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# Alternative Fuels for Shipping: Potential for reductions in $CO_2$ emissions, Financial viability for ship owners and, Optimised fleet mix design for policymakers.

By

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## Abstract

Alternative fuels for shipping have been discussed in shipping circles for a few years now. However, their adoption is mired in scepticism from various quarters of the industry. Global climate change necessitates urgent action from the shipping industry, action which goes far beyond relying on just operational measures to realise the goal of restricting global warming to less than $2^0$C by 2100.

In this study, we assess the emissions reduction potential and investment viability for ship-owners of two fossil-based fuels, four biomass-based fuels and two blended fuels. The fuels evaluated are MDO, LNG, RME, RME 50, LBG, LBG 50, Methanol and, Ethanol. To do this, we developed a multi-dimensional Maritime Alternative Fuels Emissions Assessment Model which incorporates all elements of the study. We generated a shipping emissions inventory adaptable to different fuels, and our results prove that some alternative fuels indeed have great potential for the reduction of $CO_2$ emissions from shipping. With the help of a strong emissions reduction policy, some of these alternative fuels will be a choice that ship-owners will readily invest in, as they will be more profitable than conventional marine fuels. We find that LNG, LBG and LBG 50 are already very attractive investment options for ship-owners while Methanol and Ethanol become feasible if a carbon tax/levy is implemented. We find that MDO is the least profitable option for ship-owners with RME, representing biodiesel, and RME 50 faring slightly better than MDO.

We calculate the marginal abatement costs (MAC) of emissions reduction incurred by the shift to each of these selected fuels and find that the gas-based fuels have the least marginal abatement cost followed by Methanol and Ethanol. Our model uses a simple linear programming optimisation to find the optimal fleet mix at the least MAC, and substantial reduction of $CO_2$ emissions. Our results show that policymakers need to focus on boosting the availability of the selected alternative fuels to achieve sustained emissions abatement. Our optimal fleet mix design suggests that policymakers should strive for a diverse fleet, whereby 53.2% of the energy requirement is met by gas-based fuels, other fuels also get assignment based on their availability with MDO acting as a fill-in to complete the fleet mix. This fleet mix will reduce $CO_2$ emissions by 27.89% from current levels at a marginal abatement cost of \$209.83/MT-$CO_2$ to the industry.



**Key Words**: Marine fuels, $CO_2$ emissions, Biofuels, Shipping emissions inventory, Investment Analysis, Optimised Fleet Mix, Marginal Abatement Costs, LNG, LBG, Methanol, Ethanol, RME.

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## List of Abbreviations and Acronyms

| | |
|---|---|
| AE | Auxiliary Engine |
| AIS | Automatic Identification System |
| AR4 | IPCC Fourth Assessment Report, 2007 |
| AR5 | IPCC Fifth Assessment Report, 2014 |
| BAU | Business as Usual |
| BECCS | Bioenergy with Carbon-dioxide Capture and Storage |
| BIMCO | Baltic and International Marine Council |
| BP | British Petroleum |
| CATCH | Cost of Averting a Tonne of CO2-equivalent Heating |
| CBDR | Common but differentiated responsibility |
| CCS | Carbon-dioxide Capture and Storage |
| $CH_4$ | Methane |
| CIF | Cost, Insurance and Freight Paid |
| $CO_2$ | Carbon Di-Oxide |
| COP | Conference of the Parties |
| cSt | Centi-stokes |
| DF | Dual Fuel |
| DME | Di-Methyl Ether |
| DOC | Daily Operating Costs |
| ECA | Emission Control Area |
| EEDI | Energy Efficiency Design Index |
| EJ | Exa-Joules |
| ETBE | Ethyl Tertiary-Butyl Ether |
| EtOH | Ethanol |
| ETS | Emissions Trading Scheme |
| EU | European Union |
| FOB | Free On-Board |
| g/kWh | Gram per kilo-watt hour |
| gCO2/T-km | Gram CO2 per tonne-kilometer |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| GJ | Giga-Joules |
| GT | Gross Tonnage |
| GTAP | Global Trade Analysis Project Model |
| HA | High Availability Scenario |
| HFO | Heavy Fuel Oil |
| HSD | High-Speed Diesel Engine |
| IAM | Integrated Assessment Model |
| ICS | International Chamber of Shipping |
| IEA | International Energy Agency |
| IFO | Intermediate Fuel Oil |
| IGF Code | International Code of Safety for Ships using Gases or other Low-flashpoint fuels |
| IMarEST | Institute of Marine Engineering, Science and Technology |
| IMF | International Monetary Fund |
| IMO | International Maritime Organisation |
| INDC | Intended Nationally Determined Contributions |
| IPCC | Intergovernmental Panel on Climate Change |
| IRR | Internal Rate of Return |

| | |
|---|---|
| IWGSCC | Interagency Working Group on Social Cost of Carbon |
| KP | Kyoto Protocol |
| kW | Kilo-Watt |
| LA | Low Availability Scenario |
| LBG | Liquefied Biogas |
| LCA | Life-cycle Assessment |
| LIS | Leveraged Incentive Scheme |
| LNG | Liquefied Natural Gas |
| LRIT | Long Range Information and Tracking |
| MAC | Marginal Abatement Cost of CO2 Emissions |
| MARPOL | International Convention for the Prevention of Pollution from Ships, 1973/78 |
| MBM | Market Based Measures |
| MCR | Maximum Continuous Rating of engine |
| MDO | Marine Diesel Oil |
| ME | Main Engine |
| MeOH | Methanol |
| MEPC | Marine Environment Protection Committee |
| MERS | Maritime Emissions Reduction Scheme |
| METS | Maritime Emissions Trading System |
| MGO | Marine Gas Oil |
| MJ | Mega-Joules |
| mmBtu | Million British Thermal Units |
| MRV | EU Regulation for Monitoring, Reporting and Verification of CO2 emissions from Maritime Transport, 2015/757 |
| MSCM | Maritime Sector Crediting Mechanism |
| MSD | Medium-Speed Diesel Engine |
| MT | Metric Tonne |
| MTBE | Methyl Tertiary-Butyl Ether |
| MTD | Metric Tonne Per Day |
| MTOE | Million Tons Oil Equivalent |
| NOAA | National Oceanic and Atmospheric Administration |
| $NO_x$ | Oxides of Nitrogen |
| NPV | Net Present Value |
| OECD | The Organisation for Economic Co-operation and Development |
| p.a. | Per Annum |
| PJ | Peta-Joules |
| PM | Particulate Matter |
| RCP | Representative Concentration Pathways |
| RED | Renewable Energy Directive, 2009/28/EC |
| RF | Radiative Forcing |
| RME | Rapeseed Methyl Ester |
| Ro-Ro | Roll-on, Roll-Off |
| SCC | Social Cost of Carbon |
| SEEMP | Ship Energy Efficiency Management Plan |
| SFOC | Specific Fuel Oil Consumption |
| SGMF | Society for Gas as a Marine Fuel |
| SIN | Clarksons Shipping Intelligence Network |
| $SO_x$ | Oxides of Sulphur |
| SSD | Slow-Speed Diesel Engine |
| SSP | Shared Socioeconomic Pathways |

| | |
|---|---|
| TCE | Time Charter Equivalent |
| TEU | Twenty-foot Equivalent Unit |
| TJ | Tera-Joules |
| TTW | Tank-to-Wake |
| TWh | Tera-Watt Hour |
| UNCTAD | United Nations Conference on Trade and Development |
| UNFCCC | United Nations Framework Convention on Climate Change |
| WTP | Well-to-Propeller |
| WTT | Well-to-Tank |
| WTW | Well-to-Wake |

## Conversion Factors

The following conversion factors have been used in the calculations for this study.

| Conversion Factor | Equivalent Units | |
|---|---|---|
| | Value | Units |
| 1 Centi- | $10^{-2}$ | - |
| 1 Kilo- | $10^{3}$ | - |
| 1 Mega- | $10^{6}$ | - |
| 1 Giga- | $10^{9}$ | - |
| 1 Tera- | $10^{12}$ | - |
| 1 Peta- | $10^{15}$ | - |
| 1 Exa- | $10^{18}$ | - |
| 1 $m^3$ (cubic meter) | 6.28981 | Oil Barrels (bbl) |
| 1 US Gallon | $3.785 \times 10^{-3}$ | $m^3$ |
| 1 MT (metric tonne) | 1000 | kg |
| 1 mmBtu (million British thermal units) | 1.055 | GJ |
| 1 TOE (Ton Oil Equivalent) | 41.868 | GJ |
| 1 TJ (Tera-Joule) | $2.388 \times 10^{-5}$ | MTOE |
| 1 TJ | $9.478 \times 10^{2}$ | mmBtu |
| 1 TJ | $2.778 \times 10^{-1}$ | GWh |
| 1 bcm LNG (billion cubic meters) | 0.90 | MTOE |

# 1. Introduction

## *1.1 Background*

World seaborne trade has seen a steady increase in volumes over the last five decades and continues to be driven by the global economic growth. International shipping carries as much as 90% of the trade by volume and is considered to be a key player in the supply chain contributing to economic development and prosperity (UNCTAD, 2015). This transport service, however, induces several negative externalities of which greenhouse gas (GHG) emissions has been of prime concern in the recent past.

In 2012, international shipping emitted approximately 796 million tonnes of $CO_2$ which accounts for about 2.2% of the total global GHG emissions. In contrast to the growing demand for trade in merchandise, the emissions from shipping have, in fact, decreased from the previous GHG emissions inventory for 2007 which stood at 885 million tonnes, representing 2.7% of the global emissions (Smith, et al., 2015). Emissions from international shipping are projected to increase significantly over the next three decades depending on future economic scenarios and developments in the energy sector. In a business as usual (BAU) scenario, it is estimated that maritime emissions would increase up to 250% from a 2005 baseline (Smith, et al., 2015). The shipping industry is one of the most energy and carbon-efficient modes of transportation, however, in the pursuit of an environmentally sustainable future, the industry will need to make enduring changes in every aspect of operations. In Figure 1-1, we present the comparison of $CO_2$ emissions from the main freight transport modes.

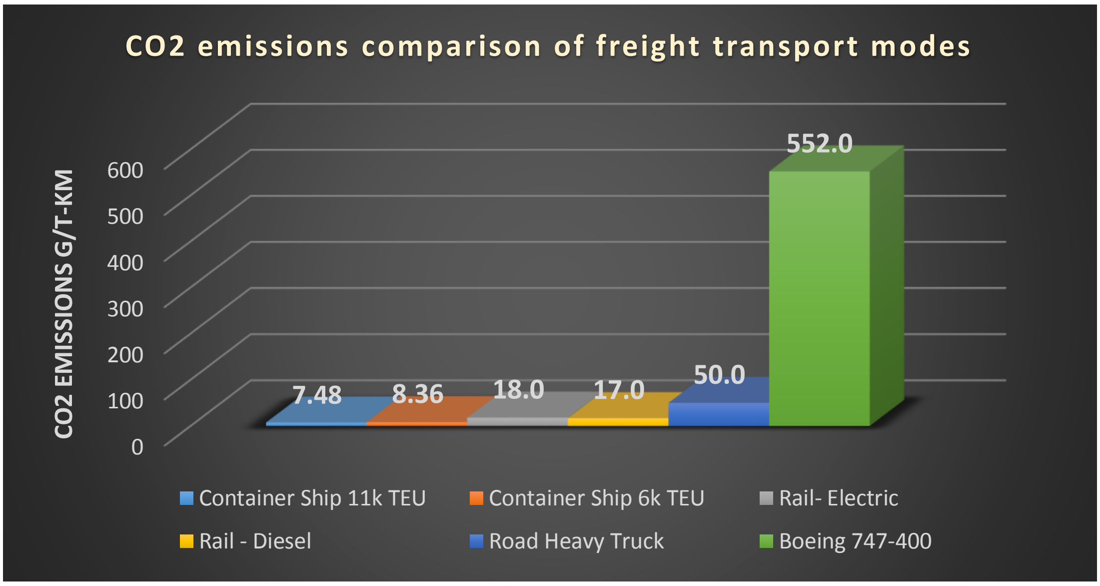


*Figure 1-1: $CO_2$ emissions comparison of freight transport modes*
*Source: Adapted from Dekker, et al. (2012)*

The primary source of emissions from global shipping is the production of exhaust gases from the vessel's main and auxiliary propulsion systems. Global shipping emissions have been largely unregulated until the establishment of emission control areas under the provisions of MARPOL Annex VI which placed a cap on $SO_x$ and $NO_x$

emissions while operating in these regions, achieved primarily by using fuels containing a sulphur content of 0.1% or less. While operating in other international waters, vessels use fuels with a sulphur content of 3.5% or less. $CO_2$ emissions have not been brought under the purview of these regulations yet. GHG Emissions from international shipping are currently not subject to limitation and reduction commitments of the UNFCCC and the Kyoto Protocol or any other legally binding international convention, but there is mounting pressure from several international fora to effect substantial reductions in these emissions (Franc & Sutto, 2014).

A wide range of emission reduction measures incorporating technical and operational improvements have been developed but to achieve sustainable levels of reduction, the IMO has delegated the Marine Environment Protection Committee (MEPC) to develop a market-based instrument applicable to the maritime industry globally (McCollum, et al., 2009). Different member states have made proposals as to the design of such market-based measures (MBM) which are still on the table for discussion. It is quite clear that some form of $CO_2$ regulations will be implemented in the near future (Eide, et al., 2009). The EU has already brought the aviation industry under the ambit of the EU Emissions trading scheme (ETS) since 2012 (Ares, 2012) and discussions are ongoing to include shipping in the scheme as well.

The last radical change in marine propulsion systems was the shift from coal-fired and later oil-fired steam turbines to diesel-based internal combustion engines, which have been the mainstay of the shipping industry for the last six decades (Chryssakis, et al., 2014). Alternative fuels have been used in the transportation industry for quite some time, on a subtle scale, however. Growing concern for climate change has stimulated greater interest in alternative fuels worldwide. The need to reduce GHG emissions from the shipping industry can be addressed by increased use of alternative fuels, some of which have extremely low carbon emissions factor. The most widely recognised alternative fuel for shipping currently being discussed is Liquefied natural gas (LNG). Methanol, Di-methyl ether (DME), Hydrogen from fuel cells and Nuclear fuel are other alternatives. Bio-fuels viz. Ethanol, Rapeseed methyl ester (RME) and Liquefied biogas (LBG) have gained popularity in the energy sector in the recent past. Ethanol is currently used as a blend with gasoline or petrol, while RME is the principal component of bio-diesel. The introduction of these alternatives in the shipping industry could have a far-reaching impact on the vessel's GHG emissions as well $SO_x$ and $NO_x$ emissions depending on the extent to which these fuels could substitute conventional fuels (Chryssakis, et al., 2014) (Brynolf, et al., 2014).

The use of bio-fuels for shipping is technically feasible, availability on a large scale is an issue, however. They are produced from a range of agricultural crops and biomass. Bio-diesels from RME can replace MDO/MGO in all types of marine diesel engines, while LBG or bio-methane can replace LNG in gas fuelled marine engines. The biofuels have a lower energy density than conventional marine fuels implying that a larger quantity of biofuels will be required to fulfil the energy requirements on a per ship basis (Florentinus et al. 2012).

## *1.2 Problem Identification*

The use of LNG, considered a promising choice as a marine fuel, will reduce $SO_x$ and $NO_x$ emissions substantially (Eide, et al., 2011). However, the reduction in $CO_2$ emissions is not sufficient to fulfil the long-term targets that the industry as a whole is working towards. Nevertheless, there has been considerable interest in LNG with industry players actively pursuing strategies to push for wider acceptance and use of LNG as a marine fuel (SGMF, 2013). Ship-owners are warming up to the idea of investing in gas fuelled ships, albeit slowly, the long-term earning potential of these ships are yet to be realised.

In comparison to LNG, Biofuels have an even more reduced emissions footprint with $CO_2$ reductions of up to 75% from that of Heavy fuel oil (HFO), which is the current mainstay fuel of the shipping industry (Bengtsson, 2011). These biofuels are currently more expensive than fossil-based fuels owing to higher production costs, lack of economies of scale and limited distribution networks. With fuel costs contributing to the largest share of operating expenses for a ship owner, a shift to biofuels presents a major hurdle unless the increased fuel costs are offset by reductions in other operating expenses (Florentinus, et al., 2012); (McCollum, et al., 2009).

Methanol and ethanol have also been considered as potential alternative fuels for shipping. Certain pilot projects for the use of methanol as a marine fuel have already been implemented and are showing positive results. Ethanol has been used in diesel engines for road transportation for many years and is considered a viable option for the shipping sector as well (Ellis & Tanneberger, 2015). Methanol and ethanol can be fossil-based or produced from biomass. It is the biomass-based methanol and ethanol which could have a greater impact on the objective of GHG emissions reductions (Bengtsson, et al., 2011) and the shipping industry is actively investigating this avenue. Ellis & Tanneberger (2015) note that the investment costs of methanol and ethanol propelled ships are significantly lower than ships propelled by LNG.

The price formation mechanisms of these alternative fuels involve a wide array of exogenous and endogenous factors. The prices of non-fossil based fuels tend to be higher than their fossil-based counterparts. It has been observed that some form of price indexation against the conventional fuels is evident (SGMF, 2014). The prevalent use of fossil fuels in the production of alternative fuels (Dekker, et al., 2012) not only props up the price of these fuels but also contributes adversely to its emissions potential when considered from well-to-wake (WTW) or well-to-propeller (WTP). Notteboom (2011) in a study of the impact on freight rates in short sea shipping by ECA requirements noted that the increase in fuel price would increase the freight rate, but a significant portion of the cost differential would be absorbed by the operator thereby inflating his expenses. The volatility in bunker prices, which closely follows the price of crude oil in international markets, makes it tough to assess the financial ramifications accurately to using alternatives to conventional marine fuels (Notteboom, 2011).

Projected increases in GHG emissions from shipping are not compatible with the internationally agreed goal of reducing global emissions by 50% in 2050 from 1990 levels to keep global temperature increase below $2^0$C in comparison to pre-industrial levels (European Commission, 2013).The EU transport policy has set a target of 60% reduction in the emissions from transport by 2050 from 2005 levels (Golinska & Hajdul, 2012). The IMO has already set the tone for substantial reductions in GHG emissions by mandating ships constructed after 2025 to be 30% more fuel efficient than those built in 2000. The industry intends to achieve the reduction target of 50% in 2050 by utilising a range of operational and technical improvement measures, a prime option among which is the use of clean, low carbon fuels (ICS, 2015).

A mandated global data collection system of GHG emissions, as approved by MEPC 69 (2016), will conform to the United Nations Framework Convention on Climate Change (UNFCCC) requirement to report inventories of anthropogenic emissions from all sources and subsequently facilitate accurate allocation of emissions to relevant players in the industry. The global nature of maritime trade makes it extremely complicated to allocate emissions to a particular nation. The MEPC 62 (2011) has agreed upon a new work plan and guidelines to develop market-based instruments viz. carbon tax and emissions trading scheme (Lee, et al., 2013). Any kind of carbon ETS or carbon levy system in international shipping could potentially alter the revenue flows for a ship owner significantly as this, being directly proportional to the amount and type of fuel used, would account for a marked increase in operating expenses. Lee, et al. (2013) estimated that for a container vessel, the increase in shipping costs per TEU from China to NW Europe would be about 8% using a carbon tax rate of $ 30/ton $CO_2$. Going by these estimates, a 8% increase in operating expenses calls for careful consideration and implementation of abatement measures. The International Chamber of Shipping which represents the ship owners and operators at the IMO has indicated a preference for a market-based measure linked to fuel consumption viz. a global fuel levy rather than a emissions trading system (ICS, 2014). Shipping companies would need to understand and analyse the options available at hand to reduce emissions in conjunction with running a ship profitably. They would need to factor these changes in their strategies for ownership and operations in the long term.

Drawing from the relationships above, one could say that the current crop of alternative fuels would, undoubtedly, contribute to the reduction of emissions from shipping. The question that remains to be answered is whether this concept will be embraced by ship-owners and could policy makers make conditions conducive for this change.

## *1.3 Research question and objectives*

Guided by the identified problem, this study pivots around the following main research question:

**How could the use of alternative fuels contribute to the reduction of carbon emissions from shipping?**

The main goal of the study is to research how carbon emissions from shipping can be reduced using alternative fuels under circumstances that we reasonably believe will pan out in the near future. In doing so, we will need to develop a model that can quantitatively allow us to assess the reduction in carbon emissions using a range of fuels and determine a fleet structure that would allow certain set target reductions. These results would lead us to the overbearing question of whether a ship-owner would benefit from the use of these alternative fuels. Under the premise that ship-owners and the industry, in general, were to behave rationally, we shall assess the fundamental capital budgeting elements of investing in ships fuelled by the different alternative fuels.

Achieving a reduction in carbon emissions that is beneficial for society does come at a price. Determining an optimum fleet mix that would give a maximum reduction of emissions at the least cost will direct policymakers to design effective climate change policies. Such measures can incentivize the industry to invest in alternative fuels for shipping treading the path to a sound conclusion to our main research question.

We need to investigate the effect of alternative fuels on carbon emissions, its benefit to society as well as the ship-owners under different conditions identified by the sub-research questions. Each of these questions is mutually exclusive but collectively exhaustive to answer the main research question comprehensively and fulfil our research objectives. Following are the identified sub-research questions:

1. What factors do we need to incorporate into a model to calculate emissions from shipping using different alternative fuels, and link the same to a financial decision support tool for ship-owners?

2. What proportion of the current fleet would need to shift to particular alternative fuels to achieve set reduction targets for the shipping industry?

3. What conditions of fuel pricing, carbon pricing and earnings would make it conducive for ship-owners to invest in alternative fuels for shipping?

4. How can policymakers derive an optimised fleet mix at the least cost to the industry considering the potential for reductions from the selected alternative fuels?

## *1.4 Research Design and Methodology*

The research intends to be focussed on the quantitative assessments using data collected from various sources. Certain qualitative elements will be inducted primarily through literature review, interactions with shipping database providers and market players that have ongoing projects dealing with alternative fuels.

The sub-research questions can be classified broadly into two distinct, but interlinked, categories based on the approach used to answer it effectively. Sub-research question one (1) focusses on building the model and data collection. The remaining sub-research questions will use the model to address the different complications posed in answering the main research question.

Sub-research question one (1) will identify the fundamental variables required to develop an accurate inventory of GHG emissions from the shipping fleet and use available data in conjunction with reasonable assumptions to estimate the current level of emissions. We shall also identify the key expenses linked to vessel operation and see how costs of operation would vary using alternative fuels considering a price on carbon emissions is in place. Finally, it will address the capital budgeting structure that a ship-owner will need to assess the financial viability of an investment in alternative fuel propelled ships.

Sub-research question two (2) will use the model to analyse possible reductions in GHG emissions while using the different alternative fuels. It will further assess the level of acceptance or penetration required within the industry for each alternative fuel to achieve certain set reduction targets for GHG emissions.

Sub-research question three (3) looks to analyse the financial viability for ship-owners under different varying market conditions using the identified alternative fuels. Scenarios for pricing of the fuels and carbon emissions price will be identified using secondary research and plugged into the model. A comparative analysis of financial viability using Net present value (NPV) will be used to develop an investment ranking that will aid ship-owners to appraise the investment proposals for alternative fuels.

Sub-research question four (4) will use the results obtained in the earlier steps to enable policy makers to find quantitatively an optimal fleet mix using the selected alternative fuels at the least cost to the industry such that ship-owning will remain competitive. While acknowledging the uncertainties of market conditions, it looks to propose a sustainable fleet ownership strategy beneficial for ship-owners and internalise the externality of GHG emissions for society as a whole.

### *1.4.1 Thesis Structure*

Chapter 1 introduces the subject, identifies the research questions and lays the foundation for the research drawn from the background of the identified problem. Chapter 2 will form the literature review and theoretical background of this research where we shall examine academic work carried out in fields pertinent to the context of our study. We shall examine studies relevant to emissions and internalisation of externalities, reduction targets for GHG emissions, the cost of emission rights, alternative fuels for shipping and, operational and technical measures to reduce emissions from ships.

Chapter 3 will introduce the alternative fuels selected for our study from a review of current literature. We will discuss the main physical characteristic of these fuels with special regards to the emissions generated. We will outline the historical pricing of these fuels and then define four scenarios considering the state of technological progression in alternative fuels. We shall define availability scenarios for the selected alternative fuels.

Chapter 4 will detail the methodology and data used in building the model. We shall explain the key assumptions and, relationships between the variables and parameters used in our model. Further, the limitations of the model will be discussed. Chapter 5 will present the output and main results from the model. We shall see how these results can be interpreted to achieve tangible results in the future. We shall carry out a sensitivity analysis to assess the effect of the different variables on our results.

Chapters 6 will provide the conclusions of the study. We shall summarise the key findings and how they relate to our research questions. Finally, we shall outline the limitations of the study and suggest fields for further research that have not been explored and could add value to this research.

### *1.5 Relevance of this study*

Global climate change dialogue and the ensuing green planet initiatives necessitate urgent changes in the way we deal with emissions from the shipping industry. The COP 21 round of talks (Paris) of the UNFCCC surprisingly did not stipulate any changes for the shipping industry. With the shipping industry contributing 3.1% of global CO2 emissions and 2.8% of GHG's emissions (Smith, et al., 2015), an ETS could well be a distinct possibility. A price on carbon emissions could, potentially, have the effect of making ship-owning not a very attractive proposition for ship-owners.

Policy makers will need to assess carefully the environmental benefits from the increased use of alternative fuels, primarily based on the reduction of emissions and achieving set targets. Should the use of these fuels indeed be beneficial for society as a whole and sustainable in the long term, then incentivizing the particular alternative fuel(s) could be explored further and policies designed accordingly.

From the shipowner's perspective, fuel costs represent a significant proportion of the total operating expenses for a vessel (McCollum, et al., 2009). The use of alternative fuels to reduce emissions might very well be mandated and not a matter of choice for the ship-owners. Ship owners will need to be prepared for these regulatory changes, whenever devised and implemented, and strategize their businesses accordingly.

To the best of our knowledge, no study yet has encompassed these different yet interrelated complications simultaneously and therefore, would be of great relevance to key players in the shipping industry and policy makers alike.

## 2. Climate change, Cost of emissions and GHG emissions from shipping

This chapter seeks to review the literature that forms the theoretical background of this study. We first look at the main discussion surrounding climate change and the need to reduce GHG emissions. We shall then address the global emissions reduction targets, costs of climate change and literature pertaining to the cost of carbon emissions. We shall then discuss carbon emissions from shipping and the current measures in place to reduce these emissions. We outline the operational and technical measures adopted in shipping to reduce emissions and the design of proposed market-based measures for the shipping industry.

### *2.1 Climate change and carbon emissions*

In humanity's relentless pursuit of a sustainable future for its progeny, climate change has often been referred to as one of the most pressing concerns of our generation. The Intergovernmental Panel on Climate Change (IPCC) released its fifth assessment report (AR5) in four parts over September 2013 to November 2014. The AR5 shows empirical evidence of the unequivocal warming of the global climate system over the past few decades. The report terms the observed changes as "unprecedented".

There is overwhelming evidence showing that the last three decades have been successively warmer compared to any other decade since 1850, with results indicating that in the last 1400 years the period 1983-2012 has been the warmest 30-year period (IPCC, 2013). This warming is not localised to areas of human inhabitancy. The oceans have warmed and, amounts of snow and ice have diminished significantly. Experts believe that climate change is driven by increased radiative forcing (RF) of the earth's atmosphere which has resulted in a marked increase of energy uptake by the climate system. The increase in stored energy propagates to the entire ecosystem with the oceans accounting for more than 90% of accumulated energy over the last 40 years. Increase in the atmospheric $CO_2$ concentrations has been determined to be the main contributor to this increase in RF (IPCC, 2013).

