DEPARTMENT OF NAVAL ARCHITECTURE, OCEAN & MARINE ENGINEERING

University of Strathclyde Engineering

COURSEWORK/PROJECT COVERSHEET

This document is the coursework/project coversheet for all NAOME classes conducted at University of
Strathclyde for academic year 2019-20. Please do the following when submitting your coursework:

- Staple a ***completed*** printed copy of this form to every piece of coursework/project work you submit for classes in the Department of Naval Architecture, Ocean, and Marine Engineering.
- Avoid the use of document containers such as cardboard or plastic covers, document wallets, ring binders or folders (unless otherwise instructed by the class lecturer).

We do not wish to discourage students from discussing their work with fellow students and collaborating in solving problems. However, you must ensure that your submitted work distinguishes your own intellectual contribution. The key point is that you must not present the results of another person's work "as though they were your own".

SUBMISSION
DETAILS
Please ensure that the details you give are accurate and completed to the best of your knowledge.

Registration Number: 201960257	Name: Zachariou Dionysios
Class Code: NM965	Coursework Title: MSc INDIVIDUAL PROJECT
Lecturer: **Evangelos Boulougouris**	

Declaration
I have read and understood the University of Strathclyde guidelines on plagiarism. http://www.strath.ac.uk/media/ps/cs/gmap/plagiarism/plagiarism_student_booklet.pdf

I declare that:

1. This is my coursework/project assignment. This is the version that I am submitting for assessment. I understand the penalties of plagiarism.

2. Wherever published, unpublished, printed, electronic or other information sources have been used as a contribution or component of this work, these are explicitly, clearly and individually acknowledged by appropriate use of quotation marks, citations, references and statements in the text.

Signature: D. Zachariou ____________________ Date of Submission: 19/08/2020________

THE LEADERSHIP & MANAGEMENT AWARDS 2017 Winner Workplace of the Year

THE AWARDS 2016 WINNER BUSINESS SCHOOL OF THE YEAR

THE UK Entrepreneurial University of the Year 2013/14 UK University of the Year 2012/13

Department of Naval Architecture

Ocean and

Marine Engineering

MSc Marine Engineering

NM965 MSc INDIVIDUAL PROJECT

WORD COUNT: 9306

Title: *Decarbonization Analysis of Capesize Bulkers serving the Australia-China trade route*

Supervisor:

Dr Evangelos Boulougouris: Director of the Maritime Safety Research Centre

Zachariou Dionysios – 201960257

Acknowledgement

Foremost, I would like to thank my supervisor Dr. Evangelos Boulougouris and PhD candidate Mr. Panayiotis Mitrou, (Global Gas Segment Manager at Lloyd's Register) for their guidance, data provision and assistance throughout this process. Their enthusiasm for this project, their support, encouragement, and patience were a very important help for me. Furthermore, I would like to express my appreciation towards Mr. Stelios Psilakis, Technical Manager at Seanergy Maritime Corporation for his contribution to data collection. I would like to also thank Mr. Peter Kontraros that strongly recommended the University of Strathclyde for his first-class teaching experience and the staff of the Naval Architecture, Ocean and Marine Engineering department. I could not forget the support of my partner Anna Chaimani, as I would not be able to complete this without her. Last but not least, my family and special thanks to my mother, who set me off on the road to this MSc a long time ago.

Abstract

The initial International Maritime Organization (IMO) Greenhouse gases (GHG) strategy has triggered numerous discussions about the level of ambition that shipping should adopt to comply with relevant requirements. This analysis attempts to optimize, in terms of cost, the decarbonization pathway with a conservative approach. For this purpose, the following assumptions are used to project the necessary actions. Shipping will continue to grow in line with gross domestic product (GDP) at an annual rate of 3-4%; hence a 50% reduction in GHG emissions compared to 2008 level could translate into 50-80% intensity reduction by 2050 because of the shipping development. Shipping cost for transported products is minimal, allowing for substantial increase on fuel cost. Shipping will be able to fund an expensive transition based on long-term generous carbon pricing. Five scenarios on shipping development are adopted. Shipping cost is concerned, and this analysis is undertaken considering the competitive nature of the shipping markets. Short, mid, and long-term measures to attain IMO GHG initial strategy targets up to 2050 are evaluated. A modular analysis starting with operational measures like speed and port call optimization is provided. Then, the available efficiency technologies are evaluated and ranked. At a third stage the use of greener fuels with a focus on Liquified Natural Gas (LNG) is considered. The analysis focuses on a specific route Australia to China for a particular type of vessel. The case study is a Capesize bulk Carrier design delivered by the mid-2020s operating up to 2050. The objective is to identify how operational (speed), design (size) and technology factors can lead to compliance while capital and operational expenditure can be kept at the minimum reasonable level.

Keywords: transition, decarbonization, LNG fuel, shipping

Table of Contents

List of figures

List of tables

List of abbreviations

AER	Annual Efficiency Ratio
Bio-LNG	Biomethane Liquefied Natural Gas
CATE	Cost of averting a ton of emissions
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CO2	Carbon dioxide
COx	Carbon oxide
CI	Carbon intensity
DWT	Deadweight tonnage
ECAs	Emission Control Areas
EEOI	Energy Efficiency Operational Indicator
ESDs	Energy-saving devices
FRCs	Foul release coatings
GHG	Greenhouse Gas
GDP	Gross domestic product
HFO	Heavy Fuel Oil

IMO	International Maritime Organization
IPCC	International Panel on Climate Change
LED	Light-emitting diodes
LNG	Liquified Natural Gas
MARPOL	International Convention on the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NOx	Nitrogen Oxide
ROI	Return on Investment
SOx	Sulphur Oxide
UNCTAD	United Nations Conference on Trade and Development
VFD	Variable Frequency Drive
VOC	Volatile Organic Compounds
ODS	Ozone Depleting Substances

1. Introduction

Evidence in the 1960s and '70s that concentrations of carbon dioxide (CO_2) in the atmosphere were increasing led climatologists and others to press for action. It took years before the international community started responding. The global warming and the atmospheric pollution produced by the Greenhouse Effect have significant impact on humans and the environment. The new regulations are stricter and there is an urgent need for greener shipping. As a result, the optimization of the pathway for shipping decarbonization from the economic perspective is of great importance. This optimization will lead the industry in a more ecological direction aiming to protect the environment. To achieve this goal, there are many stakeholders that should engage and collaborate, such as governments, class societies, the IMO, research institutions, international organizations, and others.

There are many different types of gases. The natural gas is currently at the centre of interest regarding its potential for being used as ship fuel in the future. It is the cleanest and fast-growing fossil fuel that contributes for 1/3 of total energy demand growth during the last decade, hence more than any other type of fuel. It can be used in emission control areas (ECA) where the sulphur limits are strict according to the Figure 1. In 1997, the IMO introduced a new annex to the International Convention on the Prevention of Pollution from Ships (MARPOL) to resolve the issues of marine carbon emissions.

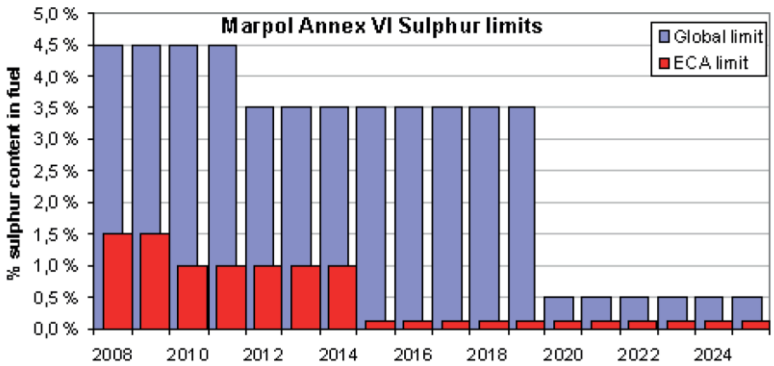


Figure 1: Sulphur limit on marine fuels Worldwide and on Emission Control Areas (DNV GL, 2017)

The aim of Annex VI is to minimize air pollutants produced from marine such as the sulphur oxides (SOx), the nitrogen oxides (NOx), the carbon oxides (COx), the non-combustible hydrocarbons (CxHy), the ozone depleting substances (ODS) and the volatile organic compounds (VOC). This also makes the energy efficiency design index (EEDI) mandatory for new vessels, and the Ship Energy Efficiency Management Plan (SEEMP) obligatory for all the new ships. In 2005, the Annex was formulated and in 2008 was adopted. Finally, in 2010 was revised and implemented (*Green Ship Technologies IMarEST and Science & Innovation Network (SIN)*). The overall goal was the reduction of GHG emissions no less tahn 50% by 2050 in comparison to those of 2008. To meet this target, the shipping industry needs to optimize the maritime trade operations and the utilization of capacity, to improve energy efficiency much faster than it has done to date, and to move towards low and zero-carbon fuels like the LNG. In the next decades, the shipping industry will tend to have better designs aiming to create more efficient ships. Currently, smart systems with even less fuel consumption and versatile powertrains are urgently required. Shipbuilders are seeking to meet IMO standards under MARPOL, which controls fewer pollution without ignoring the merchant vessels efficiency requirements.

The aim of this study is to optimize the shipping decarbonization pathway by finding what would be the easiest way, in terms of cost in shipping, to achieve the IMO's goals, and the goals of greenhouse gas reduction strategy. The target for 2050 is very ambitious (Figure 2) and vast amounts of money should be invested to improve the efficiency of ships. However, simpler ways, like improving operation at the port, could be applied in order to avoid huge investments and waste of money.

