNG	2,068	4,78	131,141

As we can see the EEDI index is extremely high based on a real operation profile in design speed and the above issue should take into consideration in the future regulation review and updated of the EEDI value.

D. An Alternative EEDI calculation Based on the Operation Profile at Operational Speed

In this chapter we will calculate the EEDI with an alternative method in order to see how the operation profile of the specific ship can change the EEDI value. For this case study, the above particulars of a conventional Aframax tanker and a LNG fuelled Aframax tanker have been used in order to calculate the energy efficiency design index based on the above year basis operation profile with real operational speed and compare it to original EEDI calculation of the specific ship type.

OPERATION	%	DAYS
LOADING	11	41,25
DISCHARGING	23	85
LADEN	25	90,8
BALLAST	29	105,85
WAITING LOADING	9	33,35
WAITING DISCHARGING	2	6,9

a. MGO Mode

DWT	112700	tons
V	13	kts
M/E	11820	Kw
M/E sfoc @ 50%MCR	162	g/kWh
D/G	545	Kw
D/G sfoc	200	g/kWh
Cf	3,206	ton CO ₂ /ton fuel

EEDI

$$= \frac{((0.5 * 11820 * 3.206 * 162) + ((0.025 * 11820) + 250)3,206 * 200) * 196.6 + ((0.025 * 11820) + 250)3,206 * 200) * 166.5}{112700 * 13 * 90.8}$$

$$\mathbf{EEDI_{MGO}=5,49}$$

b. HFO Mode

DWT	112700	tons
V	13	kts
M/E	11820	Kw
M/E sfoc @ 50%MCR	170,1	g/kWh
D/G	545	Kw
D/G sfoc	210	g/kWh
Cf	3,114	ton CO ₂ /ton fuel

EEDI

$$= \frac{((0.5 * 11820 * 3.114 * 170.1) + ((0.025 * 11820) + 250)3,114 * 210)) * 196.6) + ((0.025 * 11820) + 250)3,114 * 210)) * 166.5)}{112700 * 13 * 90.8}$$

$$\mathbf{EEDI_{HFO}=5,6}$$

c. LNG Mode

DWT	111200	tons	
V	13	kts	
M/E	11820	Kw	
M/E sfoc LNG @ 50%MCR	127	g/kWh	95%
M/E sfoc F.O @ 50%MCR	9,3	g/kWh	5% pilot fuel
D/G	545	Kw	
D/G sfoc LNG	186	g/kWh	95%
D/G sfoc F.O.	4,8	g/kWh	5% pilot fuel
Cf(MGO)	3,206	ton CO ₂ /ton fuel	
Cf(LNG)	2,75	ton CO ₂ /ton fuel	

EEDI

$$= \frac{((0.5 * 11820 * 2.75 * 127 * 0.95 + 0.5 * 11820 * 9.3 * 3.206 * 0.05) + (545 * 2.75 * 186 * 0.95 + 545 * 3.206 * 4.8 * 0.05)) * 196.6) + ((545 * 2.75 * 186 * 0.95 + 545 * 3.206 * 4.8 * 0.05) * 166.5)}{111200 * 13 * 90.8}$$

$$\mathbf{EEDI_{LNG}=3,68}$$

FUEL	EEDI att.	EEDI oper.	%
HFO	3,143	5,6	78,17
MGO	3,066	5,49	79,06
LNG	2,068	3,68	77,95

As we can see if we change the EEDI formula based on a real operation profile at reduced ship's speed the value is lower than in normal design speed but it still remains high in comparison with the original EEDI value.

VIII. LNG Modification Cost and Payback Period

Below calculation is based on the operation profile in ECA Area of Chapter VI and includes consumption of the case study vessel (Aframax tanker) in t/day, fuel prices and LNG prices in USD/t (Rotterdam Port) and shows the comparison between different fuel type for the same operation profile. Also comparison includes the approximately modification cost which is abt. USD 18.000.000 based on prices at Chapter VI Section L(a). First table 11 is based on Rotterdam port bunker price (average) on 1st Quarter 2015 and the second table 12 on 4th Quarter 2015 same port. [30,59,60]

CONDITION	LADEN/BALLAST		IDLING/LOADING		DISCHARGING	
LSMGO	41,5	t/day	3	t/day	8	t/day
LNG	32,5	t/day	2,2	t/day	4,5	t/day
PILOT FUEL(LNG MODE)	1,7	t/day	0,12	t/day	0,24	t/day
TIME	197	days	81	days	85	days
LSMGO PRICE	580	USD/t	580	USD/t	580	USD/t
LNG PRICE	380	USD/t	380	USD/t	380	USD/t
LSMGO OPEX	4741790	USD	140940	USD	394400	USD
LNG OPEX	2627192	USD	73353,6	USD	157182	USD
TOTAL LSMGO	5277130	USD/year				
TOTAL LNG	2857727,6	USD/year				
DIFFERENCE	2419402,4	USD/year				
CAPEX	18000000	USD				
PAYBACK TIME	7,440	years				

Table 11 Payback time based on bunker price 1st Quar. 2015

The above operation profile in ECA area with an LNG price of abt. 380 USD/ton and LSMGO price abt. 580 USD/ton ensures a payback time of abt. 7,5 years.