The measurable changes in the climate system can be quantified by the increased uptake of energy and heat by the oceans, melting of glaciers, soil warming, extreme levels of precipitation and intensified water cycle. The rise in global sea level due to thermal expansion of water is considered to be the most encompassing impact of global climate change (Stocker, 2013).

The atmospheric concentration of $CO_2$ has varied over the past 800,000 years. However, this variation has been within clear bounds until the last 250 years. In fact, the 9.9 billion tonnes of carbon emitted in 2013 resulted in a concentration of $CO_2$ measured in the atmosphere to be 30% higher than any concentration estimated yet (Stocker, 2013). Improved climate models since the IPCC's earlier assessment report (AR4) indicate a profound human influence on climate change and more specifically $CO_2$ emissions, primarily from the combustion of fossil fuels and augmented by intensive deforestation for land use. IPCC (2013) notes that it is "extremely likely" that human influence has been the dominant cause of global warming since industrialisation.

The AR5 estimates the total anthropogenic GHG emissions in 2010 to be 49 ± 4.5 Giga-tonnes $CO_2$-equivalent per year of which 65% has been attributed to fossil fuels and industrial processes. $CO_2$ accounts for 90% of the GHG emissions (OECD / IEA, 2015). 78% of the increase in cumulative emissions from 1970 to 2010 has been due to increased use of fossil fuels. The current concentration of $CO_2$ in the atmosphere on a global average is 404 ppm, (May 2016) (NOAA, 2016). This concentration hovered at 285 ppm in 1850 and 325 ppm in 1970 (NASA, 2011). Evidently, the concentration has grown incessantly and showed no sign of abatement yet. Using current growth rates as a baseline scenario and without further abatement measures, the atmospheric concentration of $CO_2$ is likely to be in the range of 720-1000 ppm or more. This would result in a global increase in temperature of 2.5 to 7.8$^0$C over pre-industrialization (1850-1900) levels. Limiting this change necessitates significant and sustained reductions in GHG emissions through measures adopted globally (IPCC, 2014a).

### *2.1.1 Reduction targets*

Climate models developed by the IPCC for AR5 show that to limit the global warming to less than 2.0$^0$C relative to temperatures recorded over 1861-1880, the cumulative $CO_2$ emissions until the year 2100 would need to be limited to less than 2900 Gt. The point of relevance is that 1900 Gt has already been emitted by 2011 (IPCC, 2014a). The 2.0$^0$C limit entails the atmospheric concentration of $CO_2$ to be within the range of 430 – 480 ppm in the year 2100. In terms of emissions reductions, this means by the year 2050 emissions will have to be 72 – 41% less than 2010 baseline and 118% less in the year 2100 (IPCC, 2014a). These emissions reduction targets are summarised in Table 2-1.

*Table 2-1: $CO_2$ reduction targets to contain global warming*

| **$CO_2$-eq concentration in 2100** | **Change in emissions from 2010 baseline (in %)** | | **Most likely achievable global warming threshold (relative to 1850-1900)** |
|---|---|---|---|
| | 2050 | 2100 | |
| 430 – 480 ppm | -72 to -41% | -118 to -78% | 2$^0$C |
| 480 – 530 ppm | -57 to -42% | -107 to -73% | 3$^0$C |
| 530 – 580 ppm | -47 to -19% | -81 to -59% | 3$^0$C |
| 580 – 650 ppm | -38 to +24% | -134 to -50% | 3$^0$C |
| > 650 ppm | -11 to +17% | -54 to -21% | 4$^0$C |

*Source: Adapted from IPCC (2014a)*

Risks from climate change largely depend on the cumulative emissions of $CO_2$ over the coming years which in itself depends on the annual emissions. It is quite clear that it is practically impossible to achieve concentrations of less than 430 ppm which could have potentially limited global warming to less than 1.5$^0$C. The scenarios which do comply with the reduction targets assume significant use of bioenergy, fossil fuels with carbon dioxide capture and storage (CCS), and bioenergy with CCS (BECCS). These low concentration stabilisation scenarios require all sectors of the world economy to source almost 80% of their energy requirements from low carbon energy sources like bioenergy, renewable energy, CCS and BECCS by 2050. In fact, in scenarios without

CCS, fossil fuels will need to be completely phased out by 2100 or even earlier (IPCC, 2014b).

The member parties of the UNFCCC, with a near-universal membership, recognise that stabilisation of GHG concentrations in the atmosphere could prevent the harmful human intervention of the global climatic system. The Kyoto Protocol (KP) of 1997 mandated countries on its Annex I list, comprising of 36 industrialised nations and the European Union, to set binding reduction commitments for GHG emissions by 18% below 1990 levels during the period 2013 – 2020, referred to as the second commitment period.  The twenty-first session of the conference of the parties (COP 21, Paris) brought about a landmark agreement between all the member states as they agreed to accelerate and intensify measures to mitigate global climate change (UNFCCC, 2016a).

The COP 21 agreement provides for member states to submit their intended nationally determined contributions (INDC's) to reduction of GHG emissions. The member parties agreed to report GHG emissions and status of implementation measures to reduce the emissions. One of the important elements of the agreement has been to enhance provisions for finance and support of technological developments which could accelerate the shift to a low-carbon future (UNFCCC, 2016a). The COP 21 agreement has been opened for signature on 22 Apr 2016 and as of June 2016, 19 states of the 178 signatories accounting for 0.18% of the global GHG emissions have deposited their instruments of ratification (UNFCCC, 2016b). It is expected that ratification will gain momentum in the coming months. Meanwhile, reduction of emissions continues to be prime on the agenda of all countries, industries and carbon-intensive sectors like aviation and shipping.

### *2.2 Costs of climate change and carbon emissions*

Climate change induces irreversible changes in the natural ecosystem, and its consequences are damaging to the world economy. The impact of global warming is universal in having adverse effects on lives, livelihoods, economies, infrastructure, and services as all of these players invariably interact with the climatic system is some way or the other. IPCC (2014c) notes that the consequences of climate change will manifest in many ways including the burden of human ill-health and incidence of waterborne diseases. Economically marginalised population will be especially vulnerable to the effects of climate change. Extreme weather patterns such as heat waves, droughts, floods and cyclones expose ecosystems, economies and human lives to very high risk. Disruption of food production, damage to infrastructure and settlements and high morbidity in the human race have been categorised as consequences with very high likelihood in the future (IPCC, 2014c).

In economic terms, when a market player carries out an activity that influences the well-being of a third party who does not pay or receive any compensation for this effect is defined as an externality. An adverse effect is called a negative externality, and a beneficial effect is called a positive externality. Incentives designed to make market players take account of the external effects of their actions is termed as internalising an externality (Mankiw & Taylor, 2014). The theory of externality and ways to internalise it have been defined by the works of Pigou (1932) and Coase

(1960). From our discussion on climate change, it is clear that the emission of GHG's, from a plethora of sources, is a negative externality that is universal in nature.

The environment and the atmosphere that humanity survives upon is a public good. Economic actors who use it or abuse it cannot diminish the capacity of others to use it (Samuelson, 1954). Pigou (1932) strongly advocated the use of taxes to correct the effects of negative externalities. These taxes were such as to bridge the gap between the private costs a product and its social cost which accounted for the externality. Taxes of this nature are, hence, called Pigovian taxes. A Pigovian tax system is argued to be a good option for reduction of GHG emissions as placing a price on the emissions would incentivize the polluter to look for ways to reduce the emissions produced. Of course, assessing an appropriate rate for this type of tax for carbon emissions is mired in controversy and political debate. This brings us to the argument of Coase (1960) in his paper debating the problem of social cost and the traditional approach used by most contemporary economists. He argued that determination of a social cost cannot be as objective as described by Pigou (1932). The problem of an externality is very much reciprocal in nature. The economic actor who generates the GHG emissions does cause harm to the environment or humanity, but not allowing this actor to carry out his economic activities efficiently is harmful as well. The dilemma is in determining which is the more serious harm (Coase, 1960). The evidence from IPCC's AR5 indicates that the net damages arising from climate change and global warming is substantial, from an economic perspective, and is likely to inflate exponentially over time (IPCC, 2014a) (IPCC, 2014c).

The Stern review (2007) estimated that the overall costs and risks associated with climate change would be tantamount to losing 5% of global GDP, at the very least, each year. This figure could be substantially more when considering a wider range of impacts on the economy and is pegged at close to 20% of the GDP annually. The costs of mitigating these risks by reduction of emissions are estimated to be about 1% of the global GDP. The report stresses that these stabilising measures, though manageable, would be needed to be implemented quickly, and any delays could potentially be devastating to the global economy. A global agreement on frameworks of action including linking the various emissions trading schemes has been proposed as a powerful and cost-effective measure for a reduction in emissions (N.H.Stern, 2007).

The social cost of carbon (SCC) puts a monetary value on the damage caused to the global economy from emitting a tonne of $CO_2$ into the atmosphere. The SCC allows policymakers to design optimal climate policies and incentivizing measures that aid in the reduction of GHG emissions (Bijgaart, et al., 2016). Tol (2008) describes SCC as a first estimate of a Pigovian tax that should be placed on GHG emissions. He identifies 211 different studies from 1982 to 2006 estimating SCC. Almost all of these studies used the impact analysis laid down in the assessment reports of the IPCC starting with the AR1 to the AR4. His study observes some estimates of the SCC to be extremely high and paying such a price would entail a significant proportion of the population in a few countries to be living off government subsidies alone as the taxes would be far above incomes. The meta-analysis found a downward trend in the estimated economic impacts of climate change. Noting that a reasonably sound SCC to be about $25/tC, the study points out the considerable uncertainty in determining SCC. Nevertheless, the SCC has remained to be an important benchmark and continues to be a widely researched topic. Pearce (2003) quite aptly concludes his paper observing that the SCC estimates are largely dependent on the model used, but it does play a vital role in determining whether abatement measures are adequate or not.

Bijgaart, et al.(2016) use an integrated assessment model (IAM) to connect the global carbon cycle and temperature dynamics to the global economy to assess marginal welfare costs of emissions. They estimate the SCC at €48/t$CO_2$ but identify that it could be much lower when using a higher discount rate. Havranek, et al. (2015) conducted a meta-analysis of 809 estimates of SCC from 101 studies and found an upward bias reporting of the SCC in literature. Their largest estimate equates to \$39/t$CO_2$ which more or less agrees with the value of SCC estimated by the US Government's Interagency Working Group on Social Cost of Carbon (IWGSCC).

The IWGSCC uses the SCC estimates to allow different government agencies to assess the cost-benefit analyses of regulatory actions that could potentially impact cumulative global emissions (IWGSCC, 2015). These estimates are published for successive five-year intervals using discount rates of 5%, 3%, and 2.5%. The SCC in 2015 using a discount rate of 3% was estimated to be \$36/t$CO_2$ inflating to \$42/t$CO_2$ by 2020. The IWGSCC uses three IAM's to compute the SCC and regularly updates their estimates to reflect latest data availability and information on climate change. As this estimate is already being used by policymakers, this could be considered as a benchmark for states and sectors implementing SCC for designing emission abatement measures.

## *2.3 GHG emissions from shipping*

The complexity in accounting for GHG emissions for shipping stems from the international nature of the business. The operation of shipping entails a significant portion of the emissions generated to be emitted on the high seas outside the jurisdiction of any country (Heitmann & Khalilian, 2011). The current ownership and operating structure of the shipping industry, with the involvement of multiple players from different nationalities, adds to this complexity. Global warming and climate change, as described in the earlier sections, is not localised and is very much affected, adversely, by the actions of all economic actors around the globe and actions on the high seas is no exception.

The flag state of the vessel is responsible for ensuring compliance with various international regulations and could be considered as the party responsible for reducing emissions from its fleet. Heitmann & Khalilian (2011) studied the burden sharing under different UNFCCC allocation options with respect to $CO_2$ emissions from shipping and found that these would not be in the best interests of many countries and is likely to face numerous obstacles to implementation. Emissions from international bunker fuels are reported under the provisions of the IPCC guidelines for preparation of GHG inventories and UNFCCC guidelines on annual inventories. However, these are reported separately and are excluded from the national totals (OECD / IEA, 2015). Therefore, reduction of these emissions has not been included in the INDC's of individual nations (UNFCCC, 2016c). Including shipping emissions under the purview of the Kyoto Protocol is not a feasible option either since only 35% of the world's merchant fleet is registered in Annex I countries of the KP (ICS, 2014).

In light of this, a sectoral approach would be most appropriate to regulate GHG emissions from international shipping. The IPCC (2014b) notes that sectoral and cross-sectoral approaches, in addition to national policies, to mitigation pathways and sustainable development will be required for stabilisation of the GHG concentrations. Sector-specific mitigation policies could be designed to be better suited to address barriers specific to that particular industry. More importantly, even though national or economy-wide policies are more cost-effective, political barriers and administrative burdens make them difficult to implement.

The IMO in its capacity as the international agency responsible for regulating international shipping has been actively engaged in studying the impact of shipping on climate change and designing policies to mitigate the same. The IMO first recognised the need to consider $CO_2$ emissions reduction strategies for international shipping in 1997. In cooperation with the UNFCCC, it undertook to study the emissions from shipping to establish an accurate inventory of GHG emissions. The IMO's first GHG study estimated that international shipping contributed to 1.8% of the global anthropogenic $CO_2$ emissions (IMO, 2016a). The second IMO GHG study (2007) estimated this proportion to be 3.3% while, the third IMO GHG study (2015) estimates the emissions to be 2.2% of the global total.

Sims, et al. (2014) note that although shipping is the most carbon-efficient mode of transportation in terms of $gCO_2$/t-km, the IMO has taken considerable steps to reduce the emissions from the industry further. They recognise that the mandatory energy efficiency measures (IMO, 2011) is the first such mandatory regime for an international industry and could be considered as a model for international climate change cooperation in the future. These regulations mandate existing ships to measure and record their energy efficiency and progressively improve on them such that new ships in 2025 would be 30% more energy efficient than their counterparts built prior 2014 (IMO, 2016b).

### *2.3.1 Inventory of GHG emissions from shipping*

The principal methodologies employed to produce ship emissions inventories has been well summarised by Eyring, et al. (2010). These methodologies can be broadly classified as either top-down or bottom-up approaches. The top-down approach uses total international marine bunker fuel sales summed up per reporting country to find the global consumption. A potential problem with this approach is that the definition of international marine fuel is not synchronous across statistical sources globally (Olivier & Peters, 1999). The bottom-up approach is activity-based and estimates fuel consumption resulting from the fleet activity. The consumption is broadly dependent on the installed power of the engine, an assumed engine load, running hours of the engine, and specific emission factor of the fuel (Corbett & Koehler, 2003) (Eyring, et al., 2005). Uncertainties in this activity-based approach abound yet it is a far more reliable estimation of emissions as it accounts for more variables than the top-down approach. Of course, the challenge of collecting this information from all ship operators is an onerous task (Eyring, et al., 2010) but with the IMO prodding over a global data reporting and verification regime, similar to EU's mandatory MRV rules, this approach is likely to remain a reliable methodology.

Miola & Ciuffo (2011) stressed that the geographical location of air emissions is another important dimension (the other dimension being the emissions profile of the fleet as described earlier) to be considered in calculating inventories. They categorize the methodologies as a full top-down, full bottom-up or a combination of the methodologies used in each of the two dimensions. Their meta-analysis of different modelling approaches and estimations of maritime GHG emissions points to the reliability of the bottom-up approach. They note that a full bottom-up approach using real-time information which may be available in the near future, considering progress in satellite and AIS (automatic information system) tracking of vessels, and trade statistics from port authorities should be the methodology of choice.

The IMO in its 3rd Greenhouse gas study (Smith, et al., 2015) provides a detailed and probably the most authoritative study yet on the inventory of GHG emissions generated by the shipping industry. The study estimates GHG emissions from international shipping using both the approaches independently described earlier.

For the top-down estimate, the study has used data on marine bunker sales from IEA. The sales data was categorised into international, domestic and fishing sales. It also used historical IEA statistics to quantify the potential errors arising from using the top-down approach. Using this approach, the total $CO_2$ emissions from the entire shipping industry in 2011 was estimated at 795.4 million tonnes (Smith, et al., 2015). As with the earlier IMO GHG studies, this study also uses the bottom-up estimate as the consensus estimate.

For the bottom-up estimate, the authors used global fleet technical data from IHS-Fairplay (IHSF) and combined this with fleet activity data from AIS observations. Identifying the incidence in disruption of AIS data, the available data was validated using satellite-based LRIT (long range information and tracking) for approximately 8000 ships over four years as well as noon report data collected from 470 ships. The total $CO_2$ emissions from the entire shipping industry in 2011 is estimated at 1021.6 million tonnes (2.9% of global inventory) and 938.1 million tonnes (2.6% of global inventory) in 2012.

The projected future scenarios (2012-2050), 16 in number, based on the representative concentration pathways (RCP) and shared socioeconomic pathways (SSP) defined by the IPCC in AR5 show a substantial increase in GHG emissions from shipping with all but one scenario projecting higher emissions in 2050 than in 2012. These scenarios are based on the underlying assumption that fossil fuels will remain dominant until 2050 with the share of LNG as a fuel increasing in the range of 8% - 25% of the fleet mix. The study suggests that improvements in energy efficiency of ships are paramount to the objective of emissions reduction and change in fuel mix would have only a limited impact (Smith, et al., 2015). However, it should be noted that the assumption of continued use of fossil-based fuels in the maritime industry, used in this study, is at the very least debatable and does not agree with goals and objectives of global action on climate change set by the UNFCCC. In Table 2-2, we present the projected shipping emissions from the IMO's 3rd GHG study and the increment over baseline emissions. It is quite evident that the emissions reduction measures that are considered in the IMO's study are not effective enough by themselves in checking the growth in emissions from shipping. The more disturbing finding is that while the IPCC AR5 has suggested a global reduction target of 72-41% in 2050 from 2010 levels, projected shipping emissions are nowhere close to this target.

*Table 2-2: Projected shipping emissions in 2050 – IMO 3rd GHG Study*

| | $CO_2$ Emissions in Million Tonnes | | |
|---|---|---|---|
| **Scenario** | **2010 (Baseline)** | **2050** | **Increment** |
| 1 | 810 | 1800 | 122% |
| 2 | 810 | 1400 | 73% |
| 3 | 810 | 810 | 0% |
| 4 | 810 | 1000 | 23% |
| 5 | 810 | 2700 | 233% |
| 6 | 810 | 2000 | 147% |
| 7 | 810 | 1200 | 48% |
| 8 | 810 | 1500 | 85% |
| 9 | 810 | 1900 | 135% |
| 10 | 810 | 1400 | 73% |
| 11 | 810 | 850 | 5% |
| 12 | 810 | 1100 | 36% |
| 13 (BAU) | 810 | 2800 | 246% |
| 14 (BAU) | 810 | 2100 | 159% |
| 15 (BAU) | 810 | 1200 | 48% |
| 16 (BAU) | 810 | 1500 | 85% |

*Source: Adapted from Smith, et al. (2015)*

### 2.3.2 Measures for reduction of emissions from shipping

Current measures for reduction of GHG emissions from ships has centred on energy efficiency improvements. These measures, through incorporation in the widely accepted MARPOL Annex VI, mandates all existing ships (above 400 gross tons) to adopt a Ship Energy Efficiency Management Plan (SEEMP) and an Energy Efficiency Design Index (EEDI).

The SEEMP establishes a mechanism for operators to monitor the energy efficiency of the ship's transportation work and improve it using by considering new technologies and improved operational practices. As can be seen, SEEMP is a tool for monitoring and reducing GHG emissions but does not set any reduction targets per se. The EEDI, though, is non-prescriptive in nature but requires the industry to improve progressively the efficiency index such that the ships built in 2020 would be 20% more energy efficient than ships built in 2014 and the improvement benchmark increases to 30% by 2025 from the 2014 baseline. The choice of technologies to be adopted lies with the ship operator, ship designer and builder (MEPC, 2011) (IMO, 2016b).

The IMO estimates that the EEDI would ensure the removal of 45-50 million tonnes of $CO_2$ from the atmosphere annually by 2020 and 180-240 million tonnes by 2030, and will thus contribute significantly to stem climate change (IMO, 2012). Here, we should note that the Third IMO GHG study (2015) has in the scenarios presented accounted for an efficiency improvement of 60% until 2050 in eight (8) scenarios and 40% improvement in the remaining eight (8) scenarios. This implies that although energy efficiency would have improved, the shipping industry would still be emitting GHG's in quantities not conforming to the targets laid down in IPCC AR5.

Nevertheless, these measures are important steps in the reduction of emissions from shipping.

#### *2.3.2.1 Operational and technical measures*

IMarEST (2011) lists and describes fifty (50) operational and technical measures for reducing GHG emissions from ships by improving efficiency. Operational measures are those that do not require any changes to the vessel's design, structure and build. Technical measures are those that involve retrofits of new equipment, changes in design, and other upgrades that are available in the market that aid in improving the energy efficiency.

Operating at reduced speed is the most widely used operational measure to improve energy efficiency. This is largely based on the rule-of-thumb establishing a quadratic relation between the vessel's speed and fuel consumption (IMarEST, 2011). However, it should be noted that at very low engine loads this operational measure is not very effective and commercial requirements in conjunction with market factors tend to dictate the usability of this effective measure. Corbett, et al (2009) checked the cost-effectiveness of speed reductions in reducing emissions and found 70% reduced emissions by reducing operating speed to 50%. Operating a vessel at a slower speed would obviously increase the sailing time and would probably necessitate the use of a larger number of vessels to accomplish the transport service required implying additional costs. Lindstad, et al. (2011) observed that GHG emissions from shipping could be reduced by 28% at a zero abatement cost.

Optimization of trim using ballast water and better planning of cargo stowage, voyage optimization using information from charterers and ports to adjust vessel's speed at sea, achieving economies of scale by employing larger ships, optimised autopilot adjustment, and increasing the cargo load factor are operational measures that can be implemented at very low marginal costs. The abatement potential for these measures ranges from 0.1% - 4% (Buhaug, et al., 2009) (IMarEST, 2011).

Buhaug, et al (2009) identify propeller polishing and hull cleaning to be an effective operational measure for improving energy efficiency thereby reducing emissions. They estimate propeller polishing on a regular basis to have an emission abatement potential of 2-8% at very nominal costs to the ship owner. Hull cleaning reduces the frictional resistance of the hull thereby reducing the bunker consumption and GHG emissions. Hull cleaning could potentially result in emissions abatement of up to 10%. They, however, do note that the shipping fleet is already employing most of these operational measures. Thus, the overall abatement of emissions from a current baseline is rather minimal.

The technical measures for GHG abatement have been increasing in number and improving in potential over the recent past. Smith, et al (2014) point out that the technical measures can be broadly categorised as:

- Short term measures which would require retro-fits on existing ships;
- Medium term measures requiring improved design of new buildings;
- Long term measures which necessitate research and development leading to radical concepts

These measures focus on improvements in hull and propulsor hydrodynamics, marine engineering systems, optimised hull construction and the use of alternative sources of power generation viz. wind power, solar power, fuel cells and alternative fuels.

Buhaug, et al. (2009) report improved design of hull to reduce the energy requirement by 5% and in combination with better propeller design, a reduction of 8% could be achieved. IMarEST (2011) identify lightweight construction, optimised hull design and hull openings, air lubrication and hull coating as technical measures to improve energy efficiency. Reduction of design speed, main engine adjustments, fuel efficient boilers and waste heat recovery systems are technical measures with marine engineering systems as the underpinning factor.

Wind power can be harnessed by using a kite-like structure attached to the bow of the ship so that the power generated thus could be used to substitute that generated by the ship's main and auxiliary engines. It is estimated that kites with an area of 160 sq.m could generate an equivalent engine power of 600 kW. A 5000 sq.m kite could generate 19,200 kW which is roughly the power required to propel a Panamax bulk carrier or an Aframax tanker (IMarEST, 2011). Use of solar power is another technical measure that is currently being considered. The abatement potential using solar power is quite low and estimated to be a maximum of 3.75%. It could be used as a substitute for the ship's auxiliary engine, but current development trajectories do not indicate it would be capable of substituting main propulsion power in the near future (Smith, et al., 2014).

Cold ironing (use of shore-generated power while ship is in port) and waste heat recovery systems have been noted to produce considerable savings in energy consumption. Miola, et al (2010) observe that these reductions could be up to 20% in addition to cost savings from the use of more expensive fuels which might be required in ECA areas.

High-temperature solid oxide fuel cells can be considered for future marine use as they have a long lifespan are highly efficient and very robust in nature. While fuel cells typically weigh much more than an internal combustion engine, their energy efficiency is also higher than conventional engines. This added to the fact carbon emissions from fuel cells are practically close to zero, makes them a very attractive fuel for the future (Smith, et al., 2014). Other alternative fuels will form the basis of our discussion in chapter 3.

As Eide, et al (2009) recognise, a large array of operational and technical measures is available for reduction of GHG emissions from shipping. However, currently for most of these measures the costs are prohibitive resulting in their limited use. Besides, technical maturity for a large majority of these measures still abounds (IMarEST, 2011). Studying the cost-effectiveness of the various operational and technical measures, Eide et al. (2009), suggest that a cost of averting a tonne of $CO_2$-eq heating (CATCH) less than \$50/T-$CO_2$ should be used as a decision criterion for investment in GHG emission reduction measures for shipping.

Currently, reduction of operating speed is the most effective and popular abatement measure for GHG emissions. Over the last few years, this measure was primarily used by vessel operators as a tool to counteract the adverse forces of market conditions. In the absence of any prescriptive norms for speed and emission targets, it is unlikely that this operational measure can be considered as a long-term solution for the reduction of GHG emissions from shipping.

#### 2.3.2.2 *Market-based measures*

IPCC (2014b) notes that market-based measures that set a carbon price, including fuel levies and cap and trade systems, have been implemented in a cost effective manner in different parts of the globe but mitigation of GHG emissions has been rather limited. Emission caps in cap and trade systems have been observed to be loose and not constraining. The long-term effects of tax-based policies have not been realised yet, but they did help to weaken the link between GDP and GHG emissions, which is important to note as it highlights the prospect of achieving reductions in GHG emissions without adversely affecting economic growth (IPCC, 2014b).

Any MBM would require the shipowner to pay for the emissions generated by the ship which is typical of internalising an externality under the Pigovian principle. Miola, et al. (2011) observe that emissions trading, voluntary emission crediting, and a hybrid policy combining a carbon tax with trading are MBM's that could be considered appropriate for climate change policies in the shipping industry. The IMO set up an expert group to study the feasibility and impact assessments of possible MBM's for shipping which submitted its report in 2010 at the MEPC 61st session (MEPC, 2010). Member states of the IMO have submitted ten (10) different proposals for MBM's in shipping and each has been evaluated on cost effectiveness and abatement potential (MEPC, 2010) (Psaraftis, 2012).

A global emissions trading system for the maritime transport sector (METS) as proposed by Kageson (2008) is a global cap-and-trade system with the option of being a closed system or an open system. In the closed system, all monies and revenues obtained from the auctioning of trading rights would be fed back to the maritime industry by way of subsidies to users of low carbon technologies and provide financial aid to users from developing countries for their contribution to the reduction of GHG's. In an open METS, the system would be linked to other markets and sectors so that the lower marginal abatement costs in other sectors could be harnessed to increase the cost-effectiveness of the measure. It is apparent that the open system is more beneficial for trade, but it could induce greater uncertainty in placing a cap on emissions generated (Kågeson, 2008). This system could also be used to link with other existing regional ETS like the EU ETS in a seamless manner (Kågeson, 2007).