The analysis starts with approaching the cost of transport work per ton-mile. The goal is to achieve a level of emissions at least 50% less than the respective emissions in 2008. A comparison of this approach with other less radical as well as less costly solutions follows. Such a goal is realistic if the shipping industry continues to grow in the following years at a rate of around 3%, otherwise different solutions should be implemented. Using data from Lloyd’s Register classification society, the optimal speed of a VLOC vessel is calculated for the case that it would arrive on time to enter the port terminal. The underline objective is to identify and explore the most important source of pollution with an aim to impose fees accordingly.

The main research questions of the present study are:

a) To which degree the society can achieve the target of 2050 without taking very expensive measures such as a zero-carbon fuel.
b) How feasible it is to approach this target based on the possible scenarios of fleet development in the coming years. In other words, what could be expect without the use of very radical solutions, like a new supply chain for a zero-carbon fuel (e.g. ammonia and hydrogen).

To address the above questions, a case study is presented on a specific vessel including a sensitivity analysis to investigate the results under different scenarios. The huge investment amounts for improving the efficiency of the ships should be re-considered by thinking whether simple ways, like best operation in the port or decarbonisation on shore, could be adequately effective solutions.

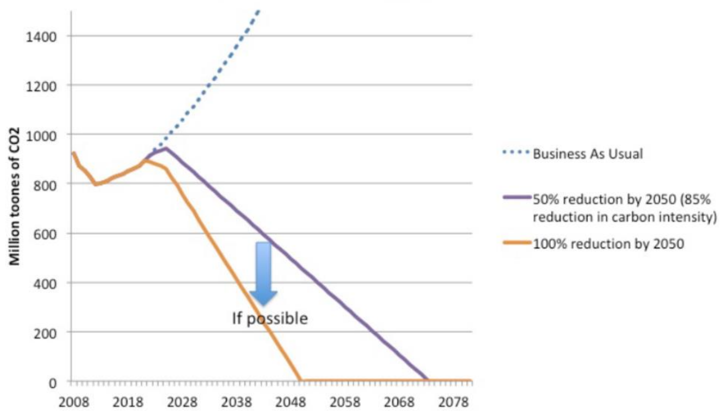


Figure 2: Pathways for international shipping's CO2 emissions (Lloyd's Register, 2019)

2. Literature review

An optimal voyage is defined on the basis of a) fuel consumption, b) minimization of costs, c) just in time arrival to the port, and d) safety. The trade-off relationship that underlines these four characteristics makes the identification of the most efficient strategy in shipping challenging. It is important to note that the performance for different types of vessel may also vary according to the voyage conditions (Boulougouris et al., 2015). In addition, predicting precisely enough the operational performance of the vessels contributes materially to the reduction of the Greenhouse Gas (GHG) emissions and brings them closer to the required levels for the next years. Applied regulations that intend to reduce the carbon dioxide (CO2) emissions do exist but, to date, they have not been evaluated in practice. Further, good operational performance could increase the safety in the ship and could reduce the voyage time and the fuel consumption levels. The latter has become even more important since 2002 due to the increase of fuel prices. Overall, it is necessary to re-consider the design of the ships, the wide use of energy efficient technologies and alternative operation approaches that may help to reach optimisation. (Boulougouris et al., 2015).

The transportation sector is one of the most challenging sectors for being decarbonized. However, transportation should realize that shares a considerable amount of responsibility and should globally adopt corrective innovative measures. There is a notable difference between the current policy for emissions, and the sector's emissions reduction. The use of electrofuels from CO2, water and electricity are possible options for reducing emissions to some degree. On the other hand, as long as there are carbon storage options, electrofuels are not sufficiently cost-effective (Lehtveer, Brynolf and Grahn, 2019). The target of the Paris agreement is 1.5°C to 2°C warming reduction and shipping is among the key players towards this effort. A future decarbonisation, though, could cause new problems such as the premature stranding of the assets (Prakash et al., 2016). As stranded assets any kind of vessel that has premature write-downs or devaluations and conversion to liabilities could be considered. Many vessels could be stranding and create new risk factors for the industry that will be incredibly difficult to predict in case that the market continues with the same failure rates (Prakash et al., 2016). However, the shipping sector has the potential to reduce the emissions without premature scraping of the vessels. This can be done by operating the vessels in reduced speed, with advanced technical and operational approaches to ensure efficiency and retrofitting ships to use zero-carbon fuels. In this way, vessels will have a more flexible design and will be easily retrofitted to adapt on the new regulations. The implementation of mitigation strategies in the next decade through a fast and solid policy, and the development of zero-carbon vessels from 2030 onwards would allow for ships that could remain under a carbon limit of 1.5°C. Further delays in policy implementation would lead to the use of additional measures in order to reach the Paris climate targets (Bullock et al., 2020).

Shipping contributes 80% to 90% of the international trade and remains the cheapest method for transportation of goods. GHG emission regulations have forced the industry to find alternative technologies to reduce harmful emissions, but the best pathway to achieve the target of 2050 is still doubtable. LNG reduces 20% to 30% of the CO2 emissions and the cost is variable according to each engine type. Other solutions to further reduce the emissions include Biomethane Liquefied Natural Gas (Bio-LNG), hydrogen, nuclear power, and scrubbers, but these materials are considerably expensive (Balcombe et al., 2019). Cheaper and simpler solutions are reduced operation speed, hull design changes and the use of renewable resources. To achieve shipping decarbonization until 2050 and accomplish 50% reduction of 2008 values, many different efficiency measures should be applied simultaneously. LNG is a promising short-term solution; additional long-term decarbonisation efforts will need strong financial incentives in the near future (Balcombe et al., 2019).

Shipping uses heavy fuel oil for propulsion, despite the fact that it remains the most efficient mode of transportation per unit of transport. Charterers such as Cargill and Unipec UK, have stopped since 2012 to chartering vessels that are no more efficient. This policy in combination with the energy prices volatility and the carbon footprint awareness, creates a threat for ships' profitability and can convert existing ships to stranded assets (Smith et al., 2015). It is necessary to ensure that investments in new buildings account for the risks of climate change in order to create ships with long-term usability and support a successful and profitable decarbonisation of shipping. The inherent risks of climate change have not been adequately realized yet. GHG emission policies are expected to assist the distinction between companies with and without innovation and effective management (Raucci et al., 2017). A significant factor for energy consumption is the condition of the hull and the produced frictional resistance that is the most important component of drag. The additional resistance from waves and wind should be considered on the total load applied to the propeller (Hughes, 2015).

The possible operational measures are generally classified into four broad categories:

1) Operational measures
2) Energy efficiency devices
3) LNG as a marine fuel
4) Gas mixture

2.1 Operational measures

The first category is linked with the voyages of the vessels between two different ports. Usually the vessels when they arrive to their destination, they anchor outside the port or away from the anchorage and they give notice of readiness. Then, they wait until they receive permission from the port authorities to enter in the terminal. Considering this procedure, it is necessary to simplify the port operations and the procedures of the customs to facilitate port optimization and reduce the waiting time of the ships. The first step would be to calculate the emissions of the vessel from a previous voyage. By knowing how long the vessel had to wait at the port, a model can be developed that would indicate the required speed of the vessel in order to arrive at the port on time. After using this model in practice, its impact on the reduction of the emissions should be evaluated (Schøyen and Bråthen, 2015). This is different from the idea of simply reducing the speed of the vessels which would decrease its productivity (Gonyo et al., 2019). Hence, this would lead to a decrease of the income of the ship owners due the limited number of voyages that would be undertaken. However, the cost of transporting the products is very small compared to the cost of the products themselves. So, in such a case the loses for shipowners could be mitigated by imposing a trivial increase in the price of the products. This would serve a turn into a ‘greener’ transportation operation. By applying the efficiency curves of a particular engine for a case study vessel, it can be determined how much is the minimum speed the vessel should travel with to keep the efficiency maximized.

2.1.1 Port call optimization

As explained above, reduced waiting time for port calls can mitigate GHG emissions since during the idle between port calls the shipping companies produce more emissions and costs. Therefore, faster port turn-around is probably one of the most cost-effective strategies to reduce the emissions. Specifically, the savings in terms of cost would be approximately 75 USD per ton of CO2. In case this is globally enforced in the future, about 60 million tons of CO2 emissions could be avoided annually only from shipping. Also, a faster port turn-around could reduce the pollution of the local air of heavily polluted ports, such as the port of Shanghai or Singapore. High pollution levels from ships may cause serious health issues for residents who leave close to the ports (Poulsen and Sampson, 2020). By replacing the idle time at ports with slow steam operation of the vessels, the fuel consumption and the emissions will significantly be reduced; that is an important improvement for both the environment and the business.

2.1.2 Speed reduction

Another measure to reduce fuel consumption and emissions is the reduction of the operational speed of the vessels. Speed optimization can develop the economic and environmental performance of the ships. To optimize trade income, the average shipping speed should be carefully chosen to avoid high fuel costs due to high vessel speeds or high capital costs due to long voyage times (Tillig et al., 2020). The optimization of speed makes round trip times ranging from 24 to 50 days except harbor times. There is a significant economic effect resulting from the fuel prices and bunker levies reflected to the CO2 emissions through the optimal speed and fuel consumption. Imposing a fuel tax will lift the fuel prices, encourage slower steaming, and thereby reduce carbon emissions (Psaraftis and Kontovas, 2014). The decision of the voyage route has a major impact on energy consumption and revenues. Slow speeds are certainly the best way for emissions reduction, but more ships will be required to cover the world trade demand. To find out the advantages and drawbacks of speed reduction, an analysis should be carried out based on the round trips of a same ship with additional paper references. Steam days and trips per year will be reduced

2.2 Energy efficiency devices

The second category of measures is based on the energy efficiency measures (Schwartz, Gustafsson and Spohr, 2020). The interest for energy-saving devices (ESDs) continues to grow aiming to improve the efficiency of the ship.