CONDITION	LADEN/BALLAST		IDLING/LOADING		DISCHARGING	
LSMGO	41,5	t/day	3	t/day	8	t/day
LNG	32,5	t/day	2,2	t/day	4,5	t/day
PILOT FUEL(LNG MODE)	1,7	t/day	0,12	t/day	0,24	t/day
TIME	197	days	81	days	85	days
LSMGO PRICE	440	USD/t	440	USD/t	440	USD/t
LNG PRICE	280	USD/t	280	USD/t	280	USD/t
LSMGO OPEX	3597220	USD	106920	USD	299200	USD
LNG OPEX	1940056	USD	54172,8	USD	116076	USD
TOTAL LSMGO	4003340	USD/year				
TOTAL LNG	2110304,8	USD/year				
DIFFERENCE	1893035,2	USD/year				
CAPEX	18000000	USD				
PAYBACK TIME	9,509	years				

Table 12 Payback time base on Bunker prices 4th Quar. 2015

The above operation profile in ECA area and an LNG price of about 280 USD/ton and LSMGO price abt.440 USD/ton ensures a payback time of abt. 9,5 years.

As we can see, the payback period depends from the fuel prices. With higher fuel prices we have smaller payback period. In general it's a huge investment and the vessel has to travel only within ECA Area for consecutive years in order such retrofit to be a successful investment for the ship owner.

IX. Conclusion

The Shipping Business is growing day by day and for this reason we must implement measures to reduce atmospheric pollution from ships. Responding to the international regulatory attempts to reduce CO₂ emissions, IMO tried to create a regulatory framework in order to reduce same from the marine industry. This framework was based on the development of an index, the Energy Efficiency Design Index (EEDI), which was created for this exact purpose.

EEDI was put into effect on August 2011, as an obligatory measure for new buildings and it was added to MARPOL Annex VI by introducing proper amendments to the convention. It basically is a mathematical formula, which represents the cost, in this instance the CO₂ emissions, divided by the gain which is the transportation ability of a ship.

Therefore with the introduction of the EEDI value to the shipping industry, it is anticipated that the energy efficiency of a vessel will be an integral part to its construction and specification that shipyards have to pay attention. Having as an immediate effect the continuous improvement of the existing efficiency technologies and even to the introduction of newer more advanced ones.

With stringent regulations on emissions from ships, LNG as a ship fuel is gaining more attention from ship owners because LNG is a cleaner burning and less expensive fuel than conventional oil.

From CO₂ emission point of view LNG is better fuel than HFO or MGO. Heat value of LNG is about 50 MJ/kg while for HFO the value is about 40MJ/kg and for MGO the value is about 42.7MJ/kg. When efficiency difference of dual fuel engines is taken into account, the specific fuel consumption of dual fuel engines, measured in g/kWh, is about 20% lower in gaseous fuel mode compared to similar size low speed two stroke HFO engine. As the carbon conversion factor for LNG is 2,75 ton CO₂/ton fuel instead of 3,144 ton CO₂/ton fuel for HFO, each kilogram of fuel burned in dual fuel engine would also emit about 12% less CO₂ than in HFO fuelled engine. In Otto-Cycle two stroke engine also the methane slip shall consider as emission but even that the advantages in specific fuel consumption and carbon conversion would give a total benefit of about -30% in carbon emissions to LNG fuelled ship. Reductions in these air emissions will benefit human health and the environment, including benefits from reduced acid deposition in our oceans.

When considering the switch to LNG fuels, price trend predictions for fuel oils and LNG fuels become a key deciding factor. So far, the price of gas has followed a similar fluctuation to that of crude oil, while maintaining a certain price gap about 35-45%. In the future, the addition of even cheaper shale gas as another fuel option is likely to further promote the wider adoption of more popular LNG fuels in place of crude oil.

The switch to LNG as a fuel source involves more than just changes in vessel specifications. It is a long process that requires a significant investment in areas such as infrastructure development to transport and supply LNG fuels. Regarding the EEDI calculation for both cases, the reduction of the EEDI value is about 30% using LNG as fuel and with LNG fuel the case study ship can meet all the future phases of the EEDI.

The lack of infrastructure has to be solved for LNG to expand as a ship fuel because ship owners will not invest in new ships running on LNG or convert existing ships unless there is a secure supply of the fuel at a reasonable price. By equipping the ships with dual-fuel propulsion running either on LNG or MGO the ship owners have fuel flexibility and can run on MGO/HFO if LNG is not available in some ports or depending on fuel prices.

Due to the high investment cost needed to build a LNG fuelled ship, the owners have to take in the consideration the operation profile of the potential LNG fuelled ship and especially the percentage of the ship's voyages within the ECA areas where emission restrictions and fuel prices are the major issues for consideration.

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