A maritime emission reduction scheme (MERS) combines the elements of the cap-and-trade system with a tax on emissions. The revenues from the taxes would be pooled to a fund which would be used to further the sector's advancements in abatement technologies, climate change adaptation in developing countries and purchase of offset credits such that the total emissions from the sector remain below a pre-defined cap (Stochniol, 2008). This system sets an emission charge of 40% of the SCC as well as places a cap on emissions set at 2005 emissions levels. This system has been considered to be more robust than the METS as it avoids the transaction and administrative costs of a global trading system (Miola, et al., 2011).

A maritime sector crediting mechanism (MSCM), a voluntary system, sets baseline emissions for the sector and any reduction of emissions below the baseline would generate tradable credits. The crediting mechanism incentivizes reduction of GHG emissions. The leveraged incentive scheme (LIS) proposed by Japan uses an international GHG fund into which the ship operator would need to contribute by marine bunkers consumed. Subsequently, on the basis of the calculated efficiency, if reduction targets are met the funds are refunded to the operator (Psaraftis, 2012).

Studies identifying the interaction of these MBM's with trading patterns of ships, and repercussions on the supply and demand of shipping is rather limited. Franc & Sutto (2014) made an impact analysis on shipping lines using the METS and note that this could potentially disrupt shipping market dynamics. A cap-and-trade system would bestow an unfair advantage on ship operators having the financial capability to renew their fleets or use expensive technologies and hence increase market concentration. They reiterate the necessity of a maritime METS to be of global coverage, as regional ETS could affect the competitiveness of ports in the region adversely. Lee, et al. (2013) used the GTAP model to quantify the impact of a maritime carbon tax on the world economy. Using a carbon tax only on international container shipping resulted in negligible economic impact globally but considering trading nations separately, developing countries did experience a loss in GDP. The cumulative effect of the tax regime on all sectors of shipping could indeed have profound effects on certain developing countries. Nevertheless, a carbon tax could drive immediate changes in ship operations resulting in net reduction of GHG emissions.

MEPC (2010) developed a model to examine the emission reductions and costs of the different MBM proposals and found that the abatement ranges from 2-40% from a BAU baseline. However, the report notes that for the MBM's to achieve the emissions reductions, an extremely robust monitoring, reporting, and verification system in conjunction with a global enforcement regime would be required within the industry. Psaraftis (2012) observes that reception of these MBM by the different stakeholders in the shipping industry has been very mixed with the main contention that MBM's are incongruent to the principle of common but differentiated responsibility (CBDR).

The lack of agreement amongst the various players in the industry, administrative issues of implementing a maritime MBM on a global scale, complexity in allocation of liabilities for shipping under the UNFCCC and political considerations have been holding back progress in the selection of a suitable MBM for shipping (Heitmann & Khalilian, 2011) (Psaraftis, 2012).

Shipping industry bodies like the BIMCO and ICS are sceptical of the effect of MBM on shipping markets and strongly advocate the possibility of GHG linked MBM's resulting in market distortion. They do, however, voice a preference for a global maritime MBM linked to fuel consumption (global fuel levy) as a reduction of fuel consumption is in their mutual interest (BIMCO, 2015) (ICS, 2014). Even though the application of a maritime fuel levy was deleted from the final text of the COP 21 agreement, there is mounting pressure for a shipping MBM with the IMF, in January 2016, calling for a carbon tax on shipping at a level approximating to $ 95/T fuel used (ICS, 2016). This level of carbon tax equates, more or less, to the SCC determined by the IWGSCC discussed in section 2.2. Recognising that fuel costs are by far a ship operator's largest cost, sustainable reduction in GHG emissions will indeed be beneficial for ship owners. The ICS has proposed the development of an Intended IMO determined contribution for $CO_2$ reductions which will be similar to the INDC's submitted by individual nations to the UNFCCC. This proposal will be discussed during the MEPC's next meeting (MEPC 70) in October 2016 (ICS, 2016).

The focus of MEPC 68 (2015) had been on further improvements in energy efficiency of ships. The call for a quantifiable reduction target for GHG emissions from shipping was deferred to a later time considering the then upcoming COP 21 in December 2015. Subsequently, MEPC 69 (2016) approved the mandatory data collection system which would form the foundation for further policy debate to address GHG emissions from shipping. This system would, in all likelihood, enter into force in 2018 (IMO, 2016c) and could potentially pave the way for a robust and transparent MBM for GHG emissions from shipping.

## *2.4 Key Outputs*

- $CO_2$ accounts for 90% of GHG emissions; current atmospheric concentrations are around 404 ppm.
- IPCC AR5 sets a target of 72-41% reduction by 2050 from 2010 levels to maintain global warming below $2^0$C.
- The cost of carbon emissions varies widely; most studies estimate it around \$40/MT-$CO_2$ in 2016.
- IMO's 3rd GHG study of shipping estimates emissions from shipping to contribute 2.2% of global totals.
- The bottom-up approach for emissions inventory is more reliable than the top-down approach.
- IMO's 3rd GHG study has used 2010 as the baseline year for projections.
- The emissions projections for 2050 in IMO's 3rd GHG study takes into account 40% and 60% efficiency improvements due to EEDI in the sixteen scenarios, yet all scenarios, except one, show a significant increase in GHG emissions.
- Alternative fuels (except LNG) have not been considered comprehensively in the scenarios.
- There is considerable debate around MBM's for shipping but no consensus reached yet.
- Until now EEDI is the only emissions abatement measure mandated on international shipping.
- Most widely used operational measure to reduce emissions is speed reduction.
- A global monitoring and reporting system for carbon emissions from shipping will be implemented in 2018.

# 3. Alternative fuels for shipping

Environmental concerns regarding GHG emissions have been driving regulatory requirements and low-carbon technological development globally. The shipping industry's action in this regards is widely limited to operational measures and some technical measures as explained in Chapter 2. However, the pressing need to reduce the carbon footprint of the shipping industry at the earliest makes a justified reason for action. Low-carbon alternative fuels have been gaining popularity in road transport and land-based industrial sectors. Their application in shipping is at a nascent stage and a subject of ongoing research.

This chapter seeks to review the literature and studies pertaining to alternative fuels for shipping, relevant to the perspective of GHG emissions reduction, and will enable us to identify data required for the model we intend to build. We shall outline the main characteristics, relevant for our research and consideration for marine use, of the different fuels and compare them with the conventional marine fuels viz. HFO and MDO. We shall discuss our methodology for generating the fuel data required for our model. We shall limit the discussion to fuels which are already in use in other energy sectors, offer a significant abatement potential, adaptable for use with current marine engines and whose availability is not a major impediment to widespread adoption.

We shall discuss the main differences between the fuels and the factors that could be considered critical in its adoption for marine use. We shall examine the historical pricing trends for these fuels and define our price scenarios on the basis of some assumptions. Finally, we shall discuss the availability of these fuels and define availability scenarios.

## *3.1 Low-carbon fuel options*

Brynolf, et al. (2014) observe that when selecting future marine fuels technical, economic and environmental aspects should be carefully considered. The safety issues linked to the particular fuel, availability and the required logistics are also dimensions that need to be carefully weighed. Chryssakis, et al. (2014) identify various alternative fuels for shipping that are currently being considered. The prime candidates amongst these, considering their compatibility with existing marine engines, are Biodiesel, LNG, Methanol, Ethanol, Di-methyl Ether (DME) and Biogas. DME is produced from methanol, so we shall not consider it separately in this study. Similarly, methyl tertiary butyl ether (MTBE) and ethyl tertiary butyl ether (ETBE) produced from methanol and ethanol respectively are also being discussed as fuel options in current literature, but we are not considering them in this research. Hydrogen and Nuclear fuel are zero carbon fuels, but the technology for their application in commercial marine use is still very immature, and the perceived risks in operation are too high at this point (Chryssakis, et al., 2015). Hence, we shall not consider these in our study.

It is important to note that biomass-based fuels are regarded as carbon-neutral since the $CO_2$ released during the combustion equates to the carbon captured by the plant from the atmosphere during its growth. Thus, the tank-to-wake emissions of the biofuels are zero. However, these fuels do produce GHG emissions during other processes linked to their production and are typically included as Well-to-tank emissions. The EU Renewable Energy Directive (RED, 2009/28/EC) reiterates the need to include emissions generated in the entire well-to-wake cycle in its rules for calculating emissions from biofuels (Ellis & Tanneberger, 2015) (European Commission, 2009).

### 3.1.1 LNG

LNG has been used as a secondary marine fuel since the 1960's on LNG carriers primarily to use boil-off gas. Currently, LNG can be used in dedicated mono-fuel engines, based on Otto Cycle, or in a diesel engine using the dual fuel process. These Dual fuel engines are referred to as gas engines (Florentinus, et al., 2012). LNG is produced by the liquefaction of natural gas, which comprises mainly of methane. The establishment of ECA for $SO_x$ and Tier III $NO_x$ standards has been driving up interest in LNG as it is a very favourable fuel vis-à-vis these emissions. In terms of GHG emissions, it does offer reductions of up to 25% when compared to HFO but even small quantities of methane slip, a current operational norm, can significantly increase the GHG emissions. It has been estimated that a methane slip of 5.5% would bring the GHG emissions from LNG at par with those from MDO. Nevertheless, with best operational practices realistic reductions of 10-20% over conventional oil-based fuels can be achieved (Chryssakis, et al., 2015).

Pablo Semolinos, et al (2013) identifies the challenges to be overcome for LNG to become a marine fuel of choice. While evaluating the advantages of LNG as a marine fuel choice, they also highlight the challenges in the transition to LNG as the primary option. It lists volatility in the price of LNG and depressed demand factors as the main challenges. It rightly points out that the infrastructure required for LNG bunkering facilities is capital intensive and acts a major barrier. Taking a step further, Acciaro (2014) studied real options analysis for environmental compliance in the context of ECA by the use of LNG-propelled ships and found the results to be encouraging for a shift to LNG.

IMO (2016d) observe that even though natural gas is significantly cheaper than HFO, the costs related to transportation, liquefaction, processing, storage and bunkering can be substantial. Chryssakis, et al. (2014) note that infrastructure for LNG is picking up pace, and it is expected that LNG uptake will grow over the next decade although the capital cost of system installation is quite high. Chrysakkis, et al. (2015) compare different alternative fuels and observe that, given current circumstances, LNG is favourably placed to take the mantle of a popular marine fuel for the future. Industry experts opine that the shift is possible if LNG can maintain the price advantage over residual and distillate fuels over the coming decades (McGill, et al., 2013).

### 3.1.2 Liquefied Bio-gas

Biogas, a first generation biofuel, can be produced from biomass using different processes viz. fermentation, anaerobic digestion and gasification. The biogas produced has to be processed further so as to be used as a fuel. The main component is biogas is methane. At ambient pressure and temperature, it is a gas and as such would require a vast storage space on board ships. Liquefying biogas makes it similar to LNG and can be used in the same way in marine engines as is LNG without any further retrofits (Chryssakis, et al., 2015). In fact, the distinct possibility of switching from LNG to LBG and blending LNG with LBG (in any ratio) has been put forth as one of the prime advantages in the marketing of LNG (Bengtsson, 2011).

### *3.1.3 Biodiesel*

Biodiesel can be produced from a range of feedstock like rapeseed, soybeans, palm, peanuts and sunflower. The oil extracted from these products is processed to produce esters which have very similar physical characteristics of diesel. In fact, Rudolf Diesel used peanut oil as fuel for his first engines. Rapeseed is the dominant feedstock for biodiesel in Europe, producing rapeseed methyl ester (RME) from the transesterification of rapeseed oil. In the USA, soybean is the main feedstock (Verbeek, et al., 2011). Biodiesel from RME due to its very close matching of physical parameters with fossil diesel can be used in marine engines without any modifications and shall thus be used as the benchmark biodiesel in our study. Biodiesel from RME can also be used with fossil diesel in blended proportions (Florentinus, et al., 2012).

### *3.1.4 Methanol*

Methanol (MeOH), also referred to as methyl alcohol or wood alcohol, is the simplest of alcohols. It is a colourless and flammable liquid that is widely used in the chemical industry. It can be produced from different feedstocks including natural gas, coal and wood-based biomass. The nature of its source does not alter the chemical composition (Ellis & Tanneberger, 2015). The WTW GHG emissions from methanol would largely depend on the feedstock used. For this study, we shall consider emissions from bio-methanol as this provides for maximum abatement potential. It has been assessed as a marine fuel, and pilot projects are underway. It has been noted that modification costs of marine diesel engines to use methanol are significantly less than costs involved in making them adaptable to LNG (McGill, et al., 2013) (Ellis & Tanneberger, 2015).

### *3.1.5 Ethanol*

Ethanol (EtOH), referred to as ethyl alcohol or drinking alcohol, is currently the most widely used biofuel across the world as it has been found to be a good substitute for gasoline. It is mainly produced from biomass viz. corn, sugarcane or wheat and also from ligno-cellulosic biomass such as wood and grass, using fermentation and distillation processes (Ellis & Tanneberger, 2015). Ethanol produces about 1 kg of $CO_2$ for every 1 kg of ethanol used, but since the origin of this emission is biogenic it does not increase the amount of $CO_2$ in the atmosphere (Florentinus, et al., 2012). Ethanol has not yet been used in marine applications, but it has been used in diesel engines involved in road transport quite extensively and is thus considered to be a viable solution for shipping for shipping in the near future (Ellis & Tanneberger, 2015).

## *3.2 Characteristics of the selected Alternative fuels*

The physical characteristics of the different fuels are an important factor to consider as this would entail an array of requirements for the handling of these fuels on board the ships. LNG and LBG are essentially the same fuel, methane, but for the nature of their origin. It needs to be liquefied for storage and transport in large quantities. It is liquefied by maintaining it at a temperature below its boiling point which is -161$^0$C. Maintaining the fuel at this low temperature needs specialised refrigeration equipment and cryogenic tanks for storage. Methanol and ethanol are liquids but are corrosive in nature, thereby requiring the use specially coated tanks for storage. RME can be stored as a marine bunker fuel without any modifications made to existing HFO/MDO bunker tanks. The low flashpoints of LNG, LBG, MeOH and EtOH entails additional safety considerations since build-up of high concentrations of fuel vapour in machinery spaces can be a serious safety hazard.

*Table 3-1: Physical characteristics of selected fuels*

| Property | HFO | MDO | LNG | RME | LBG | MeOH | EtOH |
|---|---|---|---|---|---|---|---|
| Physical state | Liquid | Liquid | Gas | Liquid | Gas | Liquid | Liquid |
| Density (Kg/cu.m) | 989 | 890 | 448.4 | 890 | 448.4 | 795.5 | 792 |
| Flash Point (deg C) | > 60 | > 60 | -175 | 149 | -175 | 12 | 17 |
| Boiling Point (deg C) | 350 - 650 | 175 | -161 | 369 | -162 | 65 | 78 |
| Fuel Switch | MDO / RME | RME / HFO | LBG | MDO | LNG | MDO | MDO |
| Blending | No | Yes | Yes | Yes | Yes | Yes | Yes |
| Engine Type | Diesel | Diesel | DF / Otto | Diesel | DF / Otto | DF | DF |
| Storage Tank Type | Steel | Cryogen ic | Steel | Steel | Cryogen ic | Speciali sed | Speciali sed |

*Source: Author's compilation*

The engine type suitable for the particular fuel play an important role in adoption since it can contribute significantly to the investment cost of the vessel. MeOH and EtOH are currently used in dual-fuel (DF) engines which can use either diesel or these alternative fuels in the combustion cycle. Gas, as discussed earlier, can be used either in DF engines or Otto cycle engines.

The interchangeability or switching between fuels is a consideration that would be critical for vessels that may trade in areas with limited availability of alternative fuels. Similarly, the viability of blending a fuel with other fuels makes the option more versatile. RME, MeOH and EtOH can be blended with MDO while LBG can be blended with LNG in any desired ratio. The blending of RME, MeOH and EtOH with HFO has not been carried out or tested on an industrial scale *(McGill, et al., 2013)*.

### *3.2.1 Energy density*

The energy density of a fuel represents the amount of energy released per unit mass of the fuel used, expressed in MJ/kg. It is an important measure for our research because we use the total amount of energy used by a ship using HFO as the energy requirement using other fuels as well. Thus, fuel consumption of ships using the alternative fuels will be ascertained by their energy density relative to HFO. This factor is charted in Figure 3-1 where we find that LNG/LBG are the most energy dense fuels, while methanol is the least dense amongst the fuels considered in this study.

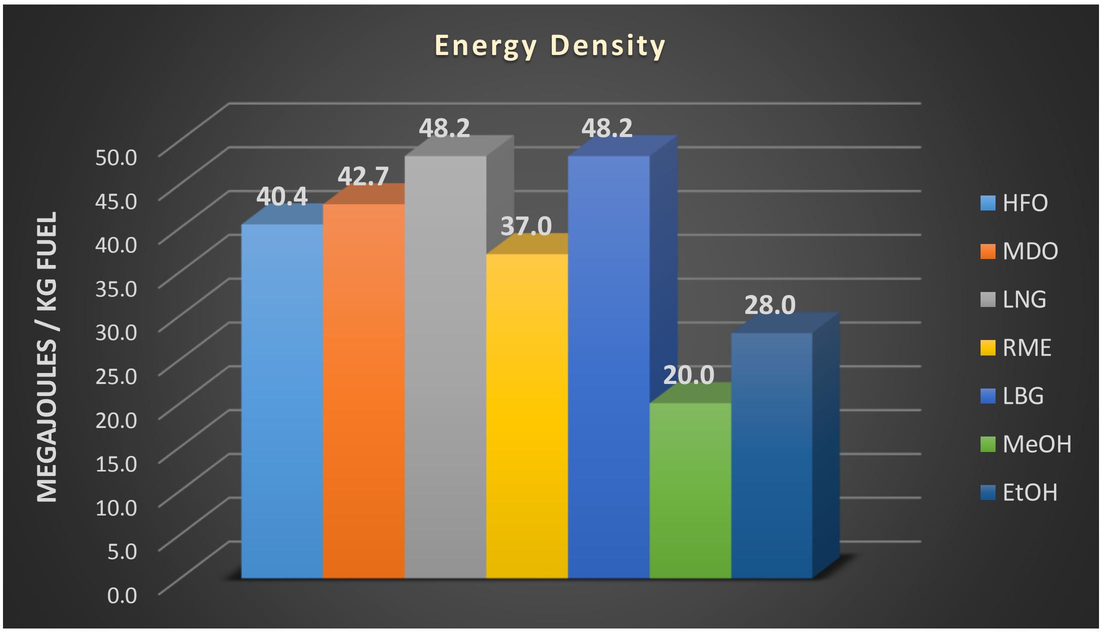

Figure 3-1: Energy density comparison of selected fuels

#### 3.2.1.1 *Storage space and fuel deadweight*

Deriving from the energy density, we calculated the storage space required for the fuels on ships per unit of energy produced. We observe that LNG, LBG, MeOH and EtOH require significantly larger amounts of storage space. One must acknowledge that the space used for fuel does not contribute to the earning potential of a vessel, so a larger fuel storage requirement is a major drawback from the ship-owner's perspective.

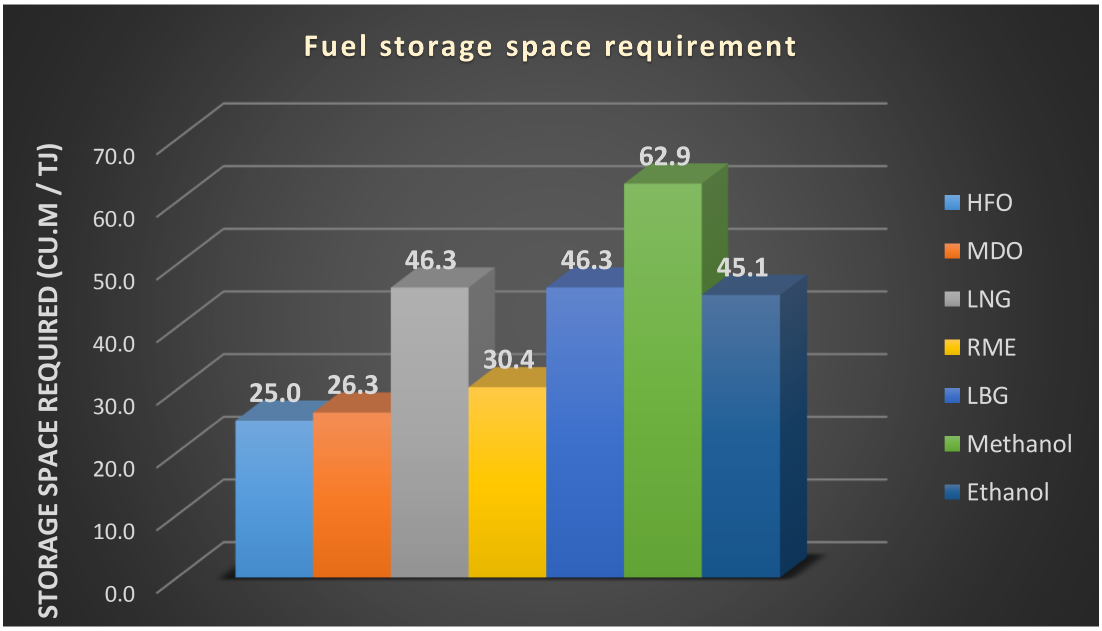

Figure 3-2: Fuel storage space requirement for selected fuels

Similarly, the weight factor of the fuel vis-à-vis the energy produced would indicate the deadweight that will need to be assigned to the fuel, thereby reducing the cargo carrying capacity for a given size of a vessel by the corresponding amount. A higher weight to energy factor implies that the vessel will need to replenish fuel supplies more often than fuels with a lower factor. Here, again we see that MeOH and EtOH can adversely affect the earning potential of the vessel. However, LNG and LBG are favourably placed in this regards due to their higher energy density.

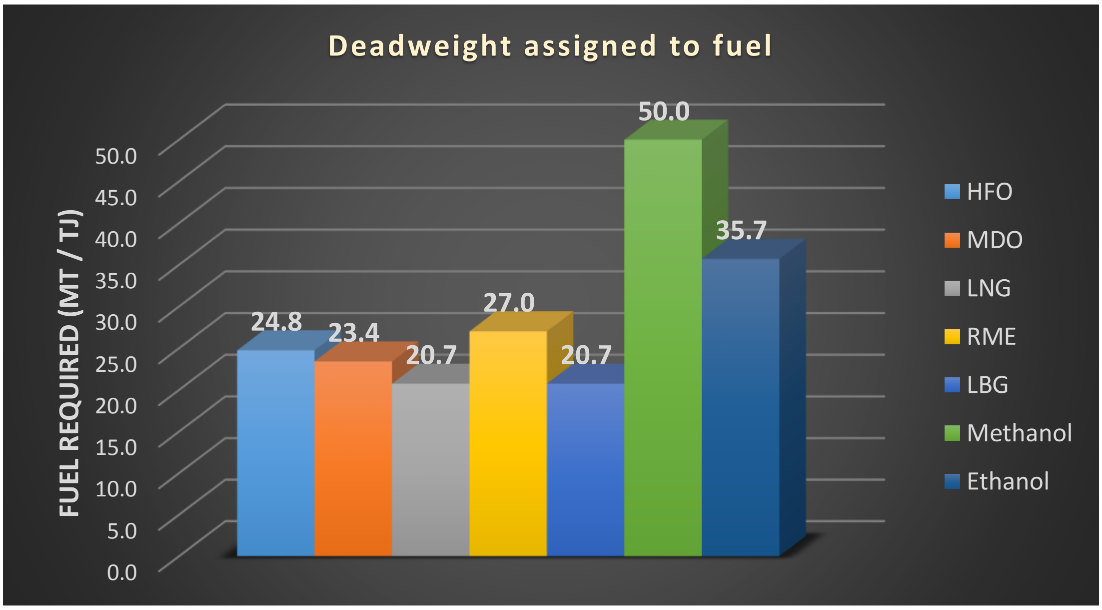


*Figure 3-3: Deadweight assigned to selected fuels*

### 3.2.2 $CO_2$ emissions from alternative fuels

The $CO_2$ and other GHG emissions generated from the combustion of different fuels is central to the discussion around the environmental impact of shipping. Every fuel has its inherent carbon content which chemically reacts to form $CO_2$ during combustion. In addition to this, we must also consider the emissions generated along the entire production and supply chain of the particular fuel. This concept is commonly known as life cycle assessment (LCA) of fuels (Bengtsson, et al., 2011). The LCA of marine fuels is composed of two primary steps – Well to Tank (WTT) chain and Tank to Wake (TTW). In its entirety the LCA measures emissions Well to Wake (WTW) and we shall refer to this as the carbon density of the fuel.

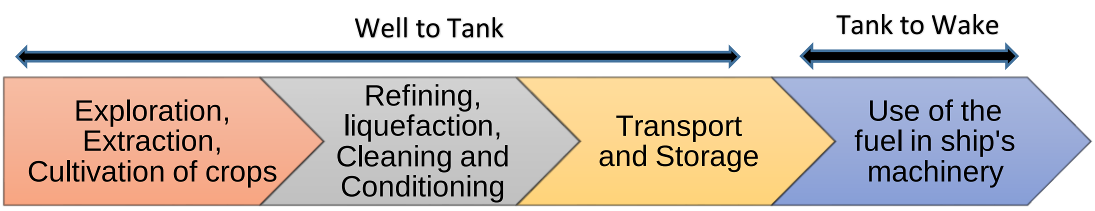


*Figure 3-4: Well to Wake LCA processes*

The WTW assessment is a more holistic approach in calculating emissions potential of alternative fuels. Verbeek, et al. (2011), Ellis & Tanneberger (2015), Brynolf, et al. (2014), Florentinus, et al. (2012), McGill, et al. (2013) and Smith, et al. (2015) have been used as sources for gathering the carbon density of the selected fuels. The carbon density is expressed in grams of $CO_2$ emitted per unit mass of fuel burnt. We present this data in figure 3-5.

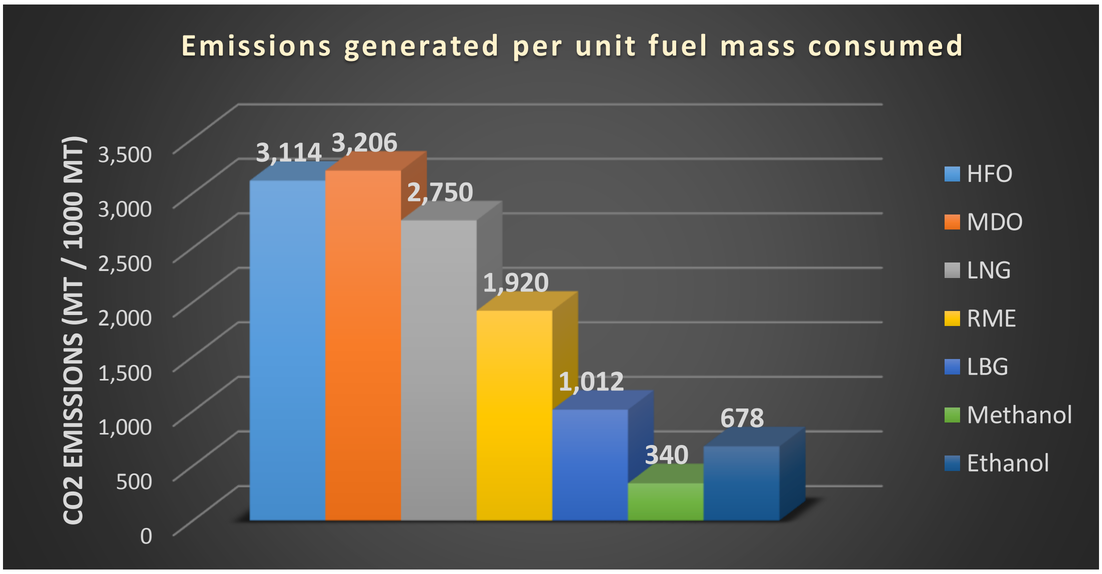


*Figure 3-5: Emissions generated per unit mass consumed*

As discussed in 3.2.1, it is important for us to compare this carbon emissions density relative to the energy produced since we need to benchmark the emissions from different fuels to a common baseline. This comparison is presented in figure 3-6, expressed in MT $CO_2$ emitted per Tera-Joules energy produced.