2.2.1 Mewis Duct

The Mewis Duct (Figure 3) is a device that is used to increase the propulsion efficiency of the vessels (Chang et al., 2018) and was originally developed for bulk carriers and container ships. It is a mix of a wake equalizing duct and pre-swirl fins, integrated in the centre line orientation of the shaft. The device accelerates the water from the ship hulls into the propeller. In addition, it generates thrust forward and better flow that reduces the hub vortex resulting in a better flow into the rudder (Nowruzi and Najafi, 2019).

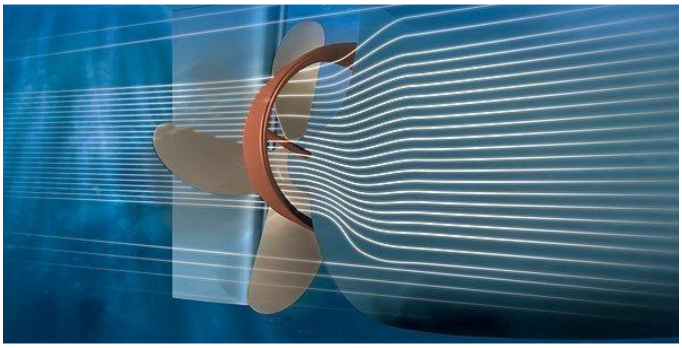


Figure 3: Propeller nozzle Mewis Duct (taken from https://www.nauticexpo.com/...)

2.2.2 Flettner rotors

Another device is the flettner rotors that has become a widely spread solution for wind-assisted propulsion (Bordogna et al., 2020). Flettner rotor is based on the physical principle of Magnus effect Figure 4. A spinning cylindrical pillar moving through the air and exerts a net force to them. According to Newton's 3rd law, the air exerts an equal and opposite force to the pillar, altering its trajectory (Talluri, Nalianda and Giuliani, 2018). The air gets dragged along with the direction of motion, experiencing an upwards force. The installation of Flettner rotors on merchant ships could lead to possible fuel consumption savings of up to 20% and related environmental emission reductions.

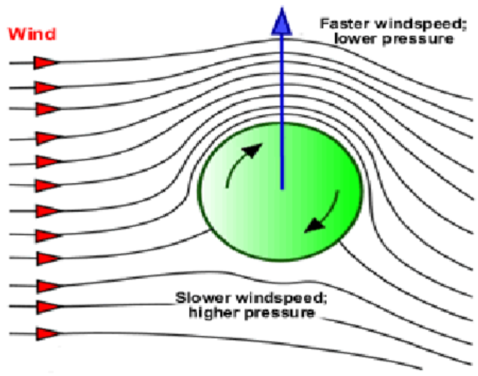


Figure 4: Magnus Effect (taken from https://byjus.com/physics/dynamic-lift/)

A description of a potential arrangements for the Flettner rotors is given on Appendix 1: Possible Flettner rotor arrangements

2.2.3 Variable Frequency Drive

An additional very effective method to optimize the shipboard systems is by using a Variable Frequency Drive (VFD). There are several ways to use variable speed drives to save energy (Figure 5) depending on the application. It is quite easy to save a lot of energy because this system can control the pumps and the fans by adjusting the power demand to the operational conditions (Räsänen and Schreiber, 2012). More specifically VFD is a device which is used to vary the speed of a 3-phase induction motor. It works by changing the frequency of the power supply to the motor with the motor speed being directly proportional to the supply frequency. Most fans and pumps working on ships are usually of over-capacity, so operating at reduced speeds is possible (Khalid, 2014). Valves and dampers are typically used to control the flow of air or liquids, which requires additional energy than controlling the flow with drives.

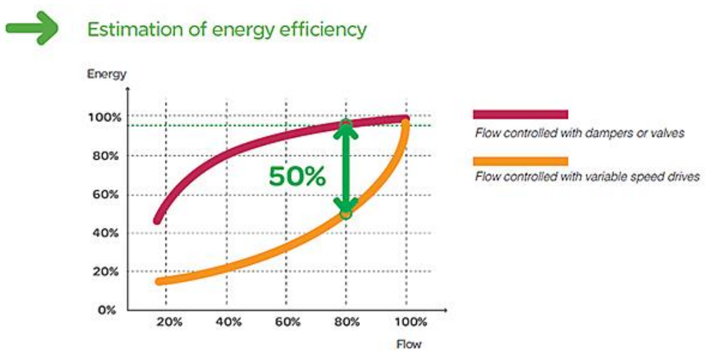


Figure 5: Variable speed drive efficiency (Taken from https://safety4sea.com/...)

2.2.4 Light-Emitting Diodes

Light-Emitting Diodes (LED) fixtures can be used for new and existing ships to replace older lighting technologies that consume more energy (Figure 6). They are used in traffic lights and mobile phones; they represent a truly ubiquitous technology for their use as power indicators on monitors and computers. LED compared to fluorescent lightbulbs cost at least two or three times more. However, these are substantially more efficient than fluorescent lighting. The LED industry has made great progress and has pioneered the traditional lighting markets by replacing significant proportion of fluorescent bulbs (Held, 2016). Typically, the rated lifetime of LED fixtures is significantly higher than for fluorescent lamps. High efficiency lamp technology can reduce the energy used to illuminate ships (Krarti, 2018).

	Incandescent	**Halogen incandescent**	**Compact florescent**	**LED light bulbs**
Lumen	1100	1200	970	1055
Power (W)	75	70	15	13
Efficacy (lm/W)	15	17	65	81
Colour temperature (K)	2700	2800	2700	2700
Colour rendering index	100	100	81	80
Rated lifetime (h)	750–2000	2000	10,000	15,000
Mercury content (mg)	0	0	≤2	0
Warm-up time to 60 % light	Instant full light	Instant full light	5–40 s	Instant full light
Sales price	Banned [109]	£2.00	£5.00	£10.00

Figure 6: LED light bulbs compared with conventional light bulbs (Zhu and Humphreys, 2016)

2.2.5 Foul Release Coatings

The ship's hull is a crucial piece of ship's efficiency and the ship's physical ability to streamline through the waves is of vital importance for fuel economy. Foul Release Coatings (FRCs) prevents or reduce the adherence of fouling organisms to the hulls of the ships. These are attributed to its low critical surface energy, low elastic modulus, low glass transition temperature and smooth surface and result in weak adhesion between the adhesives secreted by biofoulings and the surface of the coating. However, the hydrophobic nature encourages the adhesion of other marine species, which cannot always be totally removed by hydrodynamic forces (Camós Noguer et al., 2017). Still the most common method of foul-release coating is the silicone coating (McMillan, 2013). It has been shown that silicone foul release coatings achieve an average fuel saving of over 4 percent and a related emission reduction (O'Mahony, n.d.)

2.3 LNG as marine fuel

The third category of energy efficiency measures is the use of LNG. The transport sector is under considerable pressure to increase fuel efficiency. The Return on Investment (ROI) is a very important component that describes the performance measure to evaluate the efficiency of an investment on LNG. LNG has much better emissions performance than conventional fuel. The vessels that use LNG as fuel in addition to the bunkering infrastructure, provide a clear decarbonization pathway. The technology developments will allow in the future the substitution of conventional fossil fuel with bio-LNG. From SEA LNG it can be calculated that the benefit bio-LNG provides over regular fuel is about 20%. Interestingly, LNG is now the fastest growing marine fuel worldwide. However, the rising costs related to LNG infrastructure and other projects worldwide, have risen the capital expenditures (CAPEX) significantly (Agarwal et al., 2020). According to the IMO, 2.1% of 2012 global GHG emissions have been produced by the shipping sector. The main factor of these harmful emissions was the fossil fuels that were used to produce effective propulsion. The International Panel on Climate Change (IPCC) considers that the transformation to more green fuels could reduce the emissions by 22%. For example, biofuels or nuclear, synthetic fuels mixed with hydrogen that is produced with fossil and non-fossil sources, could be used as alternative more green fuels (Horvath, Fasihi and Breyer, 2018). By 2030, LNG is expected to be the second biggest contribution in the fuel oil industry. Also, until 2040, LNG and fuel oil will have equal contribution on emissions reduction and a small portion will be covered by alternative fuels (Taljegard et al., 2014). Finally, fossil fuels will remain a primary energy source between 2040 and 2050 but can be converted to cleaner fuels and facilitate the reduction of emissions (Xu, Yang and Li, 2015). By using carbon capture and storage (CCS), the GHG emissions can be tackled more properly. Several techniques of CCS exist allowing to avoid the release of emissions, such as the use of ocean storage, chemical carriers, and liquid energy carriers.

2.4 Gas mixture

The last category is a potential future gas mixture. Alternative fuels should meet the required targets to reduce air pollutants and GHG emissions particularly in the emission control areas (ECAs). LNG and bio-LNG could be suitable marine fuels to meet these goals (Figure 7). These fuels are expected to account 50% of global energy demand for shipping by 2050 (Shell, 2020). The rest will be supplied with traditional heavy fuel oil (HFO) and marine gas oil (MGO) (IMO, 2016).