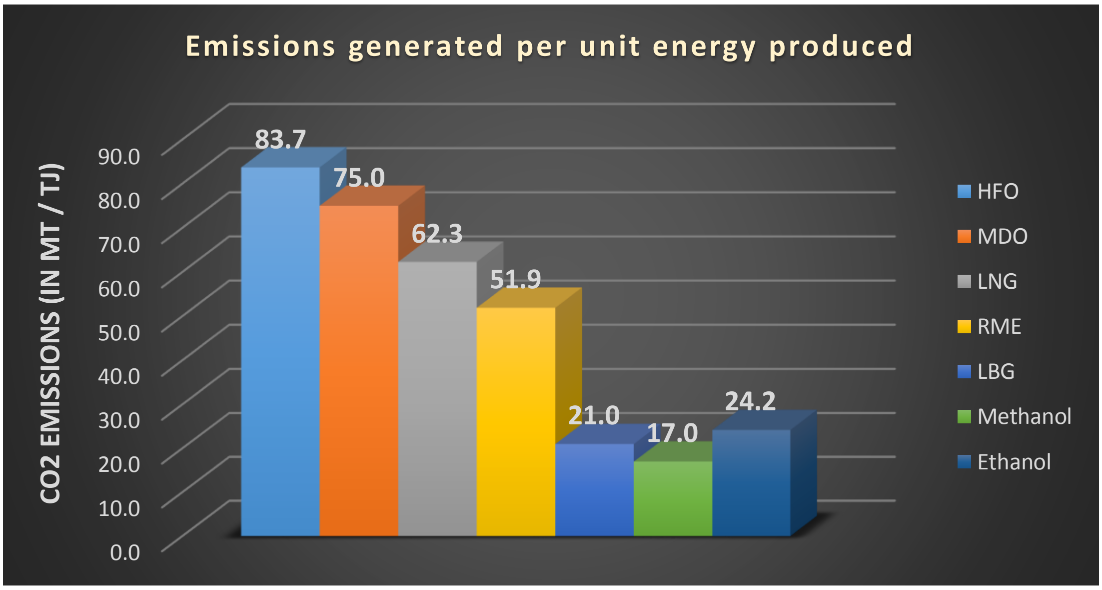


*Figure 3-6: Emissions generated per unit energy produced*

As can be seen in Figure 3-6, HFO and MDO produce the highest emissions in the selection. LBG, MeOH and EtOH offer substantial reductions in emissions for the same quantum of energy produced. LNG does not provide as large reductions in emissions as the biofuels but in comparison to HFO and MDO, these reductions are significant, nevertheless.

### *3.2.3 Environmental Impact and Safety Assessment*

The environmental impact of oil spills can be devastating. HFO is not miscible in water, does not degrade and is highly persistent causing extensive damage to the marine ecosystem. MDO evaporates to a certain degree and does not persist as long as HFO. During the time that it persists on the water surface, it does cause significant damage to marine life. LNG and LBG are gases at atmospheric pressure and consequently evaporate very quickly following a spill without any residual effects on the water it was in contact with. RME does not dissolve in water immediately but is biodegradable and does not pose and risks to the environment. MeOH and EtOH are fully miscible in water and will dissolve completely in a short span of time (Ellis & Tanneberger, 2015).

LNG and LBG are cryogenic fuels thereby requiring very robust handling systems to prevent cold burns to personnel. All biofuels are non-toxic to humans within the usual exposure limit criteria (Florentinus, et al., 2012). LNG, LBG, MeOH and EtOH are low flashpoint fuels, and consequently, the safety considerations for these fuels need to be more elaborate. However, this has already been recognised and the IMO has mandated the use of the International Code of Safety for Ships using Gases or other Low-flashpoint fuels (IGF Code) which addresses the safety issues related to these fuels exhaustively (IMO, 2015).

Further detailed risk assessments for the use of these fuels for marine use is a matter of ongoing research and outside the scope of this study.

## *3.3 Fuel Pricing*

The affordability and availability of fuels are vital elements in their adoption strategies. Fuel prices across the whole range of selected fuels have been volatile, to say the least, over the period that such records are available. We shall assess any long-term trends in these fuel prices and make reasonable assumptions to frame price scenarios.

We used *Bloomberg* commodity spot price database for gathering price data for Brent Crude Oil, LNG, RME and Ethanol. The prices for HFO and MDO are obtained from *Clarksons SIN* database. Methanol spot and historical prices were not available on these databases. So, we made use of the prices published by Methanex Corporation, which is the world’s largest producer and supplier of Methanol. We have gathered price data for these fuels since August 2006, except for RME data for which is available only from January 2011.

Spot price history of LBG is not available as it is not a commodity currently traded on commodity markets. However, the International Energy Agency (IEA) Task 37 focuses on energy from biogas and does publish the price of biogas produced from different plants in various parts of the world. Verbeek, et al. (2011) notes that Biogas costs in the range of 1.2-1.5 times the price of natural gas. We note that biogas is commercially produced and available as a road transport fuel in Finland. The price of biogas in Finland is 1.07 times the price of natural gas. We assume that the cost of sourcing the biogas and liquefying it is the same as fossil-based natural gas. For our study, we have pegged the current price of LBG at 1.3 times price of LNG.

The prices of the different fuels are quoted in varying units. For example, while crude oil is usually quoted in US dollars ($) per barrel, prices of HFO, MDO, RME and MeOH are quoted in $/MT. LNG prices are quoted in $/mmBtu while ethanol is quoted in US cents/gallon. Thus, to make a reasonable comparison we have converted all the prices to US $/MT. We have used the Japan LNG import price on CIF (cost, insurance and freight paid) terms as the price for LNG. RME and Ethanol prices are based on FOB (free on board) rates loaded from US Gulf coast.

### *3.3.1 HFO and MDO*

The spot price for HFO 380 cSt in June 2016 was noted to be $ 227.88/MT and $ 432.50/MT for MDO. We note that the price of HFO and MDO closely follow price fluctuations in crude oil.

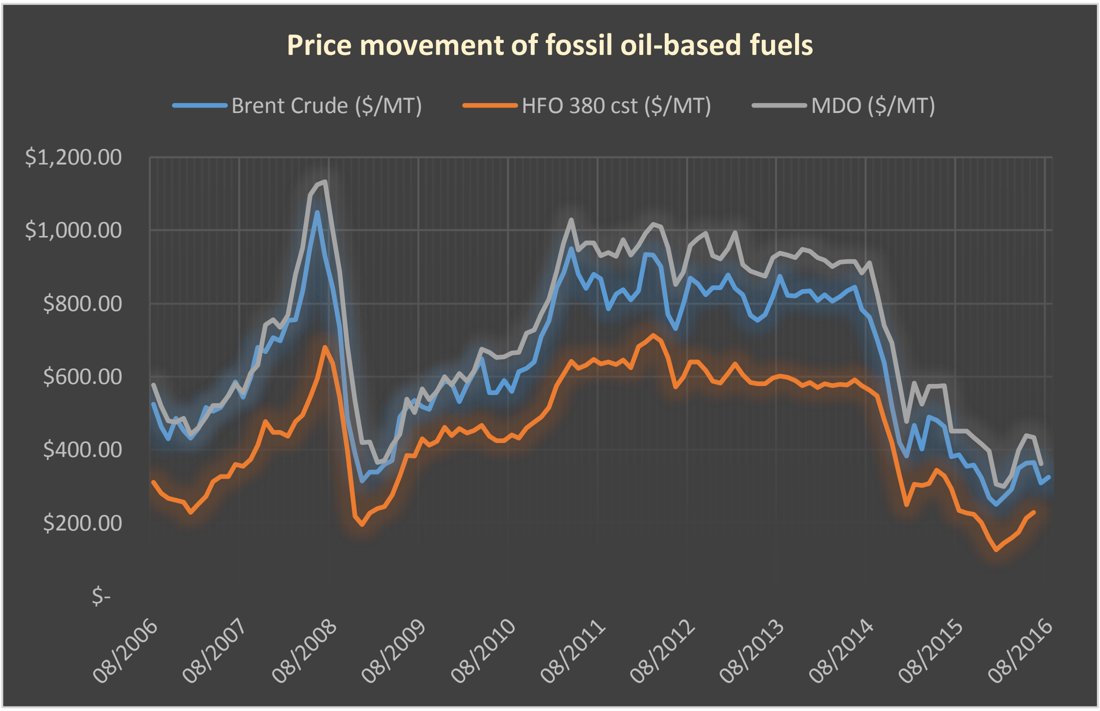


*Figure 3-7: Historical price movement of Brent crude, HFO and MDO*

We can see from Figure 3-7 that the fluctuations in HFO and MDO almost mirror the fluctuations in Brent crude. Further, it is also evident that the price of MDO maintains a positive differential with that of HFO ranging between 1.5-1.9 times the price of HFO.

HFO and MDO are abundantly available with technology for its production and refining at mature levels. The infrastructure for its storage and supply is well established.

### *3.3.2 LNG*

The price of LNG has shown a downward trend lately. Historically we can note from figure 3-8 that the temporal factor of price fluctuations is similar to that of HFO which in turn was closely linked to crude oil. LNG costs more than HFO on weight terms but in energy terms it is almost the same or sometimes even less than HFO. At a price of $ 274/MT (June 2016), the energy equivalent price is $ 5.7/GJ which is the same as HFO priced at $ 230/MT.

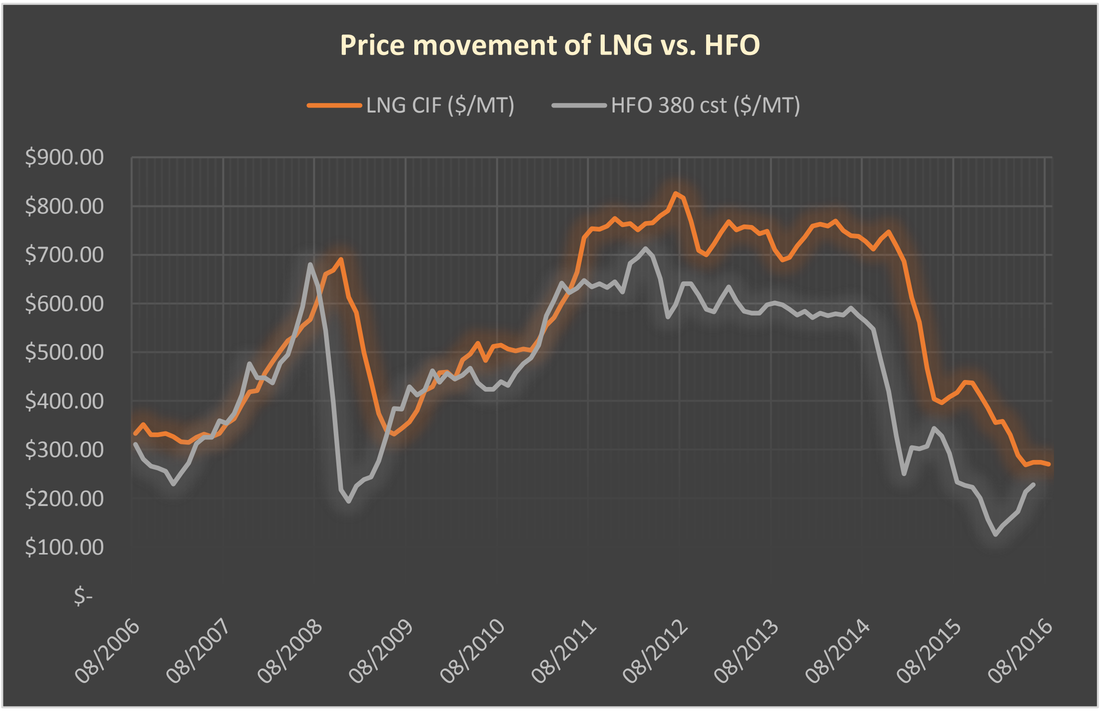


*Figure 3-8: LNG price movement v. HFO*

IMO (2016d) notes that LNG bunker price will reduce progressively in the near future and remain below the price of HFO in energy terms. BP (2016) estimates the global production of natural gas at 3199.5 MTOE in 2015 with a growth of 2.2% from 2014. IMO (2016d) observes that the largest contribution to the cost of LNG is the cost of liquefaction and the cost of bunkering infrastructure. However, this has been on the decline over the last few years. The boom in shale gas has supplemented global production levels of natural gas significantly. Consequently, availability of LNG is most likely to increase, and costs of processing are likely to decrease as well. This should ideally make LNG as a marine fuel increasingly attractive.

### *3.3.2 RME*

RME price data is available only since January 2011. We compared the price of RME with MDO since it is the fuel it is most similar to and considered as a low-carbon substitute to it. The current price of $ 825/MT is 1.9 times the price of MDO in weight terms and more than double the price in energy terms. Figure 3-9 shows a distinctive downward trend in the price of this commodity. The price volatility has not been as pronounced as we have seen for the fossil fuels. We assume that the decrease in price is linked to improvements in production technology. However, global production of biodiesel declined by 4.9% in 2015 over 2014 (BP, 2016). Whether this drop is entirely due to the unprecedented crash of oil prices in 2015 is not known, but we can reasonably assume this is the case as biodiesel is only used as a substitute for fossil fuels. The global production of biodiesel in 2015 is estimated at 26 MTOE (BP, 2016).

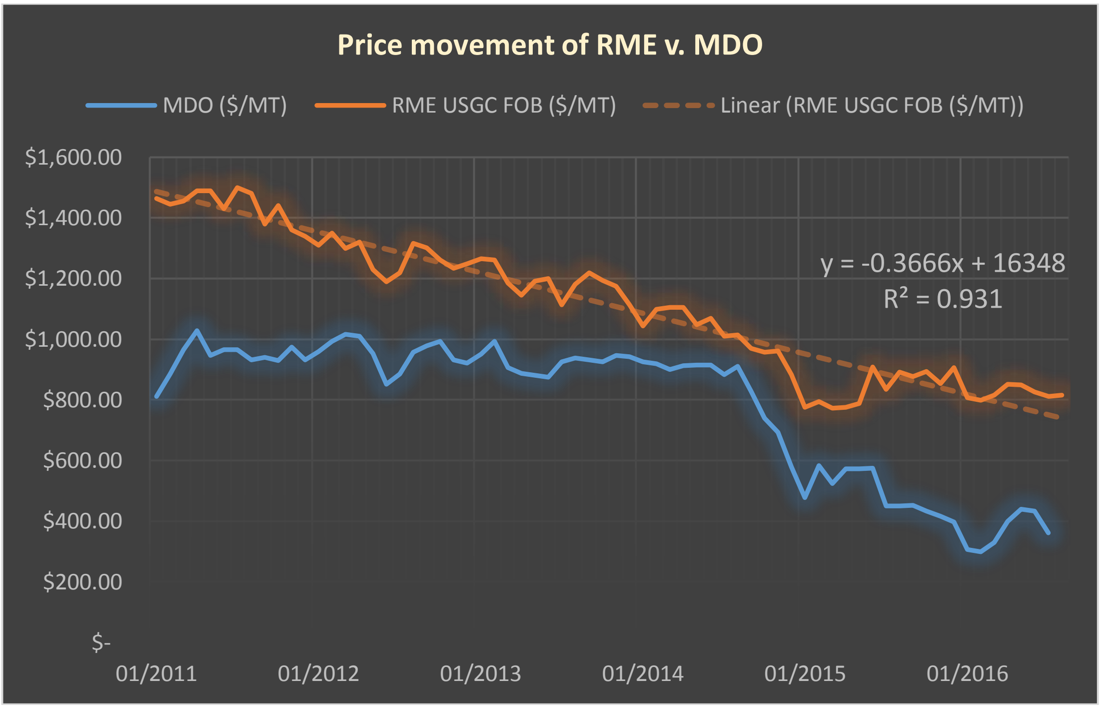


*Figure 3-9: Price movement of RME v. MDO*

### *3.3.3 Ethanol*

Ethanol is the most widely used biofuel globally. In 2015, the production of bio-ethanol was estimated at 49 MTOE (BP, 2016). It has been typically used as a blend for engines running on petrol. However, it can also be used as a substitute for diesel (Ellis & Tanneberger, 2015). In figure 3-10, we compare its price against MDO and note that over the last few years it has traded at prices below that of MDO in weight terms, but that differential has reduced since the later part of 2014 and currently it costs more than MDO. At the current price of $ 441/MT, its price in energy terms is $ 15.3/GJ which is 1.5 times that of MDO. However, the price of ethanol does not appear to mirror the trend in MDO or crude oil and hence at higher oil prices; it may be cheaper than MDO by significant amounts as was seen in the period 2011 – 2014.

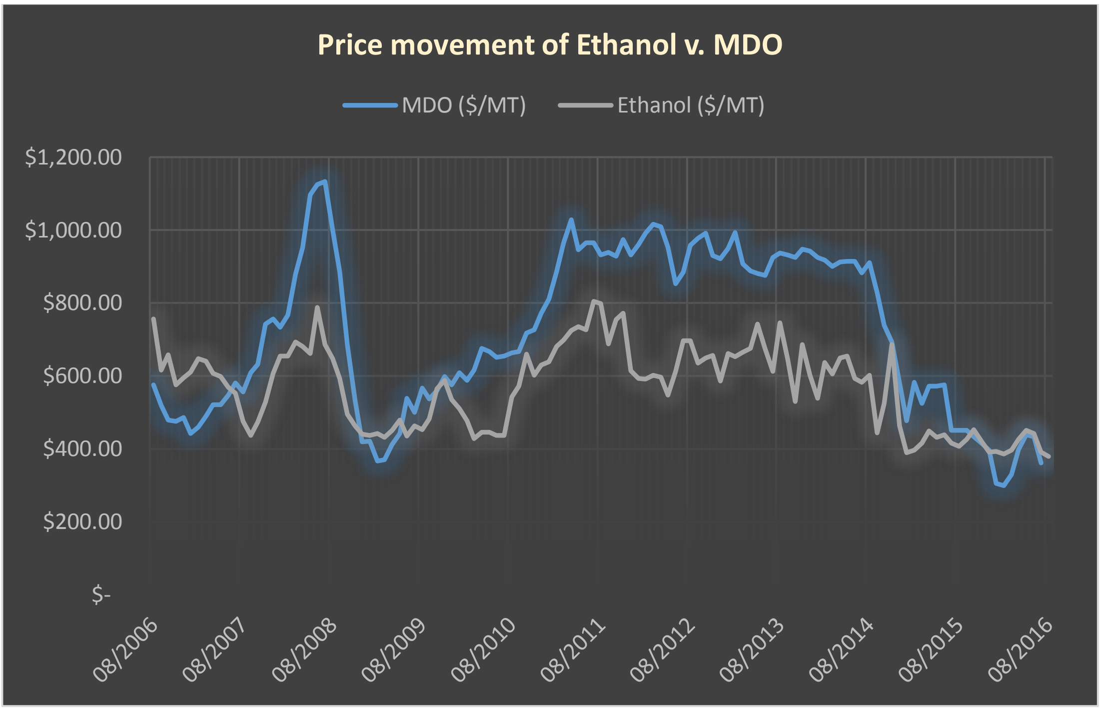


*Figure 3-10: Price movement of Ethanol v. MDO*

### *3.3.4 Methanol*

We compared the price of methanol against LNG because natural gas is one of the main feedstocks for methanol. This study relates to methanol produced from biomass but since there are no published historical prices for bio-methanol we assume it to be the same as methanol produced from chemical processing of natural gas.

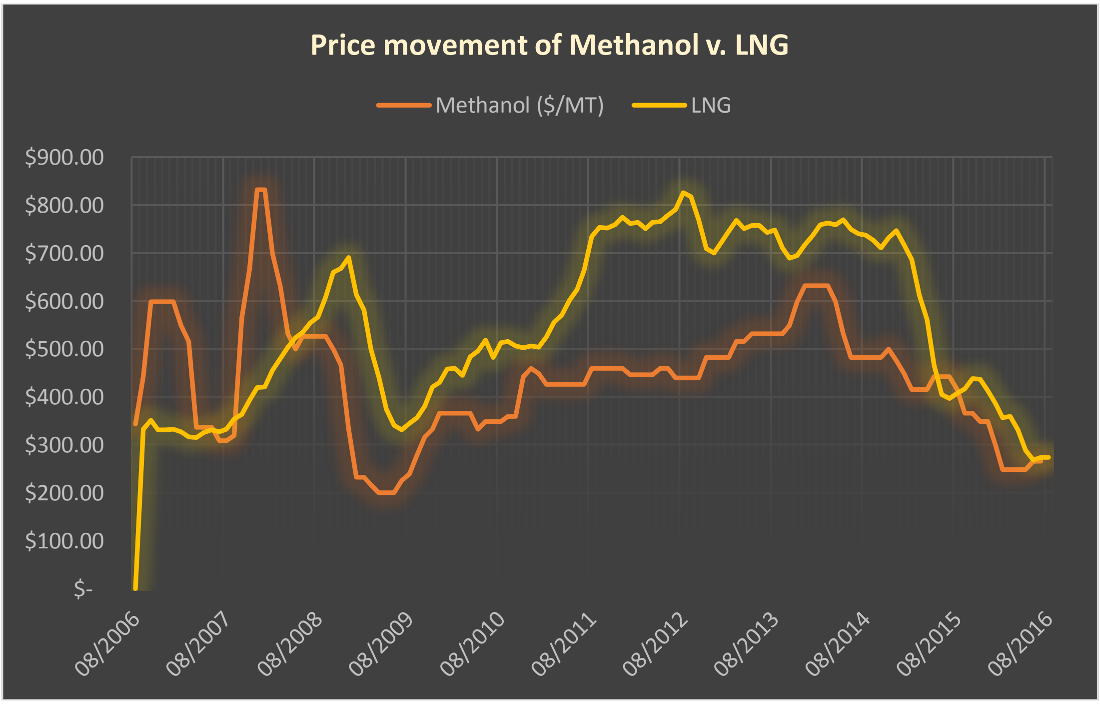


*Figure 3-11: Price movement of Methanol v. LNG*

In figure 3-11, we observe that methanol in most cases costs less than LNG in energy terms. However, the price differential between the two has narrowed down considerably following the oil price crash in 2015. At a current price of $ 266/MT, the equivalent price in energy terms is $ 13.3/GJ which is almost 2.5 times the energy equivalent price of LNG.

Methanol is a widely traded commodity for the chemical industry, and its production can be ramped up in a considerably short period. Production of methanol from biomass is already being done on a large scale. Another advantage of methanol is that it is widely available across the globe.

### 3.4 Price comparison in energy terms

As discussed in section 3.2.1, the energy density is an important measure for this study and consequentially it is vital that we compare the fuel prices using the common benchmark of the energy produced. In figure 3-12, we present the current prices of the selected fuels in energy terms, expressed in US $/GJ.

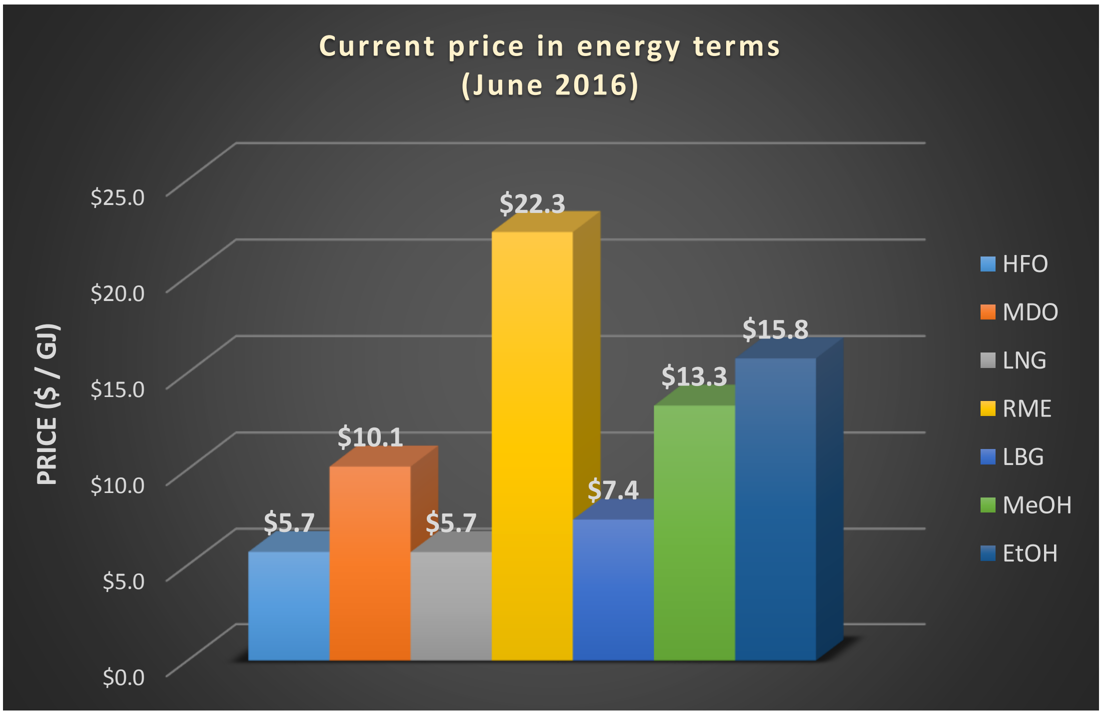


*Figure 3-12: Current price of selected fuels in energy terms*

We note that LNG is priced competitively against HFO and MDO. LBG at its assumed pricing is also well placed. MeOH and EtOH are priced above MDO by significant amounts while RME at its current price is the most expensive fuel among the selected fuels. Further technological enhancements in the production processes of these alternative fuels could lead to bridging this gap in the future, and we shall use this as one of our price scenarios for further analysis.

### 3.5 Price Scenarios

We use the price of oil and the progression in production technologies of alternative fuels as the basis for building our price scenarios. From the data gathered we note that the maximum price of HFO has been $ 712.60/MT and the minimum has been $ 125.90/MT. HFO price has hovered around $ 600/MT for a large part of the period from 2011-2014. We use this as the high oil price. The current price level of HFO is close to the least the prices have dipped to over the last ten years. We use $ 250/MT for HFO as the low oil price scenario.

We define the current level of technology in the production of alternative fuels to be a “limited level of technology”. We assume that, in the coming years, further research and development will induce improvements in technologies associated with alternative fuels defined as “mature level of technology” thereby reducing the cost differentials from fossil fuels.

#### 3.5.1 Low Oil – Limited technological progression

We believe the current price scenario is one which is characterised by low oil prices and limited technological progression on alternative fuels. The price of HFO is $ 230/MT with MDO priced at 1.88 times the price of HFO. LNG is priced marginally higher than HFO in weight terms and equal in energy terms. LBG as priced at 1.3 times LNG as discussed in section 3.3. MeOH is priced about 1.2 times price of HFO and EtOH about 1.9 times price of HFO in weight terms.

*Table 3-2: Low Oil - Limited Technology Price Scenario*

| LO - LT | HFO | MDO | RME | LNG | LBG | MeOH | EtOH |
|---|---|---|---|---|---|---|---|
| $ / MT | $ 230 | $ 433 | $ 825 | $ 274 | $ 356 | $ 266 | $ 441 |
| $ / GJ | $ 5.7 | $ 10.1 | $ 22.3 | $ 5.7 | $ 7.4 | $ 13.3 | $ 15.8 |

#### 3.5.2 Low Oil – Mature technological progression

In this scenario, we assume oil prices will stay low around current levels with technology for alternative fuels maturing enough to reduce prices by a realistic 10% from current price levels. HFO and MDO are priced at current levels without any changes, while all the other fuels are reduced by 10%.

*Table 3-3: Low Oil - Mature Technology Price Scenario*

| LO - MT | HFO | MDO | RME | LNG | LBG | MeOH | EtOH |
|---|---|---|---|---|---|---|---|
| $ / MT | $ 230 | $ 433 | $ 743 | $ 247 | $ 321 | $ 239 | $ 397 |
| $ / GJ | $ 5.7 | $ 10.1 | $ 20.1 | $ 5.1 | $ 6.7 | $ 12.0 | $ 14.2 |

In this scenario, comparing on the energy terms, LNG gets cheaper than HFO while for the other fuels the price differential against MDO or HFO reduces. This comparison is presented in Table 3-3 and figure 3-14.

### 3.5.3 High Oil – Mature technological progression

This scenario assumes a very high level of technological improvements in production processes for alternative fuels. As discussed in section 3.4, having all the fuels priced equally in energy terms is a scenario that should be assessed, and we simulate it here.

We set a high oil price with HFO at $ 600/MT and MDO at $ 900/MT. Mature technological levels for alternative fuels are such that LNG equals the price of HFO in weight terms but is cheaper in energy terms. LBG is priced equal to LNG. RME, MeOH and EtOH are priced equal to MDO in energy terms.

*Table 3-4: High Oil - Mature Technology Price Scenario*

| HO - MT | HFO | MDO | RME | LNG | LBG | MeOH | EtOH |
|---|---|---|---|---|---|---|---|
| **$ / MT** | $ 600 | $ 900 | $ 780 | $ 600 | $ 600 | $ 422 | $ 590 |
| **$ / GJ** | $ 14.9 | $ 21.1 | $ 21.1 | $ 12.4 | $ 12.4 | $ 21.1 | $ 21.1 |

We can note that even though the price by energy density is higher compared to current levels but in relative terms to fossil-based fuels they are priced equally.

### 3.5.4 High Oil – Limited technological progression

This scenario assumes a high price for oil but limited technological improvements from current levels. Assuming that price fluctuations of the biomass-based alternative fuels are disconnected from fluctuations in fossil based fuels, we inflate the price of LNG, RME, LBG, MeOH and EtOH by 50% from current levels.

We set a high oil price with HFO at $ 600/MT and MDO at $ 900/MT. This scenario formulation assumes that current production processes for alternative fuels are sustainable in terms of financial viability. The prices for these fuels do increase over current levels but do not match the quantum of change experienced by HFO or MDO.

*Table 3-5: High Oil - Limited Technology Price Scenario*

| HO - LT | HFO | MDO | RME | LNG | LBG | MeOH | EtOH |
|---|---|---|---|---|---|---|---|
| **$ / MT** | $ 600 | $ 900 | $ 1,238 | $ 411 | $ 534 | $ 399 | $ 662 |
| **$ / GJ** | $ 14.9 | $ 21.1 | $ 33.5 | $ 8.5 | $ 11.1 | $ 20.0 | $ 23.6 |

Comparing the prices by energy density, in this scenario LNG and LBG are considerably cheaper than HFO and MDO. MeOH gets cheaper than MDO, while EtOH and RME though remaining higher than MDO, the price differential does narrow from current levels.

### 3.5.5 Price scenario summary

We have summarised the price scenarios in Figures 3-13 and 3-14 whereby the price differentials in the different scenarios can be appraised.

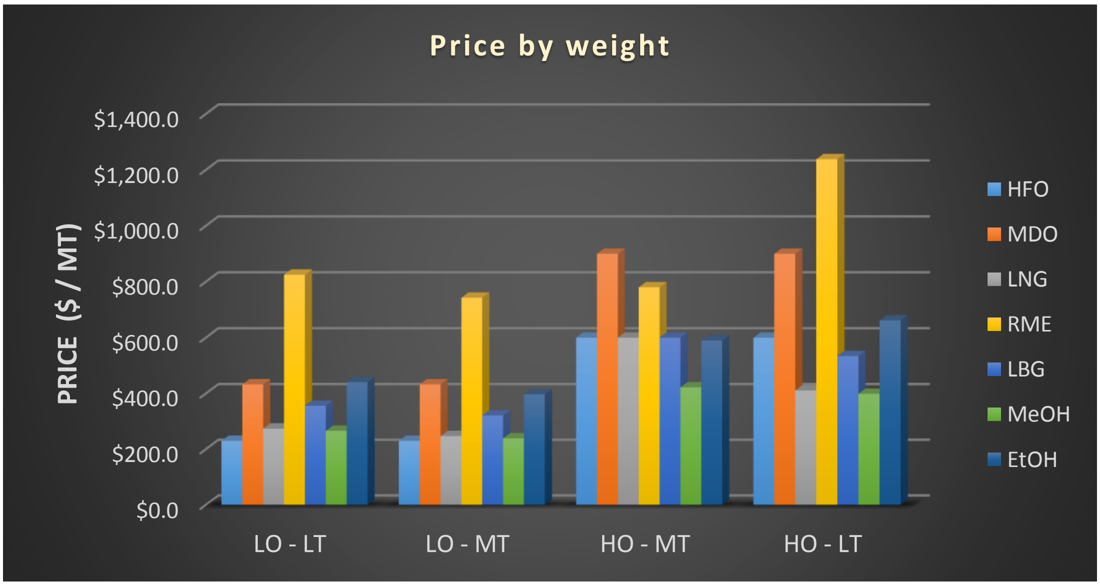


*Figure 3-13: Summary of Price Scenarios (price by mass)*

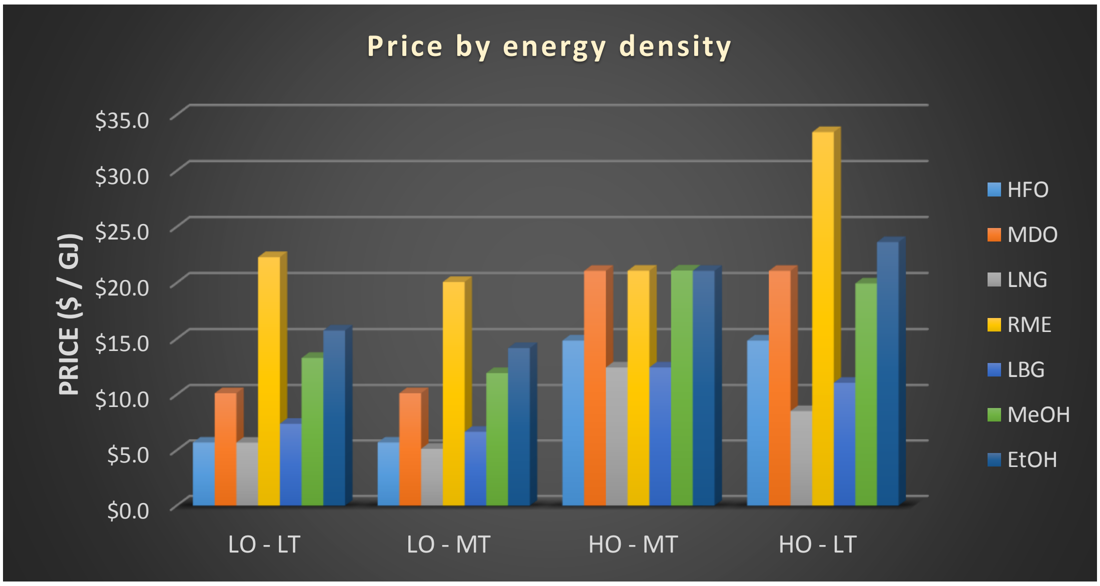


*Figure 3-14: Summary of Price Scenarios (price by energy density)*

*Table 3-6: Prices of selected fuels in defined price scenarios ($/MT)*

| Scenario | HFO | MDO | RME | LNG | LBG | MeOH | EtOH |
|---|---|---|---|---|---|---|---|
| LO - LT | $230 | $433 | $825 | $274 | $356 | $266 | $441 |
| LO - MT | $230 | $433 | $743 | $247 | $321 | $239 | $397 |
| HO - MT | $600 | $900 | $780 | $600 | $600 | $422 | $590 |
| HO - LT | $600 | $900 | $1,238 | $411 | $534 | $399 | $662 |

*Source: Author*

## 3.6 Availability of Alternative Fuels

Next to affordability, the other vital factor related to the adoption of alternative fuels is their availability. Proven reserves of natural gas have increased from 157.3 trillion cu.m in 2005 to 186.9 trillion cu.m in 2015. The global production of natural gas, in 2015, was estimated at 3538.6 billion cu.m of which 338.8 billion cu.m was traded as LNG indicating a growth of about 1.8% over 2014 (BP, 2016). These figures coupled with a growing number of natural gas liquefaction and processing projects globally increasingly point towards a growing availability of LNG as a marine bunker fuel (IMO, 2016d).

The availability of biofuels is related to sustainable sourcing of biomass for production of these fuels. Biofuels are produced from a range of feedstock including energy crops, urban waste, agricultural and forestry residues. The scarcity of water and fluctuating crop yields are major concerns that could induce volatility in the production of biofuels. The need to produce enough food crops for a bludgeoning global population is viewed as an ethical issue in kerbing expansion of energy crop production. Nevertheless, it is estimated that annually 100 EJ of biomass is discarded as residues or destroyed during harvest, which equates to about 18% of the world's primary energy supply (Chryssakis, et al., 2015).

IEA (2015) notes the primary energy supply from international marine bunkers, in 2013, to be 7910 Petajoules (PJ) equating to 188.9 MTOE. The global production of bio-ethanol in 2015 is estimated at 49 MTOE and bio-diesel at 26 MTOE (BP, 2016). The nameplate global production capacity of methanol is estimated at 114.386 million MT (Bloomberg, 2016) (Methanex Corporation, 2015) (Methanol Institute, 2013) equating to 54.63 MTOE of which we should acknowledge that a large proportion is dedicated to production processes in the chemical industry. Besides, at this point, we cannot ascertain what fraction of the methanol is produced from biomass as primary feedstock. Biogas production in 2014 is estimated at 120 TWh (IEA Bioenergy, 2015) equating to 10.32 MTOE. The IEA Bioenergy Task 37 notes that while Germany and other EU states lead the world in Biogas production, generation of biogas is growing rapidly in energy intensive countries like China and India which would supplement current production capacity significantly (IEA Bioenergy, 2015).

We summarise the current global maximum availability of the selected fuels with respect to international marine bunker consumption in Table 3-6.

*Table 3-7: Summary of selected fuels global production levels*

| | Energy Supply (approximate values) | Global supply relative to marine bunker requirement |
|---|---|---|
| International Marine Bunkers (2013) | 188.9 MTOE | - |
| LNG (2015) | 304.9 MTOE | 161 % |
| Biogas (2014) | 10.3 MTOE | 5.4 % |
| Bio-Diesel (2015) | 26.0 MTOE | 13.8 % |
| Bio-Ethanol (2015) | 49.0 MTOE | 25.9 % |
| Methanol (2014) | 54.6 MTOE | 28.9 % |

*Source: Author's compilation*

We can note from Table 3-6 that barring LNG, no other alternative fuel at this point is produced in quantities that can satisfy the entire demand of the shipping industry. Currently, these fuels are used industries, road transport and generation of electricity. Allocation of these fuels for marine use will entail substantial ramping up of production.

The blending of compatible fuels is an important strategy for improving the widespread use of these fuels. In our study, we have considered two blended fuels in addition to the selected fuels discussed earlier,

- LNG and LBG in a 50:50 ratio, named LBG 50
- RME and MDO in a 50:50 ratio, named RME 50

The carbon emissions density of the blended fuels is assumed to be in the proportion of the fuel ingredients in the blend. The price of the blended fuels is in direct proportion to the ingredient fuels. Also, we have placed a 2% premium as blending charges.

### *3.6.1 Availability Scenarios*

On the basis of the discussion in section 3.6, we have defined two availability scenarios which will be used as fuel adoption constraints in our model later in the study. Low availability (LA) refers to a case whereby the supply of alternative fuels as marine bunkers is minimal. We use 20% of the current global production levels defined in Table 3-6 as the assumed maximum realistic supply availability for marine bunkers. In the high availability (HA) scenario, we double the LA availability levels. Within the next five years, we can reasonably assume that availability of the selected alternative fuels cannot exceed the defined scenarios. We present the availability scenarios in Table 3-8.

*Table 3-8: Selected Alternative Fuels Availability Scenarios*

| | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|
| Low Availability (LA) | 100% | 2.8% | 5.6% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% |
| High Availability (HA) | 100% | 5.6% | 11.2% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% |

*Source: Author*

## 3.7 Key Outputs

- Identified alternative fuels suitable for shipping and their main physical characteristics in the context of use as marine fuels.
- Laid out the primary differences between the fuels in terms of energy production and emissions generated.
- Discussed properties of the selected alternative fuels that may affect the earning capabilities of the vessel.
- Examined price movement of the selected fuels over the last ten years.
- Defined four price scenarios on the basis of oil price and level of technology for production of alternative fuels.
- Estimated current global availability of these fuels and then defined two availability scenarios for alternative fuels in shipping.

# 4. Maritime Alternative Fuels Emissions Assessment

In this chapter, we will discuss the methodology used to gather data and develop an integrated model for assessing $CO_2$ emissions from shipping using different fuels, decision support tool for investment analysis and fleet mix optimisation. Firstly, we will generate an inventory of $CO_2$ emissions from shipping. This inventory will be linked to the fuel data and price scenarios developed in Chapter 3 to generate shipping emissions using different alternative fuels and assess the emissions abatement potential. We shall then discuss the parameters and assumptions used to build a capital budgeting model for ship-owners linked to the emissions model. We then outline a simple methodology to optimise abatement costs and maximise emissions reductions from shipping. This chapter serves to address and answer comprehensively sub-research question one of our study.

## *4.1 Shipping Emissions Inventory*

We shall use a bottom-up approach to develop the emissions inventory. The first step is to define the shipping fleet for our study. The *Clarksons Shipping Intelligence Network (SIN) 2010 database* was used to gather information regarding the fleet. The database provides a *World Fleet Monitor Report* every three months and includes a breakup of the fleet by nationality, classification society and ship type. We make use of the fleet categorization using ship type as it allows us to allocate emissions per sector of the fleet and has been used in earlier shipping emission inventory studies as well viz. Psaraftis & Kontovas (2009), Buhaug, et al. (2009) and Smith, et al. (2015). The non-cargo vessels which include Offshore vessels, dredgers, tugs, cruise ships, ferries and other non-cargo vessels have been excluded from our study. These non-cargo vessels account for a total of 37,880 vessels. However, due to their variable trading pattern and utilisation, emissions generated by these ships cannot be measured to a reasonable accuracy within the scope of time for this study. Further, these vessels represent only 8.3% of the entire shipping fleet by gross tons (as of 01 Mar 2016), and a large part of the environmental regulations do not apply to those of them that are less than 400 GT. We shall limit our study to cargo vessels. The inventory of fleet used for this study is based on reported numbers as of 01 March 2016.

### *4.1.1 Fleet structure analysis*

The cargo vessels have been sub-divided into six main categories on the basis of the type of cargo carried totalling 53,414 vessels. These categories are:

- Oil Tankers
- Specialised carriers (liquid bulk)
- Bulk Carriers
- Other dry cargo
- Container Vessels
- Other Unitised cargo vessels

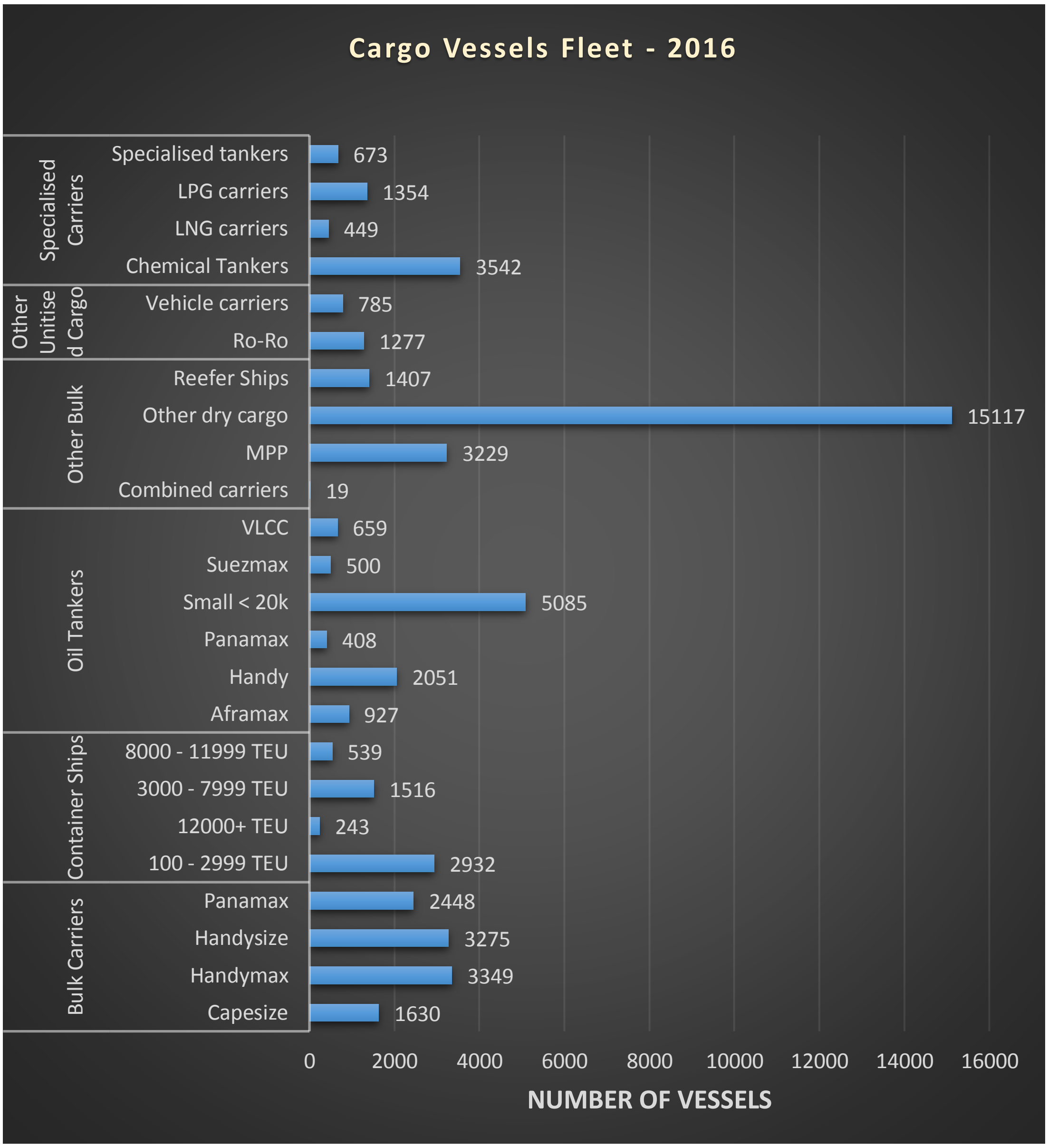


*Figure 4-1: World fleet by absolute numbers, 2016*
*Source: Compiled from Clarksons Shipping Intelligence Network*

Going by absolute numbers, the number of "other dry bulk cargo" vessels is far more than any other category of vessels. These are typically small ships carrying a range of different dry cargoes. The total numbers of bulk carriers and tankers are approximately 10,000 vessels each, while the number of container ships is roughly half this number. However, measuring the vessels by size and the amount of cargo carried presents a completely different picture. Gross tonnage is a commonly used measure in shipping representing the total of all enclosed spaces on the ship which are used for carrying cargo or other operational purposes. Profiling the fleet in terms of gross tonnage, we find that bulk carriers, tankers and container ships are the vessels which form the largest proportion of cargo carrying capacity of the global fleet. Consequently, the cumulative emissions generated from these vessels is expected to contribute significantly to the fleet emissions. It is important for us to understand this profile, since mapping the fuel consumption of these ship sub-types accurately will be critical to our emissions inventory.

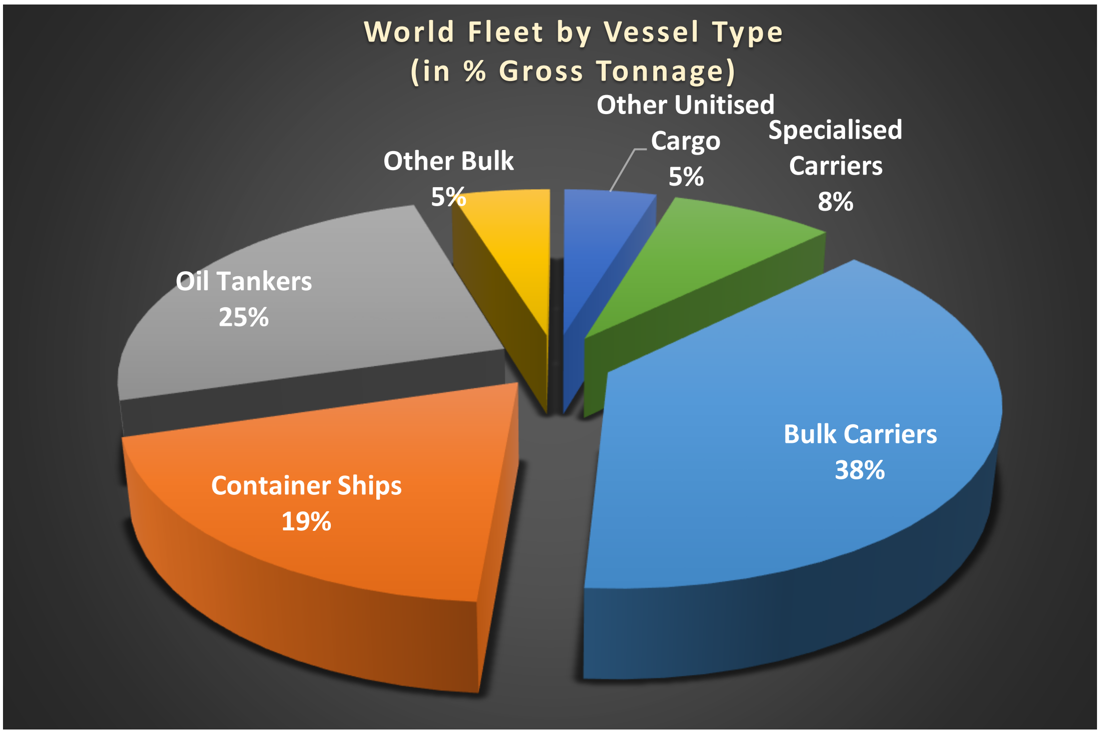


*Figure 4-2: World fleet by vessel type (in % GT)*
*Source: Compiled from Clarksons Shipping Intelligence Network*

### *4.1.2 Fuel consumption per ship*

We used the main engine details given in Smith, et al. (2015) which derives these details from IHS Fairplay (IHSF) database (2012) to establish the average installed power (in kW) for each of the vessel categories. The key assumptions used for setting up the model are:

- All the vessels in the fleet are currently equipped with conventional slow speed 2-stroke (SSD) diesel engines for main propulsion, high-speed 4-stroke (HSD) auxiliary engine (AE) for power generation and oil-fired boiler(s) for heating and cargo handling if required.
- All vessels in the fleet are currently using IFO 380 cSt, henceforth referred to as HFO, for all purposes.
- The specific fuel oil consumption (SFOC) of the main engine (ME) is 175 g/kWh, as is used by Smith, et al. (2015), under all conditions of engine load. The default tuning of engines is such that the least SFOC is obtained at ME loads of 70-80% MCR. SFOC can vary widely at loads outside this range.
- Vessels have been assumed to be operating the ME at a load factor of 75% MCR (maximum continuous rating) during the laden voyage and 35% MCR during the ballast voyage. MCR is taken to be the average installed power (in kW) available in the IHSF database. Smith, et al. (2015) report an average ME load factor for oil tankers, bulk carriers and container vessels in the range of 28 – 70%, with a large proportion of this being below 50%. The approach used in this study to separate the ME loads during laden and ballast conditions could help in reducing the variability of induced by this factor.

- Consumption in port refers to the time when the vessel is carrying out cargo operations. Consumption during idling at sea or waiting at anchorage refers to the time spent waiting for orders, favourable navigational conditions and any such activity which is largely unproductive for the vessel.
- Details of AE's and boilers fitted on vessels is very scarce (Psaraftis & Kontovas, 2009) (Buhaug, et al., 2009) (Smith, et al., 2015). Thus, best estimates made on the basis of interactions with members of the marine engineering fraternity and personal experience have been used. Vessels with an ME of 15000 kW or more have been assigned an AE consumption of 3.0 MT/day (MTD) at sea. While those vessels with ME power less than 15000 kW have been assigned an AE consumption of 1.5 MTD at sea. Container vessels are an exception to this assumption as most of these vessels use a shaft generator (drive motor being the ME) for power generation thereby obviating the need for AE use at sea.
- The AE consumption in port has been assumed to be 150% of the consumption at sea, and while idling at sea or waiting at anchorage, the consumption is assumed to be 100% of consumption at sea. While container vessels do not use AE at sea, during idling or waiting at anchorage, they will need to use their AE in port as well as while idling at sea or waiting at anchorage. For container vessels 8000 TEU and above, AE consumption has been assumed to be 4.5 MTD and 3.0 MTD in port and idling respectively. For vessels less than 8000 TEU, the consumption is assumed to be 2.0 MTD.
- The boiler consumption at sea has been assumed to be zero for all vessels. In port, oil tankers and specialised carriers make extensive use of their boilers as prime movers for cargo handling equipment and hence have been assigned a fuel consumption that is equal to the ME consumption at sea. However, instances of this consumption occur only while the vessel is discharging her cargo. During loading operations, the boiler consumption is substantially less since the cargo is being handled by shore pumps. Therefore, the total boiler daily consumption in port has been assumed to be 50% of ME consumption at sea. For the other vessels, except for container vessels, boiler consumption in port and idling or waiting at anchorage has been assumed to be equal to AE consumption at sea. For container vessels, the boiler consumption in port and idling has been assumed to be 1.5 MTD for vessels 8000 TEU and above, and 1.0 MTD for vessels less than 8000 TEU.
- ME consumption at sea has been calculated as

$$Consumption\ (in\ MTD) = (SFOC * ME\ load * \ MCR)/10^6 \ ......$$ *Equation 1*

ME load would vary with the vessel's loading condition and hence the model reflects daily consumption at sea in both these conditions.

- Oil tankers, Specialised Carriers, Bulk Carriers and Other dry cargo carriers typically travel in laden condition followed by a voyage in ballast condition towards the port of loading. The ratio of time Laden to Ballast has been assumed to be 0.5. Container vessels and Other unitised cargo vessels are typically engaged in liner services where they are neither completely laden nor entirely empty (ballast) at any point in time. For these vessels, the ratio has been assumed to be 0.70.