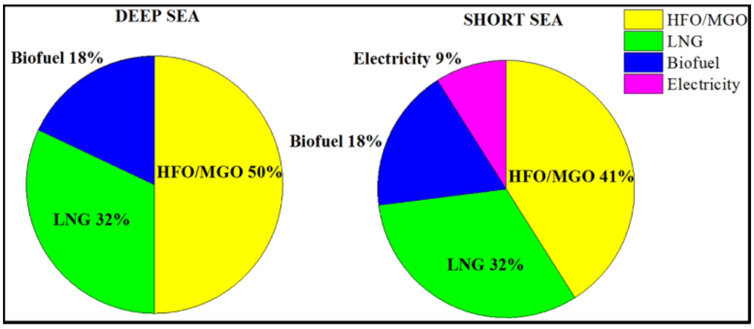


Figure 7: Fuel mix of shipping by 2050 (DNV GL, 2017)

Studies on the use of LNG as a marine fuel have indicated the need to control methane leak from LNG engines. Moreover, a lot of uncertainty has been expressed with respect to the future price and global supply of LNG, methanol and MGO. There are also some issues with HFO and Scrubbers because of the reliability and corrosion during the operation. Finally, infrastructure construction for bunkering supply, and safety when using these facilities, is also considered a difficulty when LNG is used (Chu Van et al., 2019). Potentially LNG tanks could also be used for ammonia or/and bio-fuel with a small capital. LNG supply and demand are expected to rise exponentially in the next few years (IMO, 2016a).

Table 1: Alternative fuels comparison (Chu Van et al., 2019)

Types of fuel	Environmental factors				Other Factors		
	NOx	SOx	Particulates	CO2	Capacity	CAPEX	Operating costs
LNG	++	++	++	+	Restricted	Very high	Very low
MGO	-	+	-	-	Unrestricted	Low	Very high
HFO	-	-	-	-	Unrestricted	Low	Low
HFO / Scrubber	-	+	+	-	Slightly restricted	High	Medium

+ + very positive, + positive, – negative, – – very negative

Shipowners are willing to invest in new vessels powered by LNG. However, retrofitting vessels with LNG-propelled systems is not a favourable solution for them. LNG demand as a shipping fuel is expected to rise steadily (Table 1). This will give time to build the required infrastructure and eliminate the demand for marine fuel (Sharples, 2019). Gas bunkering is not broadly available because of the lack of infrastructure and currently it is only provided by barges, pipelines at berths and road tankers. However, in the near future many ports in Europe and Asia will be ready for gas bunkering with new infrastructure (Lloyd's Register, 2014). The following Figure 8 highlights the need for shipowners to start the switch to lower-emission ships.

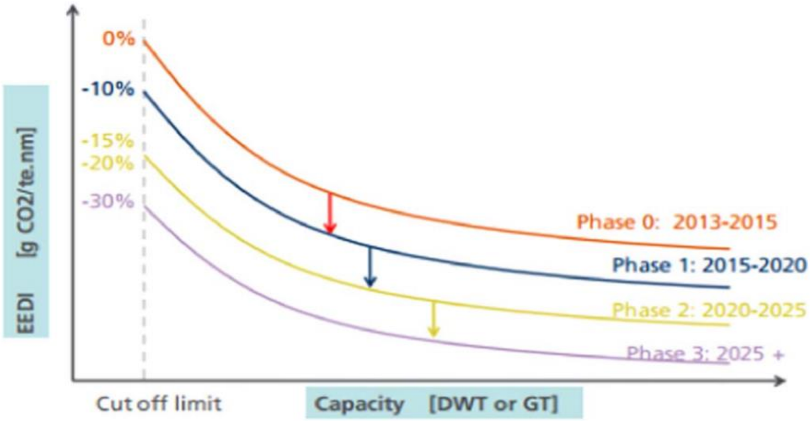


Figure 8: EEDI with required reference lines (Schinas and Butler, 2016)

2.5 Energy Efficiency Design Index (EEDI)

Numerous rules and regulations exist, the most important of which is the mandatory EEDI for newbuilding ships. The purpose of these regulations was to create the limit on the maximum content of sulphur fuel and the limit on the maximum emission of oxides. EEDI is the measure of energy efficiency of the ship by design while the Energy Efficiency Operational Indicator (EEOI) is the energy efficiency operational index. EEDI appears to be an effective solution for new ships in terms of cost and can provide a strong incentive to improve the design efficiency of new ships. The EEDI's principal drawback is that it covers ship construction exclusively and it does not examine operational measures. Thus, its usefulness might be limited under certain conditions. In addition to that, EEDI applies only to new ships without considering the old ones. This index was created under the necessity of the reducing greenhouse gases and it was established by the IMO in collaboration with the global shipping community (IMO, 2020a). The attained new ship EEDI is a measure of new ships' energy efficiency (g/t. nm) and is calculated by the following formula (Karim and Hasan, 2017) proposed from the IMO (Appendix 3: EEDI formula - four key parts) with the factors lined up on the Table 2:

$$\frac{\begin{array}{c}\left(\prod_{j=1}^{n} f_j\right) * \left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) + \left(P_{AE} * C_{FAE} * SFC_{AE}\right) \\ + \left(\left(\prod_{j=1}^{n} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) \\ - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)\end{array}}{f_i * f_c * f_l * Capacity * f_w * V_{ref}} = \frac{gCO2}{tonne * nauticalmile}$$

Table 2: EEDI factors

C_f	Non-dimensional conversion factor between fuel consumption and CO2 emission
V_{ref}	Ship speed in nautical miles per hour

Capacity	Computed as a function of Deadweight as indicated in 2.3 and 2.4 of MEPC 245(66) “2014 Guidelines on the calculation of the Attained EEDI for new ships”
P_{ME}	75% of the main engine MCR in kW
P_{AE}	Auxiliary Engine Power
P_{PTI}	75% of rated power consumption of shaft motor
P_{eff}	Output of innovative mechanical energy efficient technology for propulsion at 75% main engine power
P_{AEeff}	Auxiliary power reduction due to innovative electrical energy efficient technology
SFC	Certified Specific Fuel Consumption in g/kWh
f_j	Correction factor to account for ship specific design elements. (For e.g. ice classed ships, shuttle tankers)
f_w	Non dimensional coefficient indicating the decrease of speed in representative sea condition of wave height, wave frequency and wind speed
f_i	Capacity factor for any technical / regulatory limitation on capacity
f_c	Cubic capacity correction factor (for chemical tankers and gas carriers)
f_l	Factor for general cargo ships equipped with cranes and other cargo- related gear to compensate in a loss of deadweight of the ship
f_{eff}	Availability factor of innovative energy efficiency technology

Considering the recent Covid-19 pandemic, the freight rates for dry bulk carriers have been affected negatively because of the rapid changes in the business environment. Given that the pandemic impact remains significant, raw materials carried by dry bulk carriers cannot be stored easily. This is due to the fact that their nature requires specific storage facilities (Michail and Melas, 2020). During the last months, shipbuilders have decreased the production by almost 75% (Stopford, 2020). The pandemic would probably result in a recession, which may be moderate or serious.

3. Aim and Objectives

As discussed above, there are many different pathways in order to achieve the IMO's target by 2050. The main aim of the project is to investigate the optimal pathway in terms of cost for reducing the GHG emissions until 2050 by 50% in comparison to those of 2008. For this purpose, a capsize dry bulk carrier that will meet the criteria of IMO and at the same time will be affordable for the companies will be created. It is crucial to identify a reasonable approach of shipping decarbonization because otherwise, the cost for emission reduction on shipping will be dramatic and many shipping companies probably will close and reduce a lot their turnover. It is important to note that very radical solutions will not be easily accepted from the shipping community because they will change the market balances and shipping is generally a conservative and passive industry that prefers stability.

It is essential to use the EEDI index for a capsize dry bulk carrier that is operating a real trade route voyage (Qingdao – Port Hedland), and to analyse how this vessel could comply with the 2050 target. The objective is to reduce the emissions by using operational measures, energy efficiency measures and LNG and bio-LNG fuel. The result will be to understand what could be expected without the use of very radical solutions.

4. Research methodology

This section describes the methods that are used in order to understand how the operational, design and technology factors can lead to compliance with the international maritime organisation (IMO) regulations for 2050. It should be noted that capital and operational expenditure need to be kept at a relatively low cost. A key secondary objective is to identify those points at which CAPEX and marine investment seem to have minor effect and the non-marine decarbonization (Carbon offset) appears to substantially outperform. Carbon offset refers to any activity that compensates the emission of carbon dioxide (CO_2) or other GHG (measured in carbon dioxide equivalents [CO_2e]) by providing financial incentive for a reduction in emissions in another pollutant sector (Sapkota and White, 2020). Carbon offsetting is used to equilibrate the produced carbon emissions from other industries such as automotive, aeronautic, heating/cooling, etc.

First, it is necessary to focus on the carbon intensity (CI); that is the emission rate of a given pollutant relative to the intensity of a specific activity (CO_2/ton mile). In the shipping case, this translates into the amount of CO_2 emission that is produced to transport one ton of products for one mile. To calculate the CI of the entire fleet, the total ton mile and the total emissions are required. Based on these results, the actions for reducing the CI of 2008 by 50% can then be prioritized. Afterwards, the calculation of the CI for the under-study vessel should take place, which can be reduced by using the different efficiency measures described in Sections 2.1 and 2.2.

Starting with the "low hanging fruit" solutions (e.g. changing the size of the vessel) the operational measures are applied at a second step. These include the waiting time at the port, and the optimal speed to arrive on time to enter to the terminal. After that, energy efficiency devices such as Mewis duct, Flettner rotor, Variable-frequency drive (VFD), Light-Emitting Diodes (LED) bulbs and Silicon coatings will be used for further emission reduction. Additional energy efficiency measures should be applied in case that the targets cannot be achieved with the aforementioned measures. The use of LNG and bio-LNG fuels are the last measures to be used to achieve the IMO's targets.