- The number of days at sea has been assumed to be 245 days annually. The IHSF database for 2012 shows considerable variability for this measure ranging from 116 to 267 days for commercial vessels (Smith, et al., 2015). We used 245 days such that when added to the days in port, we get a total of at least 80% productive time i.e. either steaming at sea or carrying out cargo operations in port.
- The number of days in port for oil tankers, specialised carriers, bulk cargo and other dry cargo vessels has been assumed to be four days per month equating to 48 days annually. Container vessels, Ro-Ro and ferries typically call a far larger number of ports than other vessels due to the nature of their trade. For container vessels, the number of days in port is assumed to be six days per month and 72 days annually. While for other unitised cargo vessels, we assume five days per month and 60 days annually.
- The days not covered by sea passage or port operations have been assigned as idling at sea or waiting at anchorage.
- Total consumption at sea has been calculated as

$$Total\ consumption\ at\ sea\ (in\ MTD) = \left(sum\ of\ consumptions\ ME_L,\ AE * No.of\ days\ at\ sea * \frac{load}{ballast}\right) + \left(sum\ of\ consumptions\ ME_B,\ AE * No.of\ days\ at\ sea * \left(1 - \frac{load}{ballast}\right)\right) \quad \text{...Equation 2}$$

- Total consumption in port and during idling or waiting at anchorage is the total of AE and Boiler consumptions in the respective cases multiplied by the number of days for the particular case.
- Total consumption of HFO per vessel annually is the sum of the consumption at sea, in port and during idling or waiting.

$$Total\ consumption\ per\ ship\ (MT) = (Total\ consumption\ at\ sea + Total\ consumption\ during\ port\ operations + Total\ consumption\ during\ idling\ or\ waiting) \quad \text{...Equation 3}$$

### *4.1.3 Fleet $CO_2$ emissions*

The $CO_2$ emissions generated by each vessel is given by the product of the total fuel consumption (in MT) and the emissions factor of the particular fuel. Our baseline calculations have been made on the basis of HFO.

$$CO_2 Emissions\ per\ ship\ (MT) = Total\ fuel\ consumption\ (MT) * Carbon\ emissions\ factor\ of\ the\ fuel \quad \text{...Equation 4}$$

Here, we also introduce the fleet utilisation factor which represents the fraction of the fleet that is in active use. Some ships in the fleet might be laid up due to market conditions, in drydock for periodic maintenance and repairs, used for short-term storage or any other reason which precludes its active use. Typically, over the long-run supply of shipping tends to exceed the demand, invariably causing a small proportion of the fleet to remain inactive (Stopford, 2009). We have assumed this utilisation factor to be 0.90 for our calculations.

$$Fleet\ \mathrm{CO2}\ emissions\ (in\ million\ tonnes) = (Emissions\ per\ ship\ (MT) * Number\ of\ ships\ in\ the\ category * Fleet\ utilization\ factor)/10\text{^}6) \quad \text{.........Equation 5}$$

The total emissions from the shipping fleet is the sum total of fleet emissions from each sub-type of ships.

#### *4.1.3.1 Fleet $CO_2$ emissions using alternative fuels*

In a scenario where a particular vessel shifts to an alternative fuel, our primary assumption is that the vessel would need the same amount of energy as would have been required when the vessel would have been operating with HFO. Thus, the amount of alternative fuel consumed would be such that the energy produced by this fuel would be equivalent to the energy produced by HFO. The energy density of the alternative fuel (in MJ/kg) in relation to that of HFO is used to calculate the quantity of alternative fuel consumed and thereupon the $CO_2$ emissions while using the particular fuel.

$$CO_2\ Emissions\ Fuel_X = Total\ consumption\ (HFO) * \left(\frac{Energy\ density\ HFO}{Energy\ density\ Fuel_X}\right) * Emissions\ Factor\ Fuel_X \quad \text{.......................................................Equation 6}$$

### *4.1.4 Cost of Emissions*

From our discussion in section 2.2 and 2.3.2.2, an MBM for shipping carbon emissions is a distinct possibility that should be factored in. Thus, we make a provision for the cost of emissions which would be determined by the fuel's emission factor, the quantity of fuel consumed and the cost of carbon emissions as set by the particular MBM. In our calculations, we shall consider three scenarios of carbon pricing corresponding to \$ 0/MT, \$ 40/MT and \$ 100/MT.

$$Cost\ of\ Emissions = CO_2\ Emissions\ Fuel_X\ (eqn.6) * Cost\ of\ carbon \quad \text{....................Equation 7}$$

### *4.2 Fleet Mix required for set reduction targets*

The fleet emissions inventory using each fuel can be used to determine the required fleet mix required for each fuel so as to achieve a set target reduction of CO2 emissions. Varying amounts of a fleet mix will be required should the fleet changeover to a particular type of fuel based on its emissions factor. We model this fleet mix such that if one fraction of the fleet would use the alternative fuel while the remaining fleet would continue using conventional fuel viz. HFO. This would give us a clear indication of the abatement potential in switching to the particular alternative fuel.

$$Required\ Fleet\ Mix\ Fuel_X(\%) = \frac{(Target\ emissions - Baseline\ emissions)}{(Fleet\ emissions\ Fuel_X - Baseline\ emissions)} \quad \text{....................Equation 8}$$

## 4.3 Capital Budgeting Model

To develop a capital budgeting model for investment in a ship, we would need to make reasonable estimations of the total costs involved in operating the vessel, the revenues earned over its lifespan and the finance structure used to make the investment. We have assumed the technical life of a vessel to be 20 years for our calculations. We assume that all costs and revenues will inflate by 1.50% over the life span of the vessel. The discount rate used in our calculations is 3.00%.

### 4.3.1 Daily Operating Costs

We source our data for daily operating costs (DOC) from the *Drewry Research – Ship Operating Costs 2014/15* report. The report categorises the daily operating costs for each type of vessel under the following categories, in order of their contribution to the DOC:

- Manning (approx. 34%)
- Stores, Spares and Lubricating Oils (approx. 28%)
- Repairs and Maintenance (approx. 17.5%)
- Management and Administration (approx. 10.5%)
- Insurance (approx. 10%)

For container vessels and gas carriers, the insurance costs are marginally higher than the management and administration costs but barring these the structure is more or less the same for all vessels. These costs are incurred by the ship-owner irrespective of whether the vessel is carrying out productive freight transport for earnings or not. We annualise the DOC as all calculations in the model are based on annual figures.

### 4.3.2 Capital Costs

For the capital costs, we use the *Clarksons SIN 2010* database to gather data regarding the current newbuilding prices for the vessels identified in our model. For calculation purposes, we have assumed that the vessels are entirely funded by a bank loan or other financial instrument with a rate of interest of 4.00% p.a. and a term of 8 years. We have used a straight line repayment type loan where the redemption amount is constant over the loan term, and the interest is charged on the outstanding principal. Bullet loans, where the debtor pays only the interest regularly and pays out a lump sum amount to settle the loan at the end of the term to settle the dues, is also common in the ship finance industry. However, we have not explored this in our study. The capital costs reduce progressively over the period of the loan term. We take the sum of the estimated capital costs over the vessel's lifespan and convert it into an annualised cost and plug it in the model as annual capital costs.

In considering newbuilding prices, it is important to note that the vessels fitted with dual fuel or gas engines and engines designed to use methanol or ethanol are significantly more expensive than the vessels fitted with conventional engines. We use data regarding these cost premiums from Ellis & Tanneberger (2015) to replicate in our model depending on the type of engine to be used for the particular fuel.

*Table 4-1: Investment Costs for machinery relevant to selected fuels*

| Fuel Used | Main Engine Type | Newbuilding machinery investment required (includes ME, AE, Boiler and tanks for storage) |
|---|---|---|
| HFO / MDO / RME | Diesel Engine | $ 542 / kW |
| LNG / LBG | Dual Fuel | $ 1275 / kW |
| Methanol / Ethanol | Dual Fuel | $ 815 / kW |

*Source: Adapted from Ellis & Tanneberger (2015), IMO (2016d)*

$$Newbuilding\ price\ Vessel\ using\ Engine_X = \Big(\big(price\ differential\ (Engine_X - Diesel\ engine)\big) * installed\ power\Big) + Newbuilding\ price\ vessel\ using\ diesel\ engine$$

……………………………*Equation 9*

### *4.3.3 Annual fuel costs and carbon emission costs*

The annual fuel costs are linked to the quantity and type of fuel used, and the price of the particular fuel. For this study, we consider that a vessel will use the same kind of fuel throughout the term of its technical life. The carbon emissions costs (equation 7) would apply should there be a price for emissions and is linked to the type of fuel used.

### *4.3.4 Annual Revenues and net income*

The revenues, often referred to as freight income or time charter equivalent (TCE), has been calculated on the assumption that the base earnings will cover the vessel's operating costs, capital costs and fuel costs. In addition to this, a certain percentage above the base earnings will be required to ensure the financial viability of any investment proposition. The model is designed such that it would calculate the capital costs and fuel costs on the basis of the fuel chosen and thence generate the corresponding income.

The model provides three options for the Base earning:

- Scenario 1 – The freight earnings can cover the DOC, capital costs and fuel costs based on HFO
- Scenario 2 – As above, except the fuel costs are calculated on the basis of MDO
- Scenario 3 – As scenario 1, except the fuel costs and capital costs are calculated on the basis of LNG

The percentage points earnings above the base scenario is largely dependent on market dynamics of supply and demand. The break-even percentage points could vary between different kinds of vessels since this would vary with the newbuilding market prices which are again inextricably linked to other exogenous factors.

$$Base\ earning\ scenario = sum(operating\ costs, capital\ costs, fuel\ costs)$$ ………..*Equation 10*

$$Annual\ revenues = Base\ earning * (precentage\ points\ projected\ earnings\ over\ base\ scenario + 1)$$ ……...*Equation 11*

$$Net\ Income = Annual\ revenues - sum(operating\ costs, capital\ costs, fuel\ costs, emission\ costs)$$ ……….*Equation 12*

### *4.3.5 Net Present Value (NPV) comparison*

We use the different costs and earnings as discussed above to generate a cash flow analysis over the technical life of the ship, which we have assumed to be 20 years. The costs and revenues are inflated at 1.50% per annum to generate a discounted income which is then used to calculate the Net Present Value (NPV), the internal rate of return (IRR) and the payback period. A positive NPV indicates the proposed investment is profitable under the assumed conditions.

With a choice of alternative fuels, it would be important for the ship owner to have a comparison of the NPV's using different fuels, with the corresponding associated costs, so as to make a reasonable assessment of the feasibility of the proposed alternative fuel. Further, we model the tool to factor in a cost for carbon which may or may not be levied in the future. A cost for carbon emissions would alter the cash-flows, and the tool would allow the ship owner to make an appraisal of the choice of fuels available to him/her under such conditions. More importantly, the NPV comparisons would need to be done under the different fuel price scenarios, defined in Chapter 3, so as to enable the ship owner to exercise due diligence in his/her investment decision.

$$NPV = R_0 + \sum_{i=1}^{T} \frac{R_t}{(1+i)^t}$$

…………………………………………………….*Equation 13*

$R_0$ – Initial Investment; T – Technical life of the ship
$R_t$ – Net income at time t; i – discount rate

#### 4.3.5.1 The Zero NPV scenario

Using the set of assumptions used for the capital budgeting model and aggregate expenses on the basis of the particular fuel being used, we can generate a zero NPV scenario which indicates to the ship-owner the minimum earnings required to ensure profitability of the investment. We can express these minimum required earnings as percentage points above the expenses incurred. The minimum earnings required would vary with the price scenario, the base earning scenario and the fuel intended to be used.

### 4.4 Marginal abatement costs of carbon emissions

The shift to each alternative fuel represents an additional cost. The shift also results in an abatement of CO2 emissions. Thus, the marginal abatement cost of carbon emissions (MAC) is the cost incurred in abating per MT of CO2 emissions from baseline levels, HFO in our case. The MAC is a good indicator for policymakers when comparing different abatement measures as it represents the cost-effectiveness of a particular measure.

In calculating the MAC, we first derive the costs involved in the implementation of a shift to a particular alternative fuel. Using the fleet mix derived in section 4.2, the total fleet costs would be the price differential between the scenario with an alternative fuel implemented and the case where HFO was being used. This value represents the maximum cost that would be incurred should the fleet mix as calculated be implemented. Measuring this cost in relation to the emissions abatement achieved would result in the MAC for the particular fuel. In our model, the MAC will indicate the cost-effectiveness of using each of the different alternative fuels as an emissions abatement measure.

The MAC would vary with the different fuel pricing scenarios as the cost of fuel shift largely depends on the fuel costs and the capital costs differential from our baseline costs. We shall, thus, calculate the MAC for different fuels under the different price scenarios to enable a better assessment of the fuel shift as an abatement measure.

$$\begin{aligned} Cost\ of\ shift\ to\ Fuel_X &= \Big((Total\ fleet\ costs\ using\ Fuel_X * required\ fleet\ mix) \\ &+ \big((1 - required\ fleet\ mix) * fleet\ costs\ using\ HFO\big)\Big) \\ &- Total\ fleet\ costs\ using\ HFO \end{aligned}$$

……………………………….*Equation 14*

$$MAC_X = \frac{Cost\ of\ shift\ to\ Fuel_X}{Emissions\ abatement\ achieved}$$

……………………………….*Equation 15*

### 4.5 Optimised fleet mix and MAC

In each of the price scenarios, we would obtain different MAC's associated with the selection of alternative fuels, and one would lean towards the least MAC fuel as the ideal fuel for emissions reduction. However, as discussed in Chapter 3 availability of the alternative fuels is still a major impediment. The alternative fuel availability scenarios, defined in section 3.6.1, can be used as a constraint in a linear programming model to calculate an optimised fleet mix and a resulting aggregated MAC for that particular scenario.

The optimisation of fleet mix can be done either with the goal of minimising costs or with the goal of maximising emission reductions. From the policymaker's perspective, if an optimised fleet mix can produce a certain threshold of emissions abatement, then an optimised cost of abatement would help in setting an optimal level subsidies or other financial incentives.

The problem can be expressed as a linear programming formulation with the objective function being to minimise the aggregated abatement costs associated with an optimised fleet mix for a particular price and fuel availability scenario. This can be written as,

$c_f = MAC\ associated\ with\ fuel_f$

$m_f = proportion\ of\ fuel_f\ in\ total\ fleet\ mix$

$x_f = reduction\ of\ CO_2\ emissions\ achieved\ using\ fuel_f$

$$\boldsymbol{Objective\ function:\ Min \sum\sum\sum c_f\, m_f\, x_f}$$

…………………………………….*Equation 16*

*Decision variable:* $m_f$

Subject to,

$\sum m_f = 100\%\ (assignment\ across\ entire\ fleet)$

$m_f \leq maximum\ availability\ of\ the\ particular\ fuel$

$\sum x_f \geq set\ reduction\ target\ of\ emissions$

$x_f \leq maximum\ abatement\ potential\ of\ the\ particular\ fuel$

$$m_f, x_f \geq 0$$

#### 4.5.1 Choosing a fleet mix and MAC with scenario uncertainty

The MAC optimisation using linear programming discussed in the previous section would give us two MAC's and two fleet mix's for each price scenario since we have two fuel availability scenarios. This would result in a total of eight (8) combined scenarios. There exists a very high degree of uncertainty in the price scenarios due to the influence of various exogenous factors. However, if we consider that each of the price scenarios has an equal probability, we can generate a fleet mix that will maximise the emissions reductions at the least cost possible. Such a fleet mix would enable us to diversify our fuel allocation strategy such that we could achieve a certain threshold abatement in emissions at the least cost irrespective of the volatility in price scenarios.

In defining the probability of the combined scenarios, we assume that the low availability of alternative fuels is more likely to be associated with "limited technology progression" and high availability scenario is more likely to be associated with "mature technology" in the ratio of 60:40. Thus, the probability of each scenario is defined as follows:

*Table 4-2: Fuel price and availability probability matrix*

| Price Scenario | Fuel Availability Scenario | Probability |
|---|---|---|
| Low Oil – Limited Technology | Low | 0.15 |
| Low Oil – Limited Technology | High | 0.10 |
| Low Oil – Mature Technology | Low | 0.10 |
| Low Oil – Mature Technology | High | 0.15 |
| High Oil – Mature Technology | Low | 0.10 |
| High Oil – Mature Technology | High | 0.15 |
| High Oil – Limited Technology | Low | 0.15 |
| High Oil – Limited Technology | High | 0.10 |

*Source: Author*

By applying these probabilities to the optimised fleet mix's and MAC's obtained earlier we can develop the least cost, diversified fleet mix with maximum reduction in $CO_2$ emissions. The resulting MAC would be the least amount of subsidy that a policymaker would need to set to achieve an emissions reduction target.

## *4.6 Limitations of the model*

The emissions model developed uses a bottom-up activity based approach. The activity of the shipping fleet varies very much across sectors as well as the fleet as a whole depending on the factors of supply and demand for shipping. The installed power on ships within each category of ships is an average value. The fuel consumption is largely derived from this value. However, it should be acknowledged that some newer vessels have a lesser installed power than vessels built prior to 2010 for the same size of vessels. Thus, there is bound to be some variability of fuel consumption within vessels in the same category. The assumptions used in the model might tend to exaggerate the fleet emissions but from the policymaker's perspective, this should be viewed as the potential emissions from the fleet under given circumstances.

In the capital budgeting model, we have used an interest rate of 4.00% and a loan period of 8 years which varies widely across the fleet and also varies with the economic cycles. Similarly, changes in the discount rate could alter the NPV calculations significantly. Further, we have not attempted to make a detailed real-time earning profile of the different sectors within the fleet and thus built the costs of shifting to a particular alternative fuel on the basis of aggregate expenses and not differential incomes.

We have developed our price scenarios using the current price scenario as a baseline. There could be considerable volatility within the defined price scenarios which could change the results obtained. The alternative fuel availability scenarios have been defined on the basis of literature as the fuels considered in the study are not being currently used in shipping so volumes available as a fuel for shipping is unknown. Changes in the availability will alter the constraints in our linear programming and thereupon the optimised results.

### *4.7 Key Outputs*

- Discussed the various elements of our integrated alternative fuels assessment model.
- Outlined the fleet structure of cargo vessels.
- Discussed assumptions made to calculate fuel consumption per day per ship.
- Explained the methodology to derive the expected fuel consumption using the selected alternative fuels and the emissions generated from them.
- Examined various elements of a capital budgeting model which can be used as a decision support tool for investment analysis by ship-owners.
- Discussed the incorporation of carbon emissions costs in the cost structure for vessels.
- Linked the cost of the shift to alternative fuels to marginal abatement costs of emissions.
- Defined a linear programming model which can be used to find the optimised fleet mix and MAC such that emissions reduction is maximised.

# 5. Results and Analysis

In this chapter, we present the results of the study from the model generated. These results are broadly categorised in four parts addressing sub-research questions one, two, three and four respectively. In each section, we shall also carry out a sensitivity analysis to understand how the main variables interact with our model. Firstly, we shall discuss the results of the emissions inventory, the potential reductions in the emissions inventory using the selected alternative fuels and the fleet mix required to achieve these reductions. Then, we shall look at the results of the capital budget model and compare the results under different conditions of carbon pricing and use of alternative fuels. Finally, we will discuss the results of the fleet mix and abatement cost abatement generated from the linear programming model.

## *5.1 Shipping Emissions Inventory*

The total annual $CO_2$ emissions generated from the cargo vessels fleet in 2016 using the model is estimated at 938.655 million MT. We note that the fleet emissions from different sectors of the industry, plotted in Figure 5-1, is in sharp contrast to the fleet breakup by numbers or percentage of GT depicted in Figures 4-1 and 4-2. A case in point is the emissions from container ships which accounts for 35% of the total emissions, while these ships contributed to only 19% of the fleet by gross tonnage.

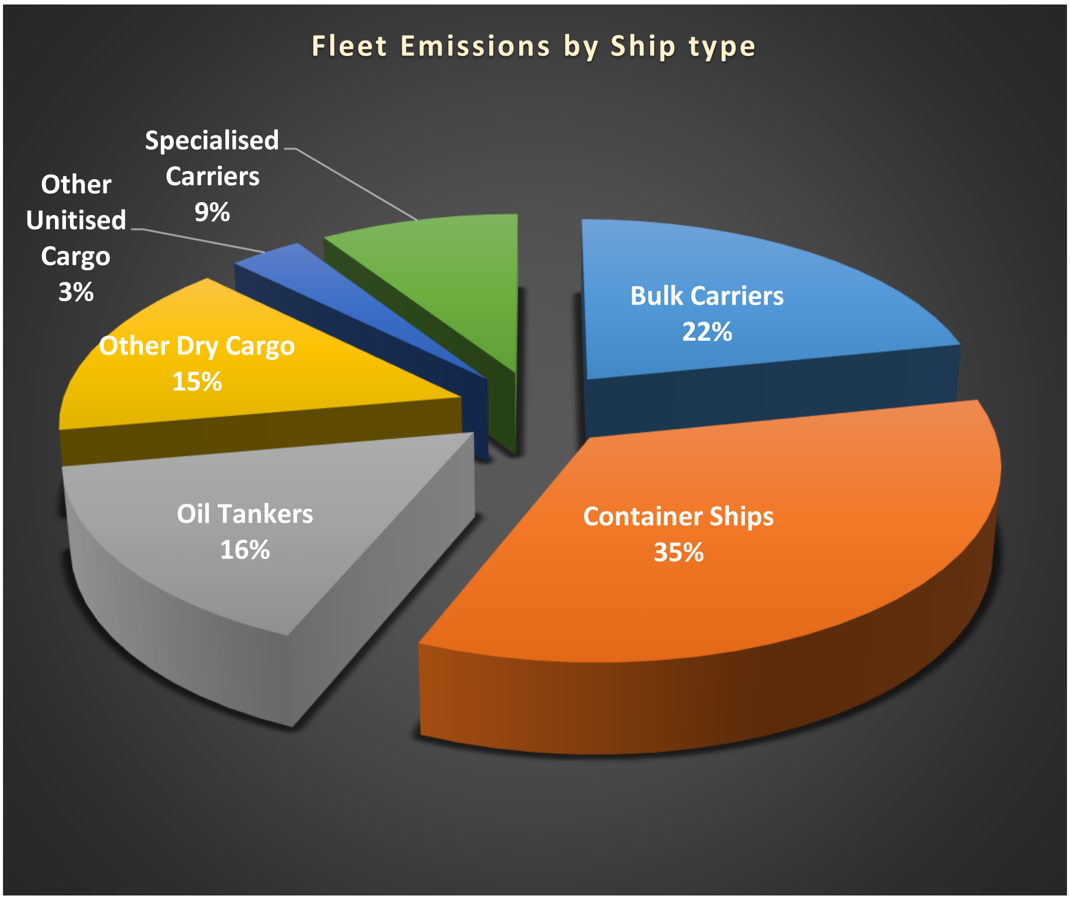


*Figure 5-1: Fleet Emissions by Ship Type*

Emissions from Bulk Carriers, Oil Tankers and Container Ships together constitute 73% of the total emissions. Within the bulk carrier fleet, the total emissions generated by Capesize vessels, the largest in size, is the highest. This pattern is not followed in the container ships sector where vessels in 3000-7999 TEU category emit the maximum amount of $CO_2$ on a fleet-wide basis. The largest container vessel category, 12000+ TEU, currently generates the least aggregated emissions within the container ship sector. In the oil tanker sector, the handy size fleet generates marginally more emissions than the VLCC category which is the largest vessel in this sector.

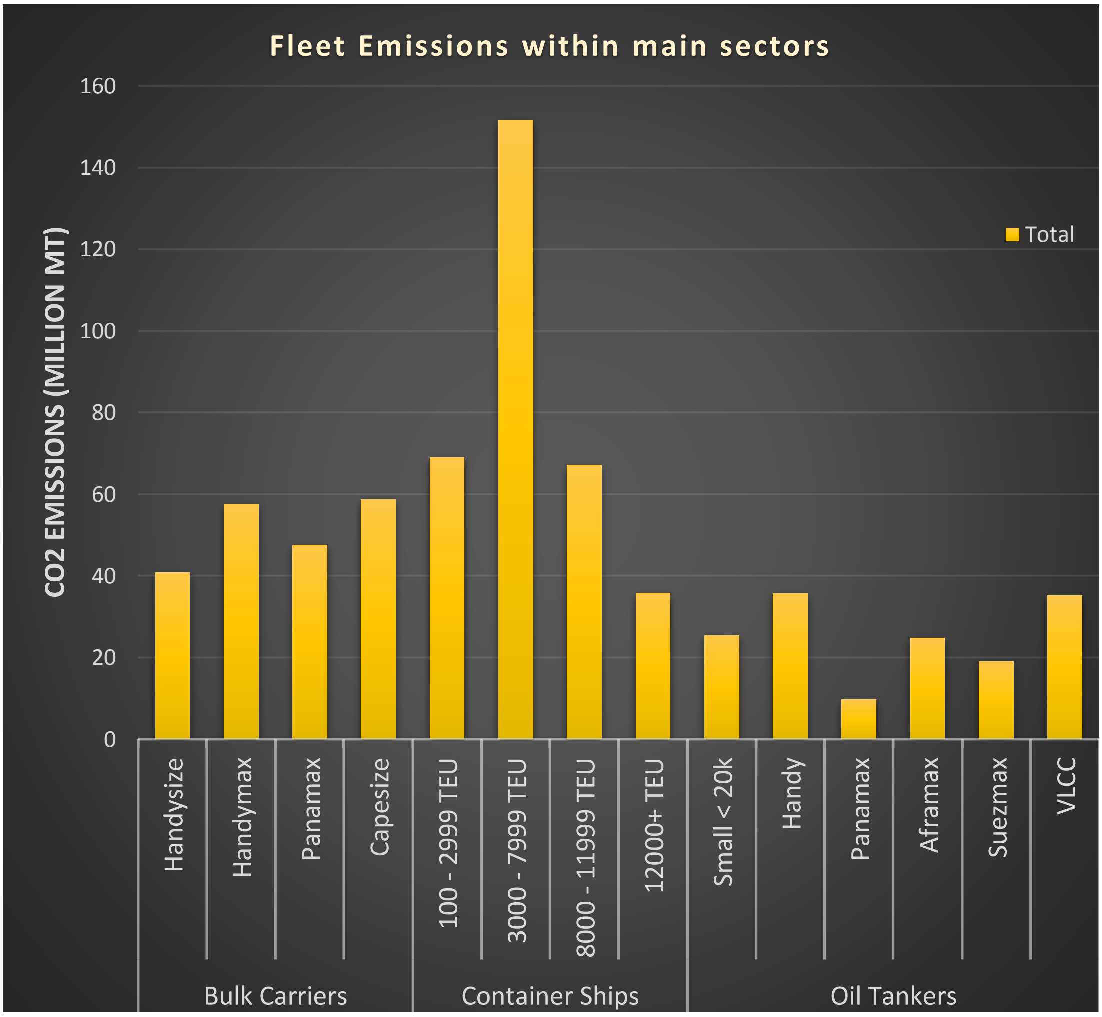

*Figure 5-2: Fleet Emissions within main shipping sectors*

Studying the fleet emissions with the main sectors in Figure 5-2, it is clear that an emissions reduction strategy by focussing on specific segments of the fleet can also give positive results. However, to do this the activity logging of the individual vessels has to be more accurate than what has been done using assumptions in our case.

### *5.1.1 Sensitivity to vessel activity, SFOC and engine load*

We note that the total emissions generated are most sensitive to vessel activity characterised by the number of days at sea, the SFOC of the main engine and the engine load used for the calculations. We present these results in Table 5-1, 5-2 and 5-3.

*Table 5-1: Sensitivity of emissions inventory to vessel activity*

| Number of days at sea | Total fleet emissions (million MT/year) | Sensitivity per day (million MT/year) |
|---|---|---|
| 235 | 908.544 | - 3.011 |
| 245 | 938.655 | - |
| 255 | 968.765 | + 3.011 |

*Source: Author's Calculations*

From our calculations in Table 5-1, we observe that with a change of 1% change in vessel activity the total fleet emissions changes by 0.8%. Therefore, the monitoring and recording of vessel activity on a global scale will be critical to maintaining an accurate inventory of $CO_2$ emissions from shipping.

*Table 5-2: Sensitivity of emissions inventory to SFOC*

| SFOC | Total fleet emissions (million MT/year) | Sensitivity per gram SFOC (million MT/year) |
|---|---|---|
| 170 | 915.050 | - 4.721 |
| 175 | 938.655 | - |
| 180 | 962.259 | + 4.721 |

*Source: Author's Calculations*

The SFOC is a good measure of the engine's efficiency. Marine engines built prior to 2001 had an average SFOC of 185 gm/kWh while those built before 1983 had an even higher SFOC of 205 gm/kWh. Further improvements in engine efficiency will be a key factor in reducing emissions from the entire fleet. From our calculations in Table 5-2, we observe that for every 1% change in SFOC, the total fleet emissions will vary by 0.9%.

*Table 5-3: Sensitivity to ME load factor in laden condition*

| Main Engine Load (% of MCR) | Total fleet emissions (million MT/year) | Sensitivity per percentage point ME load (million MT/year) |
|---|---|---|
| 70% | 897.109 | - 8.309 |
| 75% | 938.655 | - |
| 70% | 980.200 | + 8.309 |

The main engine load factor is the single largest factor that can affect the emissions inventory. Table 5-3 shows the sensitivity to ME load factor in the laden condition. Similarly, changes in the load factor in ballast condition will vary the total fleet emissions by 5.799 million MT for every one percentage point. Load optimisation should be considered as a highly useful measure to enable substantial reductions in $CO_2$ emissions. These results further point towards the need to measure accurately and record engine parameters daily as these would have a significant bearing on the emissions inventory.

## 5.2 *Reduction of $CO_2$ emissions using alternative fuels*

In Figure 5-3, we present the fleet emissions using the selected alternative fuels under the assumptions used in our emissions inventory. It is quite evident that making the shift to MDO would only result in marginal reductions in emissions from the current baseline of HFO emissions. Methanol gives the largest reduction in emissions followed by LBG and Ethanol. We find that biodiesel generates far less than MDO but its differential below LNG is not very significant, and the primary reason for this is the high energy density of LNG which results in far less usage of LNG for an equivalent amount of energy produced. It is important to note that all the low-carbon options pointed to in Figure 5-3 cannot be used in conventional marine diesel engines. These fuels can only be used in specialised engines which would entail additional capital costs. We shall address this interaction in section 5.3.

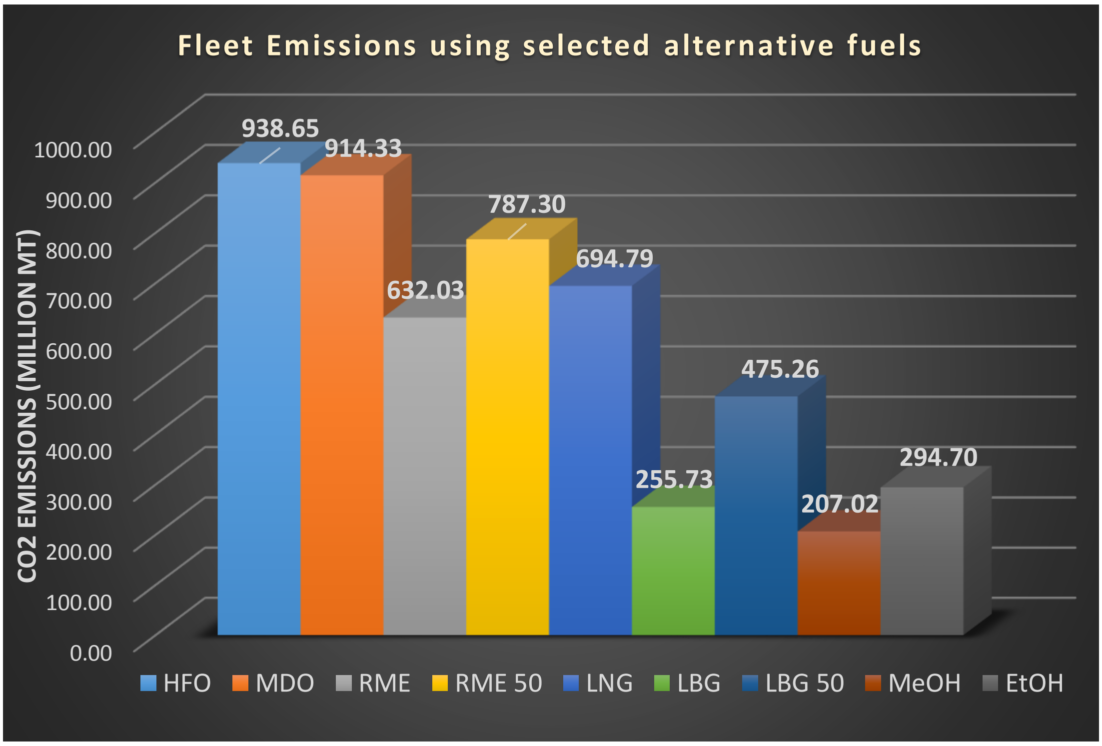


*Figure 5-3: Fleet emissions using selected alternative fuels*

### 5.2.1 Fleet mix required for set reduction targets

We calculated the fleet mix or penetration required by each of the selected alternative fuel in achieving different reduction targets. The results are summarised in Table 5-4. For example, if 30.6% of the fleet energy requirement were to be met by RME and the remaining fleet continues using HFO, we would achieve a reduction of 10% in the total fleet emissions annually. Figures in red indicate that the corresponding reduction target cannot be reached by the particular fuel. We note that a shift to MDO will not be able to reduce emissions by 10% also. In fact, if the entire fleet were to shift to MDO the reduction in fleet emissions is only 2.6%. Similarly, the maximum reduction possible by a full fleet shift to LNG is 26%.

A shift to RME can result in 32.7% reduction in emissions, while LBG, LBG 50, Methanol and Ethanol are capable of achieving far more reductions by themselves. As we can see, certain fuels enable substantial reductions in emissions with less than 100% penetration in the fleet. This finding implies that the use of these fuels in conjunction would result in far greater emissions reductions than that achieved by using only a single alternative fuel with HFO. An optimised fleet mix to maximise emissions reduction will be discussed in section 5.4.

*Table 5-4: Fleet penetration required to achieve set emissions reduction target*

| Target | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|
| **10%** | 386% | 30.6% | 62.0% | 38.5% | 13.7% | 20.3% | 12.8% | 14.6% |
| **20%** | 772% | 61.2% | 124% | 77.0% | 27.5% | 40.5% | 25.7% | 29.2% |
| **30%** | 1158% | 91.8% | 186% | 115% | 41.2% | 60.8% | 38.5% | 43.7% |
| **40%** | 1544% | 122% | 248% | 154% | 55.0% | 81.0% | 51.3% | 58.3% |

*Source: Author*

#### 5.2.1.1 Sensitivity to emissions density

The results of the fleet mix requirement to achieve reduction targets are affected mainly by the carbon emissions density and the energy density of the fuel. This is especially true for the alternative fuels of biomass origin. The carbon emissions density varies widely with the kind of feedstock used for the production. Bio-diesel from different feedstocks can have a carbon emissions density ranging from 15-70 g/MJ. In our study, we have used RME with an emissions density of 51.9 g/MJ which could also vary depending on the area of cultivation (Florentinus, et al., 2012). We calculate for every 1g/MJ change in the emissions density of RME, the fleet emissions changes by 2%. The same applies to biogas, ethanol and methanol. Thus, it is critical that in calculating the fleet mix requirement, the accuracy of the emissions density measurement is verified.

### 5.3 Decision Support tool for investment analysis

We made a comparative analysis of the NPV for each of the 24 vessel categories using the selected alternative fuels in all the four price scenarios. In each price scenario, we calculated the NPV's considering three carbon prices of $ 0/MT, $ 40/MT and $ 100/MT as explained in section 4.1.4. The values of the NPV's differ between different vessels. The earnings generated have a high bearing on the value of the NPV. Since the volatility in the earnings is very high, we consider a ranking system amongst the selected alternative fuels that can be used as an investment appraisal tool. In Figures 5-4, 5-5 and 5-6, as representative examples, we present the comparative analysis of NPV for VLCC's under the "Low Oil – Limited Technology" price scenario and different carbon prices.

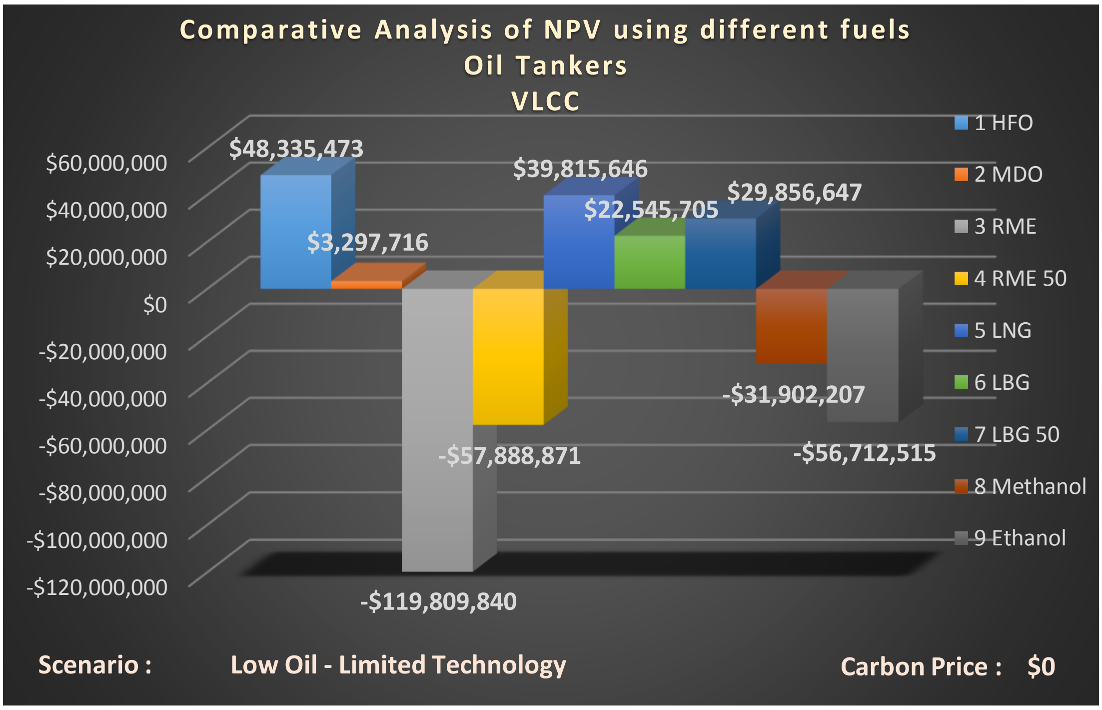


*Figure 5-4: NPV comparison VLCC - Price Scenario 1; Carbon price $0/MT*

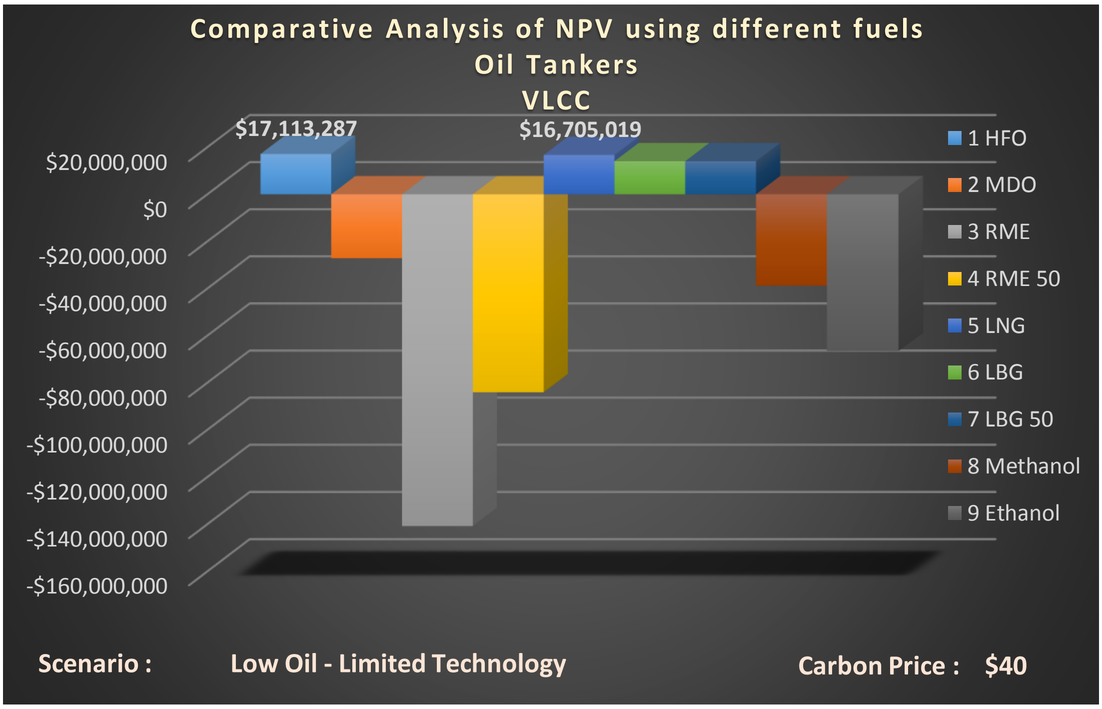


*Figure 5-5: NPV comparison VLCC - Price Scenario 1; Carbon price $40/MT*

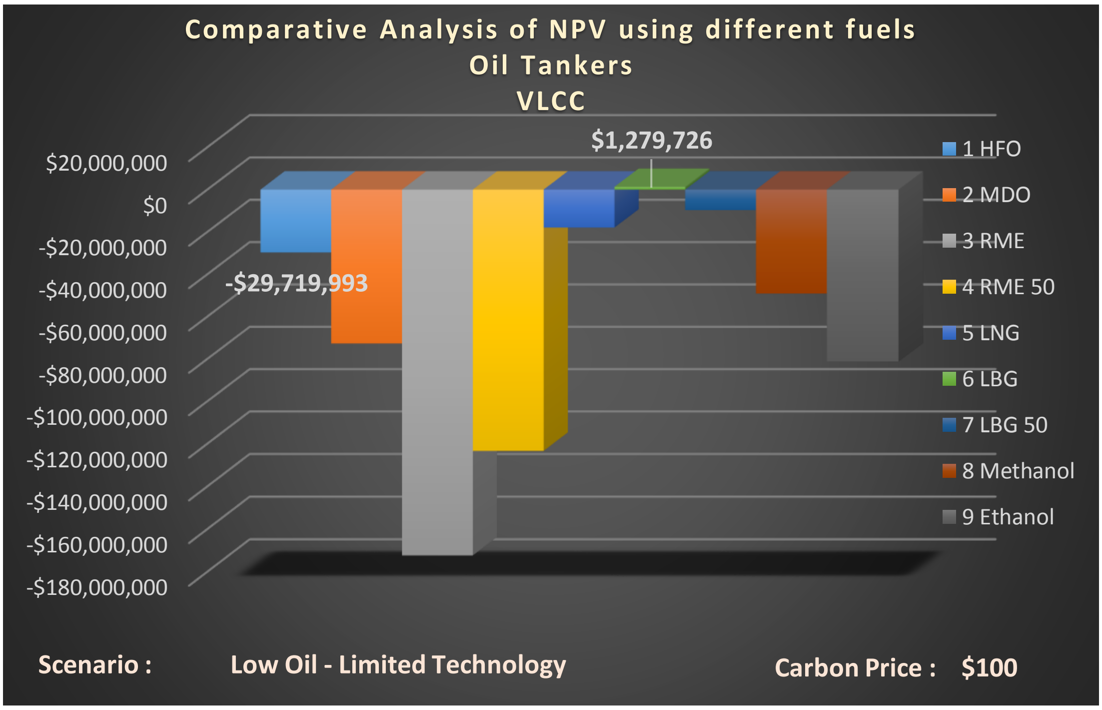


*Figure 5-6: NPV comparison VLCC - Price Scenario 1; Carbon price $100/MT*

In figure 5-4, which is the current price scenario, HFO is the most profitable option. However, should shift to an alternative fuel for a reduction in $CO_2$ emissions be required, then LNG is the primary choice and not MDO. In fact, MDO is ranked below LBG and LBG 50 in the investment rankings. If a carbon price of $40/MT is levied

(Figure 5-5), then the ranking remains the same, but the differential between HFO and LNG is only marginal with LBG and LBG 50 following closely. If the price of carbon is increased further to $100/MT (Figure 5-6), then LBG becomes the most profitable option followed by LBG 50 and LNG. We note that this pattern holds good for all vessels within this "Low Oil – Limited Technology" price scenario. The investment rankings change with the price scenarios. In Tables 5-5 to 5-8, we summarise the investment ranking results in the four defined price scenarios. Only one vessel shows a marginal deviation in price scenario two, but otherwise, the pattern is same for all vessels. The choices ranked first, second and ninth are highlighted.

*Table 5-5: Investment rankings - Low Oil-Limited Technology scenario*

| Carbon Price | HFO | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|---|
| $0 | 1 | 5 | 9 | 8 | 2 | 4 | 3 | 6 | 7 |
| $40 | 1 | 5 | 9 | 8 | 2 | 4 | 3 | 6 | 7 |
| $100 | 4 | 6 | 9 | 8 | 3 | 1 | 2 | 5 | 7 |

*Table 5-6: Investment rankings - Low Oil-Mature Technology scenario*

| Carbon Price | HFO | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|---|
| $0 | 1 | 5 | 9 | 8 | 2 | 4 | 3 | 6 | 7 |
| $40 | 4 | 6 | 9 | 8 | 1 | 2 | 3 | 5 | 7 |
| $100 | 4 | 7 | 9 | 8 | 3 | 1 | 2 | 5 | 6 |

*Table 5-7: Investment rankings - High Oil-Mature Technology scenario*

| Carbon Price | HFO | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|---|
| $0 | 4 | 5 | 6 | 9 | 1 | 1 | 3 | 8 | 7 |
| $40 | 4 | 8 | 7 | 9 | 3 | 1 | 2 | 5 | 6 |
| $100 | 4 | 9 | 7 | 8 | 3 | 1 | 2 | 5 | 6 |

*Table 5-8: Investment rankings - High Oil-Limited Technology scenario*

| Carbon Price | HFO | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|---|
| **$0** | 4 | 6 | 9 | 8 | 1 | 3 | 2 | 5 | 7 |
| **$40** | 4 | 6 | 9 | 8 | 1 | 3 | 2 | 5 | 7 |
| **$100** | 5 | 7 | 9 | 8 | 3 | 1 | 2 | 4 | 6 |

Studying the results noted in Tables 5-5 to 5-8, it is found that in the low-oil price scenarios HFO is the most profitable option best option only when there is no additional levy on carbon emissions. In the presence of a carbon levy, natural gas-based fuels viz. LNG, LBG and LBG 50 are more profitable. One must also consider that the interchangeability of fuels using HFO based engines is limited to MDO and RME, both of which are expensive and rank very low on the investment ranking index.

In mature technology scenarios, gas-based fuels have a clear advantage over other fuels. Methanol and ethanol, though, not competitive against HFO, they are better than MDO, RME and RME 50. The capital costs for gas-based engines as well as those using methanol and ethanol are far substantially higher than the HFO/MDO based engines (section 4.3.2). If these capital costs for alternative fuel propelled machinery were to decrease with improving technology as well, then the competitive advantage alternative fuels hold will be fortified further.

In the high oil price scenarios, the total expenses using HFO and MDO is too high compared to those by the gas-based fuels. Surprisingly, RME and RME 50 are consistent among the lowest ranked fuels in our study. The current price bias of benchmarking it to MDO makes it very expensive compared to other fuels. Besides, the reduction in emissions using RME and RME 50 is not significant compared to other alternative fuels. In fact, even in the "High Oil-Mature technology" price scenario where RME is priced equal to MDO, MeOH and EtOH in energy terms, it fares better than MeOH and EtOH in the absence of a carbon levy but moves down the table on the introduction of a carbon levy. If the price of RME were to continue steadily on a downward trend (Figure 3-9) irrespective of price movements of fossil-based fuels or other fuels, these results would change, but we have not explored that possibility in our research.

### 5.3.1 Sensitivity to changes in capital budget parameters

We note that the results of the investment rankings do not change with varying levels of the discount rate, loan interest rate or the loan term period. The values of the NPV's does change with the discount rate for the investment, loan interest rate or term period. In Tables 5-9 and 5-10, as a representative example, we show the results of changing discount rates and loan interest rates on the NPV comparison for VLCC's in the Low Oil-Limited Technology price scenario without a carbon levy. The central values represent the results generated using the assumptions for this study.

Table 5-9: Sensitivity to varying discount rates – VLCC in price scenario 1

| Fuel Type | Discount Rate 2.5% | | Discount Rate 3.0% | | Discount Rate 3.5% | |
|---|---|---|---|---|---|---|
| | NPV (in million $) | IRR | NPV (in million $) | IRR | NPV (in million $) | IRR |
| **HFO** | $60.345 | 9.12% | $48.335 | 8.66% | $37.729 | 8.20% |
| **MDO** | $11.325 | 3.87% | $3.298 | 3.43% | -$3.792 | 2.98% |
| **RME** | -$122.66 | < -20% | -$119.81 | < -20% | -$117.28 | < -20% |
| **RME 50** | -$55.271 | -6.49% | -$57.889 | -6.91% | -$60.201 | -7.33% |
| **LNG** | $52.854 | 7.35% | $39.816 | 6.90% | $28.300 | 6.45% |
| **LBG** | $34.057 | 5.73% | $22.546 | 5.27% | $12.379 | 4.83% |
| **LBG 50** | $42.014 | 6.43% | $29.857 | 5.97% | $19.119 | 5.52% |
| **Methanol** | -$26.323 | -0.80% | -$31.902 | -1.24% | -$36.830 | -1.67% |
| **Ethanol** | -$53.327 | -5.14% | -$56.713 | -5.56% | -$59.703 | -5.98% |

Table 5-10: Sensitivity to varying loan interest rates – VLCC in price scenario 1

| Fuel Type | Interest Rate 3.50% | | Interest Rate 4.00% | | Interest Rate 4.50% | |
|---|---|---|---|---|---|---|
| | NPV (in million $) | IRR | NPV (in million $) | IRR | NPV (in million $) | IRR |
| **HFO** | $47.471 | 8.56% | $48.335 | 8.66% | $49.200 | 8.75% |
| **MDO** | $2.433 | 3.31% | $3.298 | 3.43% | $4.162 | 3.54% |
| **RME** | -$120.67 | < -20% | -$119.81 | < -20% | -$118.94 | < -20% |
| **RME 50** | -$58.753 | -7.13% | -$57.889 | -6.91% | -$57.024 | -6.69% |
| **LNG** | $38.752 | 6.80% | $39.816 | 6.90% | $40.879 | 7.00% |
| **LBG** | $21.482 | 5.17% | $22.546 | 5.27% | $23.609 | 5.38% |
| **LBG 50** | $28.793 | 5.87% | $29.857 | 5.97% | $30.920 | 6.07% |
| **Methanol** | -$32.841 | -1.38% | -$31.902 | -1.24% | -$30.963 | -1.10% |
| **Ethanol** | -$57.651 | -5.76% | -$56.713 | -5.56% | -$55.774 | -5.37% |

The NPV value is far more sensitive to the discount rate than the loan interest rates or loan term. More importantly, these factors do not affect the rankings presented in section 5.3 implying that even under varying conditions of capital budget modelling, some of the alternative fuels can be competitive vis-à-vis the conventional marine fuels.

### 5.3.2 Minimum earnings required using alternative fuels

The response of the freight market to changes in fuel strategy of ship-owners is rather uncertain. From the ship-owner's perspective, it would be important to assess the minimum annualised earnings over the technical life of the vessel that would be required to ensure profitability of investment into any of the alternative fuels. We calculated the minimum annualised earnings using HFO needed to ensure a zero NPV and used this as a benchmark index, set at 100, to calculate the earnings required when operating the vessel using alternative fuels.

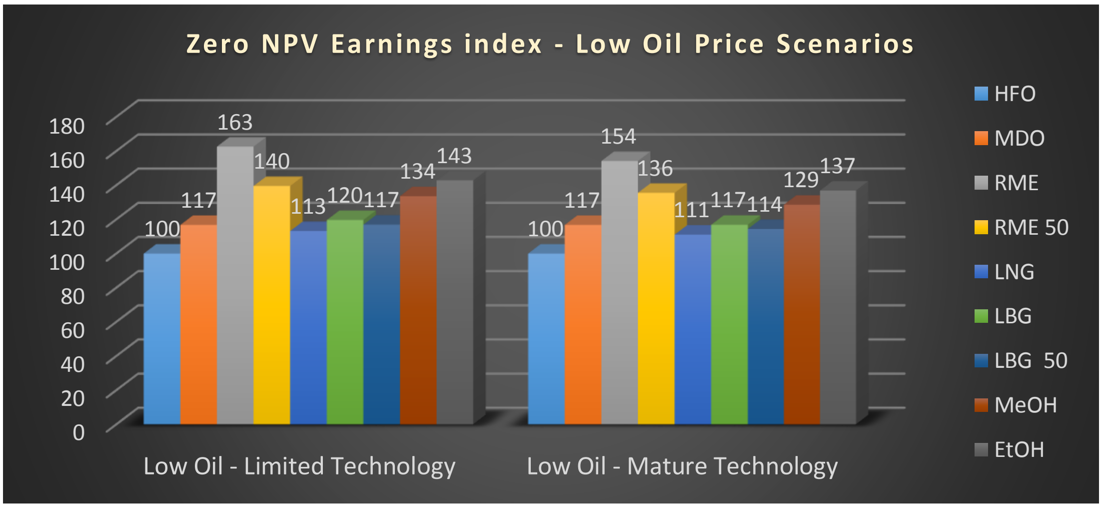


*Figure 5-7: Zero NPV earnings index - Low Oil price scenarios; VLCC*

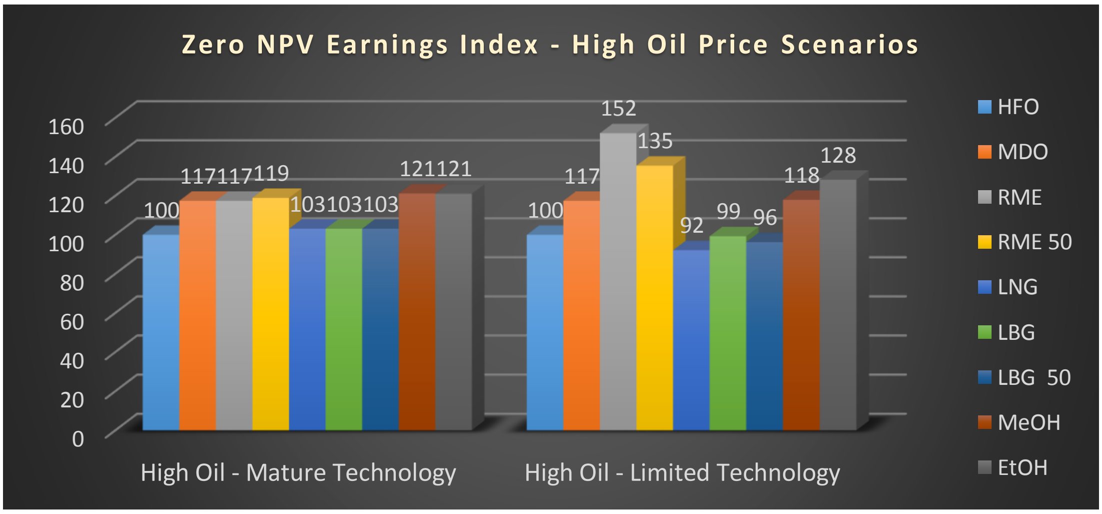


*Figure 5-8: Zero NPV earnings index - High Oil price scenarios; VLCC*

Figures 5-7 and 5-8 represent the earnings required by VLCC's to ensure a zero NPV without a carbon levy. For example, in price scenario one if the required time charter equivalent is $10,000/day (vessel using HFO), should the vessel shift to MDO the necessary TCE will be $11,700/day and $11,300/day in the case of LNG. The values of these indices will vary with different vessels, but the pattern is very much the same. The use of LNG will require lesser earnings than when using MDO in all cases. In the "High Oil-Limited technology" price scenario, all the gas-based fuels require lesser earning than HFO as well. Methanol and Ethanol, though requiring a higher earnings level than MDO, they demand lesser earnings than RME and RME 50.