4.1 Assumptions

It is estimated that 921 megatons of carbon dioxide ($MtCO_2$) was emitted from shipping industry in 2008 (Longva, 2019).

The first assumption that underlies what follows is that shipping will continue to grow in the following years at a rate of around 3% (United Nations Conference on Trade and Development, 2018). The issue is that 50% of pollutants at an absolute value, means that the target for 2050 is more than 50% reduction compared to 2008, given the continuous grow of shipping. If shipping continues to increase, these 410.5 megatons will greatly reduce the amount of carbon pollutants per transported item. It turns out that the target will be finally more than 50% reduction given the growth of shipping that makes the transition quite challenging.

The second assumption deals with the fact that the cost of transporting the goods is very small compared to the cost of the goods themselves. For that reason, consumers will probably not oppose to give an additional minimal amount of money, in order to have a green transfer of goods. In the air transport industry, travellers have the option to pay carbon charge to offset emissions of their flight. This method could also be applied in the shipping industry. The funds could be used to buy carbon credits, which offset the emissions through projects worldwide to protect deforestation.

The third assumption is related to the carbon pricing. Carbon pricing is a carbon-reducing strategy that uses market processes to pass the emission costs on to emitters through taxes. The goal is to prevent the use of carbon dioxide-emitting fossil fuels to protect the atmosphere, address the impacts of climate change and comply with national and international climate agreements. It is generally expected that carbon pricing will be very generous, and it will be able to finance any demanding transition to any demanding fuel. The barrier is that no one guarantees a brave carbon pricing, so ship owners should continue working on the investigation of the most efficient transition in terms of cost. A climate levy to a competitive price would be probably the most effective maritime emissions mitigation measure. The carbon price depends on a variety of factors, such as total shipping services demand, and technological progression. A carbon price of up to US$250 per ton of fuel could make zero-emission alternatives very competitive and could probably lead to the total decarbonisation by 2035 (Kachi, Mooldijk and Warnecke, 2019).

4.2 Reference line value

The reference line is defined as the curve that represents the average index value. This line applies to a specific type of ship. The constants a and c are determined from the regression curve fit (IMO, 2011). The reference line is given by the following formula:

$$Reference\ line = a * (capacity)^{-c}$$

Values for a and c for the most common vessel types are available in Table 3.

Table 3: Parameters for determination of reference values for the different types of ships

Ship type	a	c
Bulk carrier	961.79	0.477
Gas carrier	1120	0.456
Tanker	1218.8	0.488
Container ship	174.22	0.201
General cargo ship	107.48	0.216
Refrigerated cargo carrier	227.01	0.244
Combination carrier	1219	0.488

4.3 Development

Since 2008, there was a downturn on seaborne trade in 2009, but then the development continued to increase at a constant rate. Figure 9 represents the emissions, trade, and CI trends as they have been estimated in the 4th IMO GHG Study. The red lines represent the size of trading. The United Nations Conference on Trade and Development (UNCTAD) Seaborne trade (tnm) means that either the same ships make more voyages or there are more ships on the market that cumulatively make more voyages. The projection shows that from 2008 until 2018, there was an increase on trades of around 40%. The yellow lines illustrate the increasing efficiency of the fleet and show that there are fewer emissions per ton-mile. Overall, the vessels are improving, and the trades are increasing. A key question is which of the two will increase faster in order to achieve the final reduction of emissions. We observe that the CO2 emissions remain stable, although the trades are increasing.

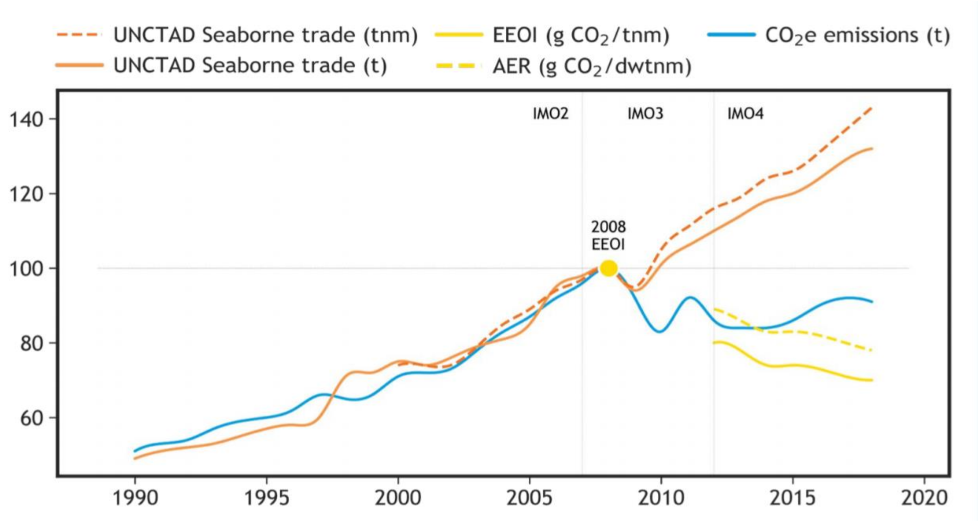


Figure 9: International shipping emissions and trade metrics (IMO, 2020)

To find the target value, the development of bulk carriers' fleet should also be considered.

4.4 Fuel Consumption

In order to find the fuel consumption, we use the excel file obtained from Seanergy Maritime Corporation. This file contains internal information (see Appendix 2: Seanergy Maritime Corporation data) for a capesize bulk carrier operating the voyage from Port Hedland to Qingdao. The total fuel consumption for this particular ship would be:

$$Total\ fuel\ consumption\ (voyage)$$
$$= Consumption, Ballast * (1 + Weather\ factor) * \left(\frac{Distance, Laden}{\frac{Speed, Laden}{24}} \right)$$
$$+ Consumption, Laden * (1 + Weather\ factor) * \left(\frac{Distance, Ballast}{\frac{Speed, Ballast}{24}} \right)$$

$$Total\ fuel\ consumption\ (port\ ) = Port\ fuel\ consumption * (Port\ days + Fueling\ days)$$

$$Total\ fuel\ consumption$$
$$= Total\ fuel\ consumption\ (voyage) + \ Total\ port\ fuel\ consumption, IFO$$

$$Steam\ days = \frac{\frac{Distance, Laden}{\frac{Speed, Ballast}{24}} + \frac{Distance\ Ballast}{\frac{Speed, Laden}{24}}}{(1 - \ Weather\ factor)}$$

$$Loading\ days = \frac{Size}{80000} + \frac{Size}{30000}$$

$$Turn\ days = \frac{6}{24} + \frac{24}{24}$$

$$Port\ days = Loading\ days + Turn\ days$$

$$Total\ voyage\ days = Steam\ days + Port\ days + Fueling\ days$$

$$Total\ steaming\ days = Trips\ per\ year * Steam\ days$$

$$Total\ port\ days = Available\ days - Total\ steaming\ days$$

$$Trips\ per\ year = \frac{Available\ days}{Total\ voyage\ days}$$

4.5 Emissions

By using the fuel consumption data gained from the reports of the ship, the emissions are estimated as (Bilgili, Celebi and Mert, 2015):

$$Emissions = \text{fuel consumption (tons)} * \text{emission factor} \left(\frac{\text{kg}}{\text{tons}}\right)$$

The emission factor was not provided from Seanergy Maritime.

4.6 Cost

The cost of operating a ship is described on the 3rd edition of the book Maritime Economics from Martin Stopford (Stopford, 2009) as follows:

$$Operating\ Costs = \text{manning} + \text{stores} + \text{maintenance} + \text{insurance} + \text{administration}$$

$$\text{Voyage costs} = \text{fuel costs} + \text{dues} + \text{tugs}$$

$$\text{Fuel consumption} \left(\frac{\text{tons}}{\text{day}}\right) = \text{design fuel consumption} * \left(\frac{\text{actual speed}}{\text{design speed}}\right)^{a}$$

$$where\ a = 2\ for\ steam\ engine\ and\ a = 3\ for\ diesel\ engines$$

$$\text{Cargo handling costs} = \text{loading costs} + \text{discharging costs} + \text{cargo claims}$$

4.7 Target value y (-50%)

The target value is 50% less than the value of 2008. The following equation calculates the target value for each capacity. It is important to include in the formula the factor of shipping development (Table 6)

$$Target\ value = a * (capacity * development)^{-c}$$

Starting from the reference line values (Figure 11) for 180000 DWT, the EEDI value is 2.89. The emissions of 2008 are:

$$emissions\ 2008 = x * 2.89\ \frac{kg\ CO2}{tonmile}$$

where x are the ton-miles of 2008. A ton-mile is the unit that describes the transport of one ton of commodities for a single mile. This metric is calculated by multiplying the cargo weight in tons by the number of miles that it is transported.

The emissions of 2050 are:

$$emissions\ 2050 = f * x * y\ \frac{gr\ CO2}{tonmile}$$

where f is the factor development of shipping between the baseline of 2018 and the 2050, x is the ton-miles and y is the target value that we aim to calculate. This is possible using the following formula:

$$emissions\ 2050 = 50\% * emissions\ 2008 =>$$

$$f * x * y = x * 2.89 * 0.5 =>$$

$$y = \frac{2.89 * 0.5}{f}$$

4.8 Energy efficiency measures

The application of energy efficiency measures (Table 4) on the ships is expected to further reduce the EEDI value. These measures are classified into operational measures and energy efficiency devices (see Sections 2.1 and 2.2). Operational measures represent the “low hanging fruits” and they are considered the most effective way to reduce the emissions of a vessel.

Table 4: Percentage of emissions reduction

Operational measures	Max emissions reduction
Waiting time at port	-
Just in time - optimum speed	-
Speed Reduction	-
Energy efficiency devices	
Mewis duct	6%
Flettner rotor (rotor sails)	6%
VFD (Var Freq Drive), LED (Light-Emitting Diodes) bulbs	1%
Silicon coatings	4%
LNG	20%
Bio-LNG	12%
Total	48%

4.9 Methodology Flowchart

This chapter describes the steps to be followed in order to determine the target values of EEDI for potential future new buildings.

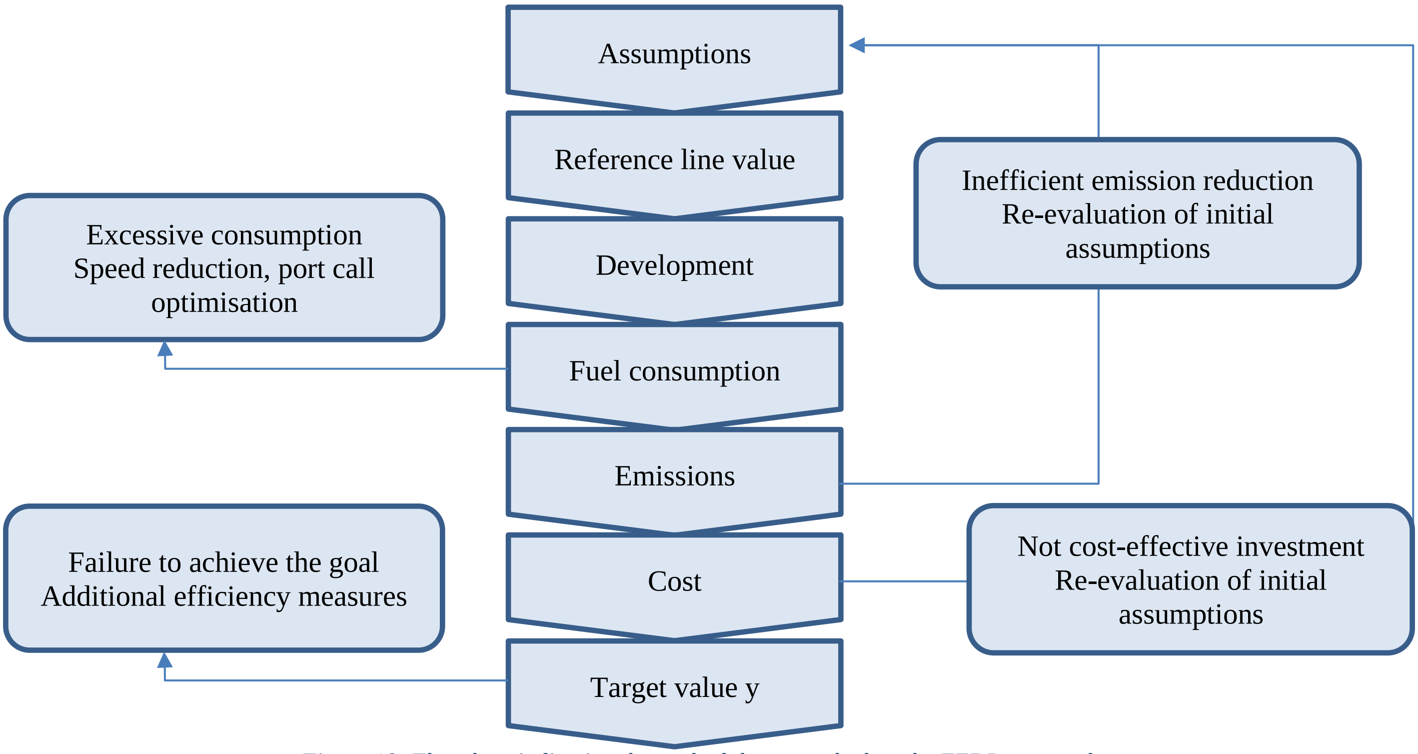


Figure 10: Flowchart indicating the methodology to calculate the EEDI target value

5. Case study

The idea is to consider a real trade route, a real voyage, and try to analyse how this trade route could comply with the 2050 goal. The initial approach is to take the China-Australia route from Qingdao to Port Hedland, find a capsize bulk carrier that was operating this route and try to create a new design that will be complied with the IMO's regulations for 2050. In this section, three case studies could be investigated from more conservative to more radical scenarios.

5.1 Models description

The first case study vessel will have a capacity of 180000 DWT and will be equipped with a main engine of 12500 kW and reduced service speed of 12.5 knots. As mentioned in 2.1.2 the reduced speed has immediate emission reduction benefits because of the reduced fuel consumption. The low engine load increases the lifecycle of the engine. The vessel will be fully operated from the second semester of 2020. This vessel will be equipped with a Mewis Duct, one Fletner rotor, LED fixtures and foul release coatings with a total emission reduction of around 17%.

The second case study will investigate a bigger size of 190000 DWT that will replace the initial vessel that was 180000 DWT with 14000KW main engine and 12.5 knots service speed. The reduced engine power and service speed compared to the old design, will mitigate the emissions. In addition, the energy efficiency measures, and operational measures will increase the efficiency of the new vessel that will be adapted on the new regulations. This vessel will be ready at the beginning of 2021. The equipment includes the same energy efficiency devices of the first case vessel.

A third case will be a much bigger size of 200000 DWT that will be moved with a main engine of 15000kW. The service speed will be 12.5 knots in order to get the aforementioned benefits of reduced speed. The vessel will be ready at the end of 2021. In this case all the energy efficiency measures will be adopted with the use of LNG. The total efficiency will be 48% less emissions according to Table 4

Table 5: Case studies characteristics

Case study	Total KW Main Eng	Capacity	Service speed	Delivery Date	Efficiency
1	12500	180000	12.5	2020	17%
2	14000	190000	12.5	2021	17%
3	15000	200000	12.5	2021	48%

6. Results and discussion

This part of the report contains the results of the methodology.

6.1 Reference line value

In the present study a bulk carrier with 180000 deadweight tonnage (DWT) capacity is considered. The corresponding reference lines are calculated in Figure 11.

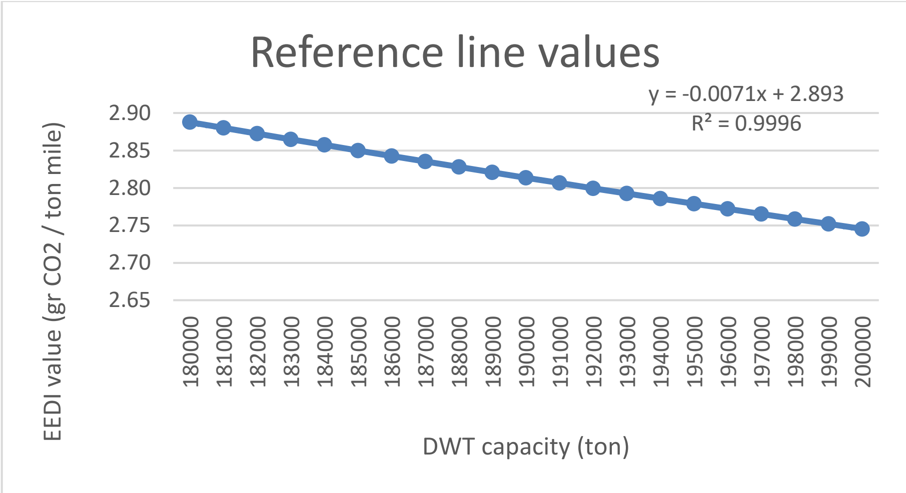


Figure 11: Reference line values for each deadweight tonnage (DWT) capacity for 2020.

6.2 Development

Table 6 describes the development of shipping. The total development from 2008 up to 2050 is the projection of development of shipping from 2018 until 2050 (factor development of shipping), plus the development of shipping from 2008 until 2018 (total 40%) according to the 4th IMO GHG Study (IMO, 2020).

Table 6: Factor of development (f) of shipping in 2050 compared to 2008

	1% dev/year	2% dev/year	3% dev/year	3.5% dev/year	4% dev/year
2008 reference year	1.0				
2018 acc. 4th GHG Study	1.4				
% of development 2018-2050	1.37	1.88	2.58	3.01	3.51
% of development 2008-2050	1.92	2.64	3.61	4.21	4.91

The growth of the fleet from 2008 to 2018 is mainly associated with the trades and not only with the ships. Considering these values, the emissions will increase further according to the factor development of shipping. This means that the target value should be more than -50% in comparison to the 2008 emissions. Considering the first scenario the fleet will increase around 92%. Consequently, in order to achieve the 50% reduction in absolute value compared to 2008 values, the reference line value should be reduced further than 50%. This happens because there will be more available ton-miles due to the increased fleet by around 92%.