Ship-owners can use freight rate forecasts to check if the projected freight earnings would cover the total expenses requisite to ensure profitability of the investment. The results show a clear advantage in using gas-based fuels over MDO in the current circumstances. A carbon tax/levy or mandatory emissions reduction requirements will make gas-based fuels, methanol and ethanol more attractive.

## *5.4 Marginal Abatement Costs and Optimised Fleet Mix*

We used the costs of the shift to a particular alternative fuel relative to the emissions reduction potential of the fuel to generate marginal abatement costs for each selected fuel, expressed in $/MT-$CO_2$ reduction from baseline levels (HFO). The MAC varies with the price scenarios as the cost of any shift of fuel is inextricably linked to the fuel costs. We have also accounted for the changes in the capital costs of the vessel depending on the type of fuel in use. We find that the MAC for each fuel varies marginally with the ship type as well. However, for this study, we have aggregated the costs over the fleet and present the MAC of each fuel for the entire cargo vessel fleet. In Figures 5-9 and 5-10, we present the results graphically to highlight the differentials in MAC between the selected alternative fuels.

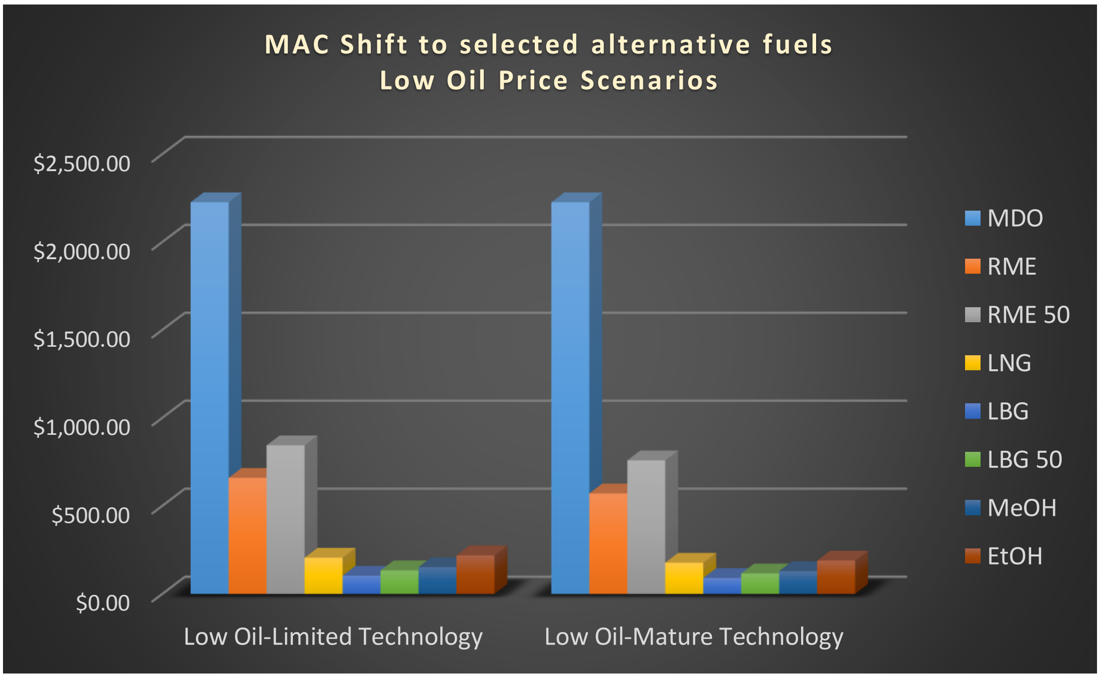


*Figure 5-9: Marginal Abatement Costs - Low Oil Price Scenarios*

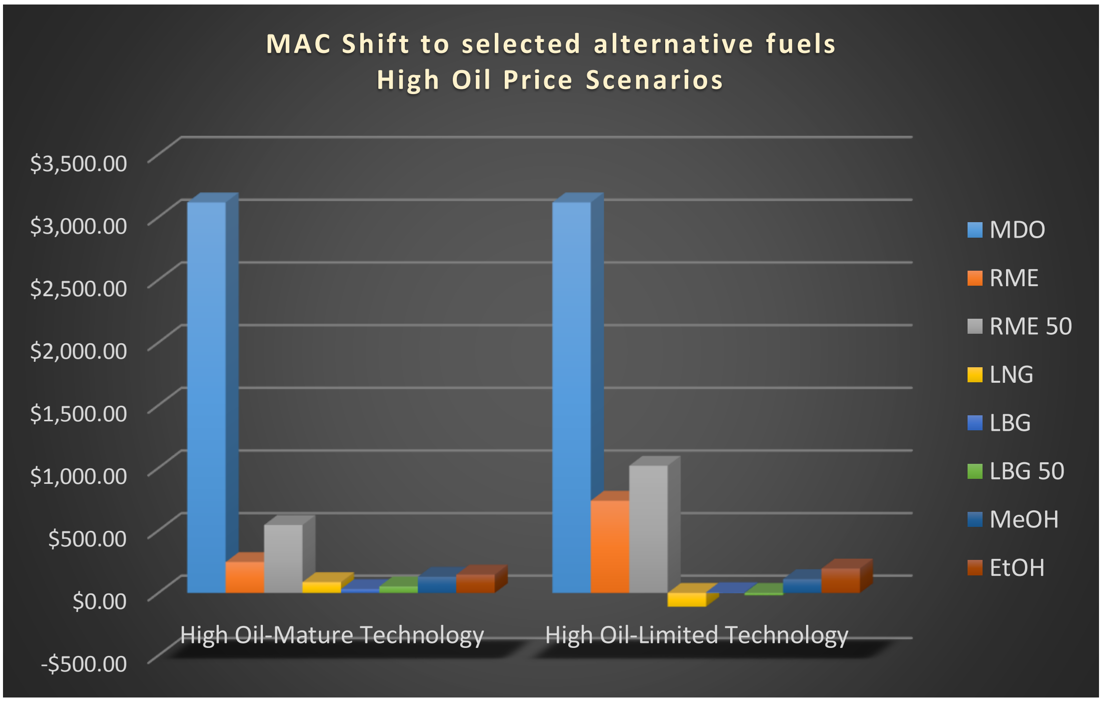


*Figure 5-10: Marginal Abatement Costs - High Oil Price Scenarios*

In all the four price scenarios, the MAC's for gas-based fuels, Methanol and Ethanol are significantly lower than MDO, RME and RME 50. This differntial implies that the most cost-effective fuels for reduction of $CO_2$ emissions are the ones which will require a shift from the conventional marine engines.

LBG has the least MAC in three price scenarios, while LNG has the least MAC in one scenario. In the High Oil-Limited technology scenario (PS4), the MAC for LNG and LBG 50 are negative. MDO is the least cost-effective fuel, from an emissions reduction measure perspective, in all the price scenarios. RME 50 and RME fare better than MDO in all the scenarios. In the low oil price scenarios, Methanol has a MAC lower than LNG justifying the recent growing interest in Methanol as a low carbon marine fuel. The MAC for Ethanol, though, higher than the gas-based fuels and Methanol in all the scenarios, it is significantly lower than MDO, RME and RME 50. These results increasingly point towards a shift to gas-based fuels, methanol and ethanol as the alternative fuels of choice for shipping striving for a low carbon future. In Table 5-11, we present a summary of the calculated MAC values in the four price scenarios.

*Table 5-11: Summary of MAC of selected alternative fuels*

| | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|
| **PS1** | $2,226.8 | $659.44 | $843.99 | $205.89 | $103.93 | $134.20 | $152.23 | $219.29 |
| **PS2** | $2,226.8 | $570.89 | $758.60 | $177.51 | $90.75 | $116.67 | $130.09 | $189.50 |
| **PS3** | $3,117.2 | $247.41 | $543.88 | $86.30 | $30.82 | $51.96 | $129.62 | $146.72 |
| **PS4** | $3,117.2 | $738.48 | $1,017.4 | -$109.51 | $6.51 | -$18.86 | $110.48 | $195.02 |

### 5.4.1 Fleet mix optimisation

The results in Table 5-11 indicate that gas-based fuels have a distinct advantage over other fuels implying policymakers should design policies to promote adoption of gas-based fuels. However, the availability of these fuels is a major constraint, and it should be carefully considered when designing a fleet mix which can achieve emissions reductions at the least cost to the industry. We used the linear programming model developed in section 4.5 to calculate the fleet mix using the selected alternative fuels such that we could achieve emissions reductions at the least cost (MAC) to the industry. This fleet mix would vary with the price scenarios and within each price scenario, the availability scenarios are used as constraints to generate an optimised fleet mix. In each of the combined sub-scenarios, we generate an aggregated marginal abatement cost of $CO_2$ emissions reduction from the baseline emissions, expressed in \$/MT-$CO_2$. Each sub-scenario will also generate the emissions abatement achieved by using the optimised fleet mix.

We find that the entire availability of LNG, LBG, LBG 50 and MeOH is assigned to the fleet in all the sub-scenarios. EtOH is assigned to the fullest extent in all sub-scenarios except one. The availability scenario definition is such that MDO, even though having the highest MAC, will need to be assigned to the fleet mix, in all sub-scenarios except one, to ensure fuel assignment to the entire fleet. RME and RME 50 get assignment only in the High Oil-Mature Technology scenario where all they are priced equal to MDO in energy terms.

We used the probability assigned to each sub-scenario as discussed in section 4.5.1 to obtain expected values and thereby calculated the optimised fleet mix, MAC and emissions abatement for all the eight sub-scenarios together. These results are presented in Table 5-12.

Further, we also calculated the optimised fleet mix with maximised emissions abatement. In this configuration, all the low-carbon fuels and LNG get maximum assignment possible with MDO filling-in to complete to fleet assignment. We used the probability assignment as discussed above to calculate an optimised fleet mix for all the eight sub-scenarios together and present these results in Table 5-13.

In the least cost optimisation, we find that 27.89% emissions reduction can be achieved at an abatement cost of \$209.83/MT-$CO_2$, while in the maximised emissions reduction optimisation 29.95% abatement can be accomplished using a MAC of \$224.46/MT-$CO_2$. As we can see, the difference in abatement potential is not significant in the two cases implying that we can achieve substantial reductions at the least cost.

The fleet assignment for LNG, LBG, LBG 50 and MeOH is the same in both cases while it differs for MDO, RME, RME 50 and EtOH. These results imply that a diversified fleet mix will be required to achieve emissions reductions in a cost-effective manner in the near future.

*Table 5-12: Optimised fleet mix with least marginal abatement costs*

| Price Scenario | Availability Scenario | Probability | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH | MAC | Abatement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PS1 | Low | 0.15 | 53.5% | 0.0% | 0.0% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $331.86 | 19.67% |
| PS1 | High | 0.10 | 7.0% | 0.0% | 0.0% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% | $198.25 | 36.75% |
| PS2 | Low | 0.10 | 53.5% | 0.0% | 0.0% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $307.70 | 19.67% |
| PS2 | High | 0.15 | 7.0% | 0.0% | 0.0% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% | $172.38 | 36.75% |
| PS3 | Low | 0.10 | 45.1% | 2.8% | 5.6% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $294.89 | 21.27% |
| PS3 | High | 0.15 | 0.0% | 5.6% | 1.4% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% | $113.91 | 38.62% |
| PS4 | Low | 0.15 | 53.5% | 0.0% | 0.0% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $234.55 | 19.67% |
| PS4 | High | 0.10 | 18.6% | 0.0% | 0.0% | 64.4% | 2.2% | 4.4% | 10.4% | 0.0% | $18.39 | 29.09% |
| | | 1.00 | **29.52%** | **1.12%** | **0.77%** | **48.30%** | **1.65%** | **3.30%** | **7.80%** | **7.54%** | **$209.83** | **27.89%** |

*Source: Author*

Note: 1. MAC is the Marginal abatement cost per MT $CO_2$ reduction from baseline emissions generated by the fleet using HFO, expressed $/MT-$CO_2$ reduction.

2. Abatement refers to a reduction in $CO_2$ emissions from baseline emissions generated by the fleet using HFO.

*Table 5-13: Optimised fleet mix with maximum emissions abatement*

| Price Scenario | Availability Scenario | Probability | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH | MAC | Abatement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PS1 | Low | 0.15 | 45.1% | 2.8% | 5.6% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $348.30 | 21.27% |
| PS1 | High | 0.10 | 0.0% | 5.6% | 1.4% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% | $214.34 | 38.62% |
| PS2 | Low | 0.10 | 45.1% | 2.8% | 5.6% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $318.52 | 21.27% |
| PS2 | High | 0.15 | 0.0% | 5.6% | 1.4% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% | $185.04 | 38.62% |
| PS3 | Low | 0.10 | 45.1% | 2.8% | 5.6% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $294.89 | 21.27% |
| PS3 | High | 0.15 | 0.0% | 5.6% | 1.4% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% | $113.91 | 38.62% |
| PS4 | Low | 0.15 | 45.1% | 2.8% | 5.6% | 32.2% | 1.1% | 2.2% | 5.2% | 5.8% | $259.95 | 21.27% |
| PS4 | High | 0.10 | 0.0% | 5.6% | 1.4% | 64.4% | 2.2% | 4.4% | 10.4% | 11.6% | $56.06 | 38.62% |
| | | 1.00 | **22.55%** | **4.20%** | **3.50%** | **48.30%** | **1.65%** | **3.30%** | **7.80%** | **8.70%** | **$224.46** | **29.95%** |

*Source: Author*

Note: 1. MAC is the Marginal abatement cost per MT $CO_2$ reduction from baseline emissions generated by the fleet using HFO, expressed $/MT-$CO_2$ reduction.

2. Abatement refers to a reduction in $CO_2$ emissions from baseline emissions generated by the fleet using HFO.

#### 5.4.1.1 *Sensitivity to fuel pricing*

The marginal abatement costs calculated using the fleet mix optimisation is sensitive to price changes within the pricing scenarios. To check this, we changed the prices of the fuels within each price scenario by +/- 10% and ran the model on the least cost optimisation configuration for each of the eight sub-scenarios. Changes in the pricing do not affect the fleet mix and consequentially has no effect on the emissions reduction. It does alter the optimised marginal abatement cost in a linear fashion. We present these results in Table 5-14.

*Table 5-14: Sensitivity of least MAC to fuel pricing*

| Fuel prices vis-à-vis scenario definition | MAC ($/MT-$CO_2$) | Price differential in the least MAC obtained |
|---|---|---|
| (-) 10% | $200.08 | -$9.75 |
| Defined Fuel Pricing | $209.83 | - |
| (+) 10% | $219.58 | +$9.75 |

#### 5.4.1.2 *Sensitivity to availability scenarios*

The sensitivity of the optimisation results to the availability scenarios is far more profound than the fuel pricing. Changes to the availability scenarios will alter the optimised fleet mix, the marginal abatement costs and the emissions reductions achieved by the mix. We tested this by changing the availability of all the fuels by +/- 10% within each availability scenario. We did not alter the availability of MDO and let it remain at 100% in all cases. We ran the model on the least cost optimisation configuration on each of the eight sub-scenarios and obtained results presented in Tables 5-15 and 5-16.

*Table 5-15: Sensitivity of fleet mix optimisation results to availability scenarios*

| Fuel Availability | MDO | RME | RME 50 | LNG | LBG | LBG 50 | MeOH | EtOH |
|---|---|---|---|---|---|---|---|---|
| (-) 10% | 35.3% | 1.0% | 2.0% | 43.5% | 1.5% | 3.0% | 7.0% | 6.8% |
| Defined Availability | 29.5% | 1.1% | 0.8% | 48.3% | 1.7% | 3.3% | 7.8% | 7.5% |
| (+) 10% | 25.7% | 0.3% | 0.6% | 53.1% | 1.8% | 3.6% | 7.4% | 7.4% |

*Table 5-16: Sensitivity of least MAC and abatement to availability scenarios*

| Fuel Availability | MAC ($/MT-$CO_2$) | MAC differential | Emissions Abatement (% reduction from baseline) | Abatement differential |
|---|---|---|---|---|
| (-) 10% | $236.63 | + $26.80 | 25.53% | - 2.36% |
| Defined Availability | $209.83 | - | 27.89% | - |
| (+) 10% | $188.12 | -$21.71 | 28.63% | + 0.74% |

Studying the results in Tables 5-15 and 5-16, it is clear that the availability of fuels can be critical in assessing the optimised fleet mix. Reduction in availability of the fuel will increase the marginal abatement costs and reduce the emissions abatement potential of the fleet considerably. This sensitivity analysis points out to the policymakers, the areas that need to be focused upon in expediting adoption of the selected alternative fuels.

## 6. Conclusions

This chapter will summarise the study, our key findings and its implications. In doing so, we will briefly recap the results in the context of our sub-research questions. We shall also make note of the limitations of this study and suggest areas for further research within the realm of emissions assessment and abatement from shipping.

### *6.1 Summary and Key Findings*

The primary aim of this study was to assess the potential of alternative fuels in the reduction of $CO_2$ emissions from the shipping industry and the conditions conducive for ship-owners to invest in these technologies. We used the results of these sub-parts to design an optimised fleet mix that policymakers should strive to achieve by implementing appropriate economic and policy instruments.

Firstly, we examined the most relevant literature surrounding climate change and the need to reduce $CO_2$ emissions on a global footing. We note that a reduction of $CO_2$ emissions by 41-72% from 2010 levels is required by 2050 to ensure the global warming remains below $2^0$C by the end of this century. Then, we examined the literature on carbon emissions from shipping and note that shipping contributes to approximately 2.2% of global carbon emissions. The most striking finding from this literature is that even after applying substantial efficiency improvements due to the mandated EEDI requirements, the emissions from shipping are projected to rise steadily in the coming years. This shortcoming calls for urgent action and concerted effort from all stakeholders in the shipping industry. We identified the current measures in place to reduce emissions and outlined the debate on MBM's for shipping.

Second, we selected eight alternative fuels - two fossil-based, four biomass-based and two blended fuels, for shipping which are currently available, some in limited quantities, however. We examined their main characteristics relevant to shipping. We studied the historical pricing of these fuels and made reasonable assumptions to define four price scenarios. Similarly, we also defined two availability scenarios of alternative fuels for shipping based on the current global production levels of the selected fuels. We found that every fuel has its advantages and disadvantages vis-à-vis adoption for shipboard use. Gas-based fuels have a high energy density but require large volumes for storage aboard ships. Methanol and Ethanol are less energy dense but are very efficient in reduction of carbon emissions and the capital costs needed to use them on ships is far less than the capital costs involved in engines propelled by gas.

To answer sub-research question one and two, we used the information from above steps and data gathered from commercial shipping databases to generate an emissions inventory of the current cargo vessels fleet. We created a model that can calculate the equivalent energy quantity of alternative fuel mass required for the current level of shipping activity and thence the emissions generated by each alternative fuel. We found that Methanol is the most carbon efficient fuel for shipping followed by LBG and Ethanol. LBG 50 stands fourth in our ranking followed by RME and LNG. While an LNG powered fleet generates far more emissions than a fleet powered by biofuels, it is still the most carbon efficient fossil-based fuel for shipping, and this supports the recent interest in promoting LNG as a marine fuel. We translated these results to a fleet mix that will be required to achieve set emissions reduction targets from each of the selected alternative fuels. While shifts to LBG, LBG 50, Methanol and Ethanol could achieve significant emissions reduction, more than 30%, with a low to moderate level of penetration, we find that a shift to MDO can achieve only 2.6% reduction. LNG, if used across the entire fleet, can reduce fleet emissions by 26%. Use of the alternative fuels in tandem across the fleet will result in a far greater reduction in emissions than can be achieved by two or three selected fuels.

To address sub-research question three, we developed a simple capital budgeting model that could be linked to our emissions assessment so as to make a comparative analysis of investment in vessels propelled by each of the selected alternative fuels. We ranked the fuels in order of their projected profitability in the four price scenarios. Drawing from the current debate on MBM's for shipping, within each price scenario, we generated the NPV under three carbon pricing scenarios of \$0/MT, \$40/MT and \$100/MT. We found that while HFO is the most profitable option in the low-oil price scenarios without a carbon price, a carbon tax/levy makes other fuels extremely competitive against HFO. LNG, LBG and LBG 50 consistently rank high in our findings indicating that gas-based engines for shipping are a very attractive option for ship-owners as well. We find that methanol and ethanol are also very competitive against MDO, RME and RME 50. Further, we also calculated the minimum earnings required when using alternative fuels to ensure profitability of the investment and found that in the case of gas-based fuels the required earnings are marginally higher than that currently earned by vessels using HFO. However, when comparing these earnings to MDO, the gas-based fuels fare better with methanol following closely. These findings imply that with a strong emissions reduction policy, use of gas-based fuels and methanol can be an attractive investment option for ship-owners. Future improvements in technology and reduction in capital costs involved with vessels using these fuels will drive a sizeable portion of the ship-owning fraternity to these fuels.

Finally, to answer sub-research question four, we calculated the marginal abatement costs of $CO_2$ emissions involved in a shift from HFO to the selected alternative fuels. We found that the MAC is highest for MDO in all price scenarios and least for LBG in three scenarios and LNG in one scenario. We used these results to generate an optimised with least MAC and also a fleet mix with maximum emissions abatement for each price scenario using the availability scenarios as constraints in a linear programming model. Due to the uncertainty in price scenarios, we assigned each price scenario equal probability to find expected values for the aggregated fleet mix. We found that in the least MAC configuration, an emissions reduction of 27.89% would be achieved at an abatement cost of \$209.83/MT-$CO_2$. In the maximised emissions abatement configuration, the findings were 29.95% abatement and MAC of \$224.46/MT-$CO_2$. The calculated optimised fleet mix suggests that policymakers should strive to achieve an assignment of 53.25% of the fleet to gas-based fuels, 15-16% of the fleet to Methanol and Ethanol, 1-4% to RME, 1-3% to RME and the remaining fleet to be assigned to MDO. The sensitivity analysis showed that the results were very sensitive to fuel availability scenarios. An increased availability of the alternative fuels can reduce the MAC considerably while increasing the calculated emissions abatement further, not significantly, however.

An important conclusion that we draw from this study is that LNG is indeed a very good alternative fuel for shipping from the perspective of ship-owners looking for a profitable investment as well as policymakers striving for $CO_2$ emissions reduction. The increasing possibility of blending LNG with LBG and running the gas-based engines wholly on LBG makes LNG an attractive choice of fuel for all stakeholders. Policymakers should design policies that could improve the availability of LNG as a fuel for shipping. We believe the availability of the low-carbon alternative fuels is the major bottleneck, as shown in our fleet mix optimisation tool, in achieving maximum emissions abatement at the least cost to the shipping industry.

## *6.2 Limitations of the study*

The results of this study quite profoundly suggest that the selected alternative fuels will go a long way in reducing carbon emissions from the shipping industry. However, we should acknowledge that this study is based on some assumptions which could affect our findings considerably. The single most important limitation is that we have considered only a limited selection of fuels. There are other sources of energy like solar and wind energy, which are practically carbon-free, and fuels like hydrogen have not been taken into account in this study. Further, we should note that we have focussed our study on $CO_2$ emissions alone. We have not considered the emission of $CH_4$, $NO_x$, $SO_x$, and PM from the selected fuels which can also play pivotal roles in designing fuel strategies.

In calculating the emissions inventory, we have assumed homogeneity of the fleet within each sub-type of ships. In actuality, every segment of the fleet is composed of different ships each with a different fuel consumption profile depending on the individual ship's age, trading pattern, levels of maintenance and the weather encountered. Our inventory is based on the entire fleet using HFO while some of the ships in the fleet are already using MDO, MGO, LSFO and LNG as well, implying that our inventory could be a bit on the higher side. The emissions density of the selected biofuels could vary with the feedstock used which will alter our results.

When applying a carbon emissions levy/tax, we have not considered the elasticity of shipping supply. The reaction of the shipping industry to an MBM cannot be predicted as there is no precedent for it. It is possible that should an MBM be implemented, a portion of the fleet might be laid up and only the most carbon efficient ships will continue to operate. The volatility of fuel prices within each price scenarios can change the results of the NPV rankings. Also, the capital costs are based on current newbuilding prices which can vary significantly depending on market conditions.

One vital aspect that was not included in this study is the individual earning profile of each sub-type of vessel. Differential earning patterns could imply fleet mix optimisation would work better if approached from a bottom-up sectoral level instead of a fleet level as we have done in our study.

## *6.3 Further Research and Reflections*

This thesis has encompassed a few aspects relevant to adoption of alternative fuels in shipping. However, the complexity and diversity of the shipping industry call for a more integrated approach that will take into account the limitations we discussed in section 6.2 and even more. The Maritime Alternative Fuels Emissions Assessment Model we created can be used as a building block for software with real-time inputs and statistical projections of fuel pricing, freight earnings and multi-layered constraints for fleet mix optimisation. Changes in fuel strategy will affect maintenance costs, personnel training costs and operational costs. The changes in these costs should be included in the model to improve the accuracy of the results. Considering the interaction of operational and technical measures with fuel strategies would enable further reductions in the marginal abatement costs. Safety and environmental risk assessment is another dimension that can play a vital role in a risk-averse shipping industry in the adoption of alternative fuels and this should be incorporated into the model to improve its robustness.

Finally, sustainable policies for emissions reduction is the need of the hour, and further delays can cause irreversible changes to our ecosystem. While key players in the shipping industry are pushing towards greater acceptance of alternative fuels, the fragmented structure of the industry is a hindrance that allows conventional marine fuels to stay deeply rooted, unchallenged. Policymakers urgently need to induce changes by boosting availability of alternative fuels and promote co-existence of different marine fuels to mitigate climate change, a potential killer more lethal than war!

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## Appendices

### *Appendix I. Properties of selected fuels used for calculations with references*

| Property | HFO | MDO | LNG | RME | LBG | MeOH | EtOH |
|---|---|---|---|---|---|---|---|
| Density (kg/cu.m) | 989[2] | 890[1] | 448.4[2] | 890[1] | 448.4[6] | 795.5[2] | 792[2] |
| Energy Density (MJ/kg) | 40.4[2] | 42.7[1] | 48.2[2] | 37.0[1] | 48.2[6] | 20.0[2] | 28.0[2] |
| $CO_2$ Density (g/MJ) | 83.7[3] | 75.0[4] | 62.3[3] | 51.9[4] | 21.0[3] | 17.0[3] | 24.2[2] |

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