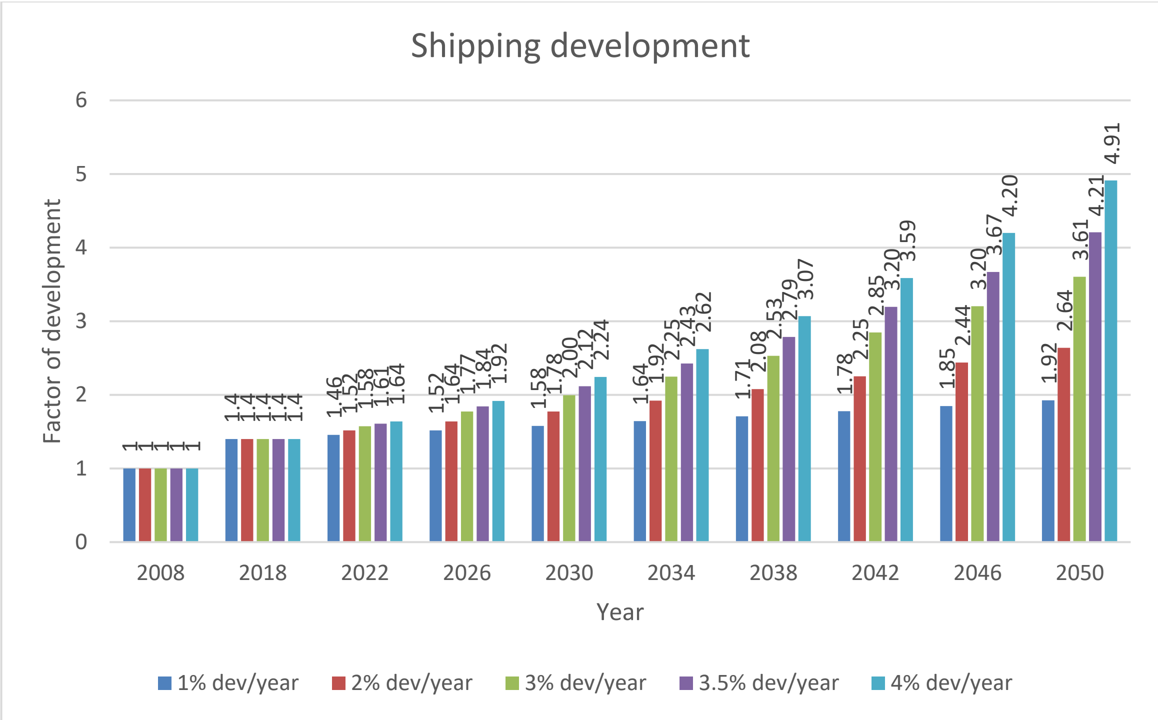


Figure 12: Development of shipping in 2050 compared to 2018 according different scenarios

Five analyses are conducted for 1%, 2%, 3%, 3.5% and 4% development per year until 2050 in Figure 12. The factor of development from 2008 until 2018 (Figure 13) is given using:

$$x^{10} = 1.4 => x = \sqrt[10]{1.4} => \ 1.034219694$$

So, the factor of development is calculated to be 3.4% according to 4th IMO GHG study and it is assumed to be constant.

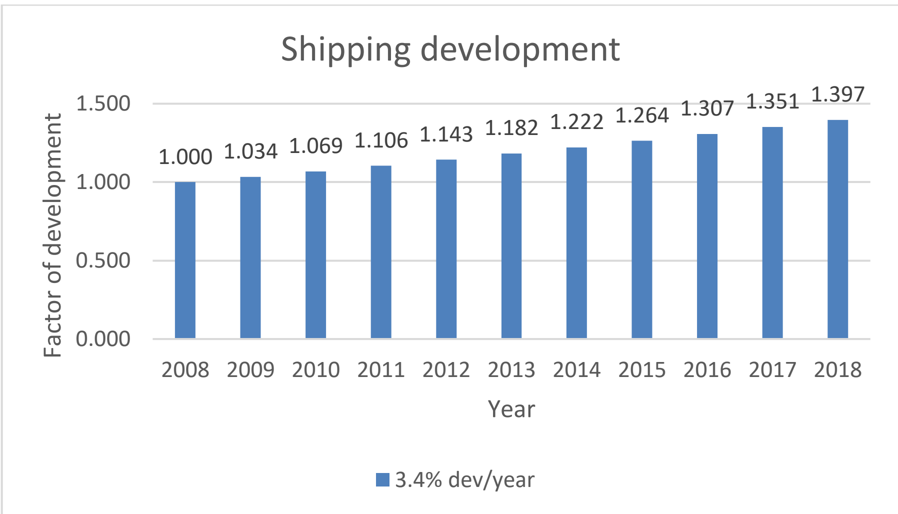


Figure 13: Development of shipping in 2018 compared to 2008 according to 4th GHG Study 2020

6.3 Fuel consumption

The total fuel consumption per voyage for this particular ship is estimated to be 1113 tons. The total fuel consumption at the ports is 51 tons. The sum of total fuel consumption per voyage and total fuel consumption at the ports is 1165 tons. The steam days are almost 24.26 days. The loading days are 8.11, the turn days is 1.25, and the port days are almost 9.36. Furthermore, total voyage days are 34.52, total steaming days are 253 days, total port days are 107 and finally the trips per year are 10.43.

6.4 Target value y (-50%)

Table 7 describes the EEDI target value according to each development scenario. To reach half of the levels of 2008, each ship should produce a 0.25-fold the emissions it has now.

Table 7: The target values for EEDI in 2050 according to each development scenario

	1% dev/year	2% dev/year	3% dev/year	3.5% dev/year	4% dev/year
Target value y (gr CO_2 / ton mile)	1.44	0.72	0.48	0.41	0.36

It is worth to notice that Figure 11 suggests that an increase in the capacity results in a decrease in the target value. This means that the larger the size of the vessel the more efficient to achieve the targets of IMO. So, if the fleet remains unchanged, the capacity should be increased in order to achieve a reduced target value according to Figure 11. Figure 14 illustrates a reduced target value for the same vessel of 180000 DWT (green arrow), and a potential future vessel with bigger capacity (red arrow) with a smaller EEDI critical point of around 2.81 gr CO_2 / ton mile.

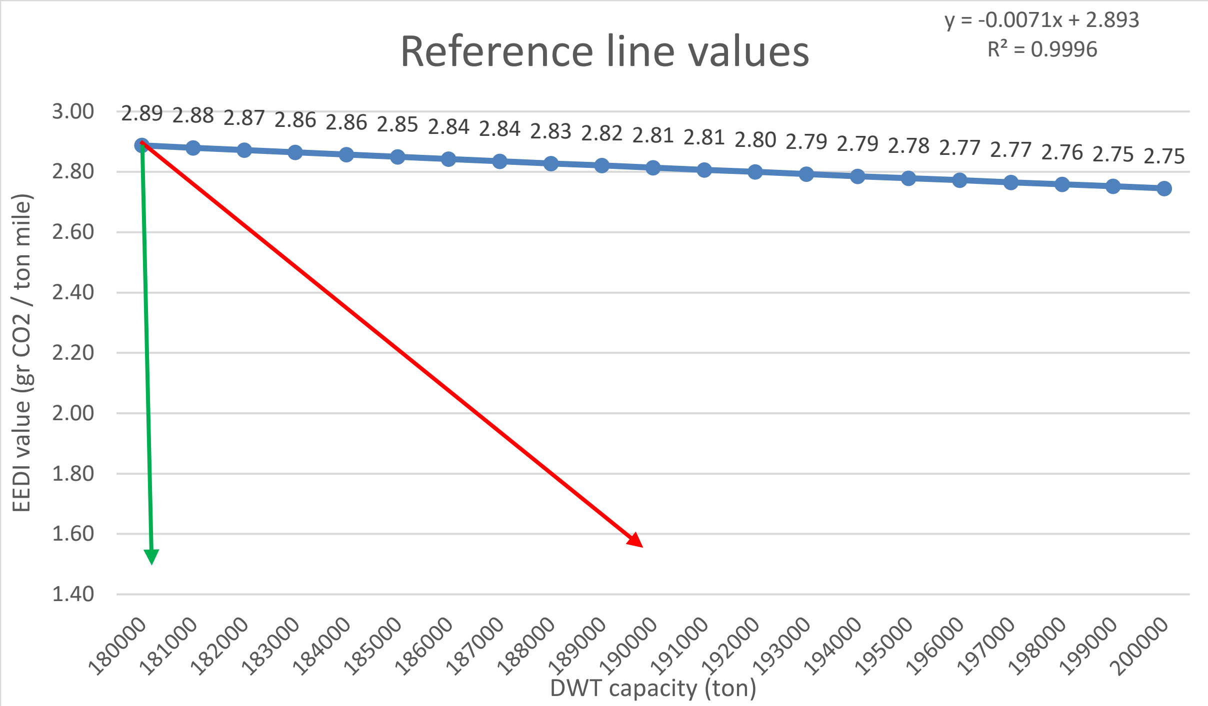


Figure 14: Reference line values

Figure 15 illustrates the EEDI target values for 2050 according to each development scenario and according to each capacity. Orange bars represent the actual reference line values (Figure 11) while non-orange bars represent each one of the different development scenarios.

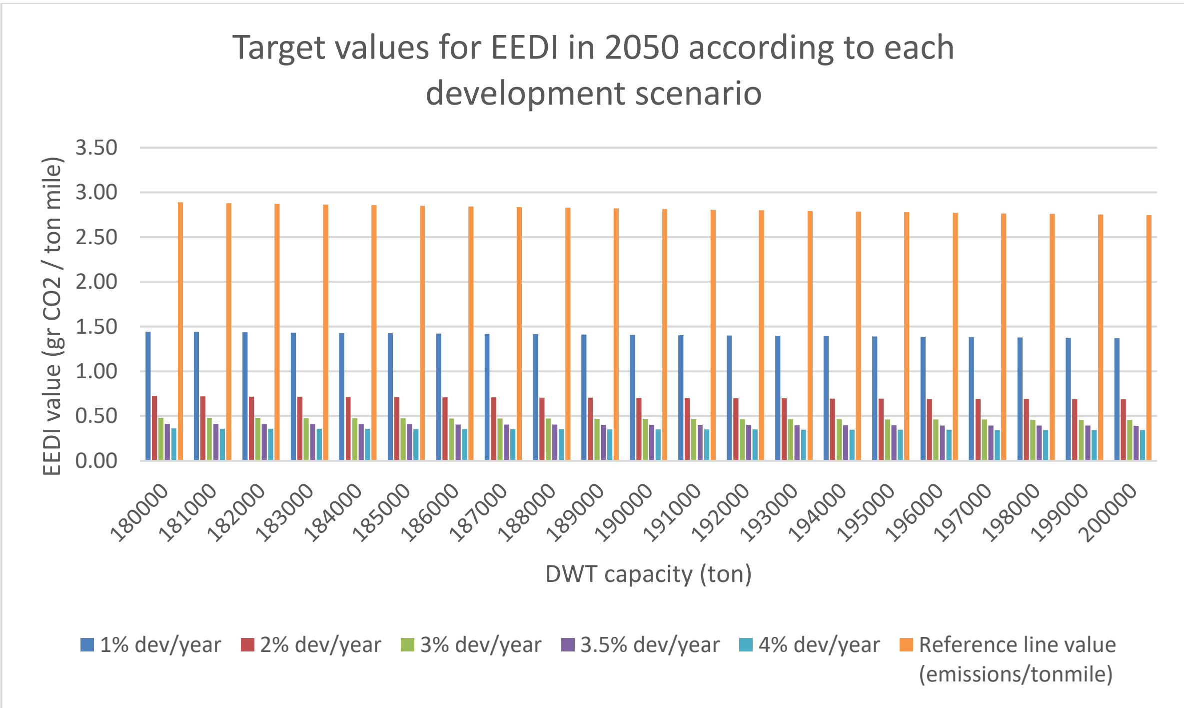


Figure 15: EEDI target values by 2050

6.5 Energy efficiency measures

According to Table 4, using the energy efficiency devices the target of IMO for 50% reduction is almost achieved for the first scenario of 1% development per year. It seems that the largest contribution of emissions reduction comes from the use of LNG.

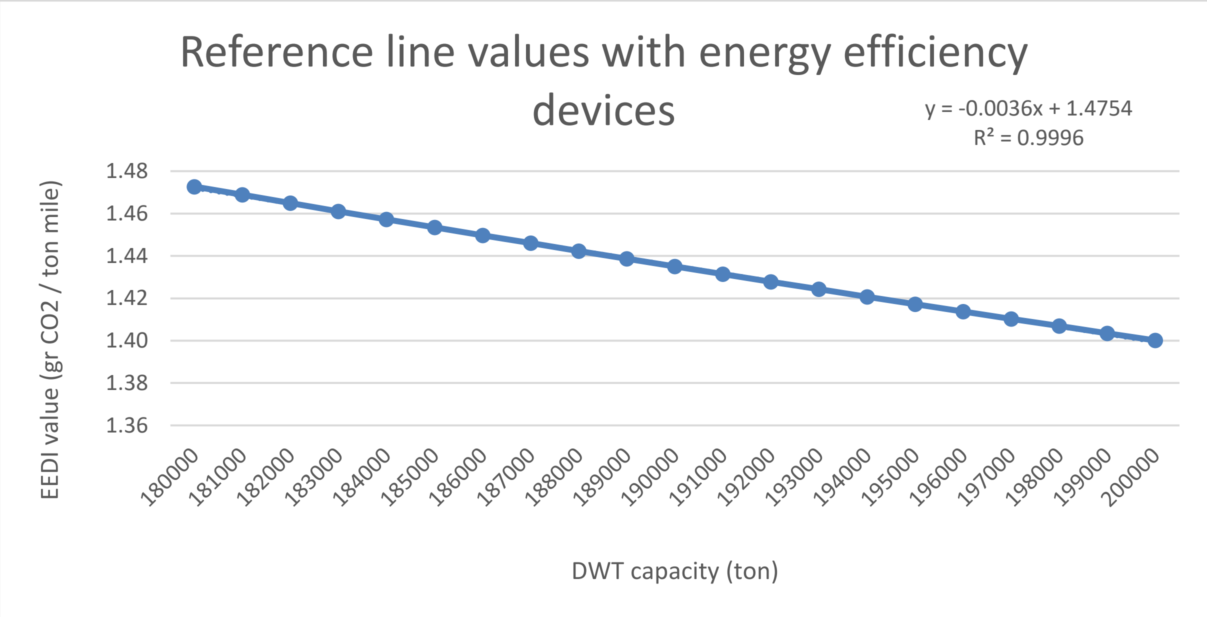


Figure 16: Reference line after implementation of energy efficiency devices

In case of higher development rate, the shipping industry needs to introduce additional measures such as the use of fuel cells, ammonia, and hydrogen; these may further help to achieve the targets.

Overall, the size of vessels will increase because the demand becomes greater and also due to the factor development. This results from the economy of scale which shows that the bigger the ship is, the bigger the profit it makes. For this reason, and by reducing the reference line by 48%, the green and red arrows in Figure 14 represent the EEDI target values that shipping should target. For the green arrow, the target value has been calculated to be 1.44 gr CO2 / ton-mile and for the red arrow is 1.43 gr CO2 / ton-mile. So finally, the solution lies in bigger ships that have been implemented energy efficiency and operational measures.

6.6 Discussion

The main research question of the present study is to investigate to which degree the target of 2050 can be achieved without imposing very expensive measures such as a zero-carbon fuel. To this end, it is of great importance to explore how feasible it is to approach this target based on the possible scenarios of fleet development in the coming years. The potential of a strategy that would avoid very radical solutions, like a new supply chain for a zero-carbon fuel (e.g. ammonia and hydrogen), has not been studied extensively to date.

Seanergy Maritime Corp. is the data provider shipping company specialised in capesize bulk carriers listed in the United States capital markets. Seanergy provides marine transportation services with a modern fleet of 11 Capesize dry bulk vessels. The cargo-carrying capacity is almost 1,926,117 DWT. The average age of the fleet is approximately 11 years. The executive offices are in Athens, Greece, and the company is incorporated in the Marshall Islands.

Australia has rich energy resources and is a leader in coal exportation, uranium, and LNG. Nevertheless, the energy sector of Australia goes through a profound change with a combination of solar and wind energy to increase significantly. In addition, the energy sector of China has changed the direction amid the President's call for an "energy revolution," and the "fight against pollution" and a switch to a service-based business model. Energy plan focuses on electricity, natural gas, and renewable, high-efficient, and digital technologies. Coal remains the biggest source in worldwide power generation, responsible for nearly 40 per cent of power generation and therefore more than 40 per cent of greenhouse gas emissions associated with it.

The results of these analysis and the 4th GHG study show that the decarbonisation of the fleet will accelerate in the next decades. This happens because the average development of shipping per year will continue to be greater than 3%. Since 2012, emissions have also been increased but to a lower growth rate than total shipping emissions. Emissions of shipping are projected to increase according to the factor of development and the efficiency of new ships. The more conservative scenario of 1% development was chosen because the coronavirus pandemic implications for the international trade and shipping development could not be studied until some significant scientific results become available. The spread of coronavirus will have a significant impact for at least the next three years.

According to the present analysis, the emissions will continue to increase. The factor development of shipping is the indicator for those emissions, but the emissions are calculated in conjunction with the efficiency measures. This means that emissions continue to increase but in a low level compared to the development of shipping and the target value would be even less than -50% finally. Figure 12 describes the development scenarios in a constant base. However, nothing guaranties that development wound be constant every year without any fluctuation. According to any possible fluctuation, the pathway of decarbonisation should be adapted to meet the requirements. In the same way, the development from 2008 until 2018 without considering possible fluctuations has been calculated. Fuel consumption on the port and during voyages are estimated using the provided data from Seanergy Maritime. The values of consumptions are in reasonable levels. Steam days are calculated by also taking into consideration the weather factor. That means that, in the presence of big waves in the opposite direction of the voyage, additional drag was produced, and extra engine load was needed. Hence, consumption and production of emissions are extremely important to overcome this drag and keep a constant service speed. Loading, turn, and port days are calculated approximately. The results were very satisfactory supporting the port call optimisation that have already applied on main ports in China and Australia. However, there is still room for improvement and further emission reduction. The total trips per year have been also evaluated.

Data on the emissions factor of the provided vessel were not provided and as a result it was not possible to calculate the real emissions. In addition, the provided data do not contain the costs for the operation of the ship and did not allow the calculation of the costs for that particular ship. However, the necessary formulae have indicated in Section 4.6 and only the exact values are missing. Finally, EEDI target values are calculated according to the development scenarios.

Overall, this study aimed to identify how operational, design, and technology factors can lead to compliance. The operational measures of low steaming and port call optimization are the first to be implemented. In this way, capital and operational expenditure are held at a reasonable level. A key secondary objective was to identify potential cut-off points where CAPEX and marine investment would seem to have no significant impact and non-marine decarbonization (offsetting) will seem to substantially outperform. However, the required data were not provided and consequently this will constitute future work (see Section 10.2).

7. Conclusion

This study examined the potential of international shipping decarbonization options. New technologies for better energy efficiency, alternative fuels that produce less emissions, operational measures that are the most effective in terms of cost, and international agencies that introduce new policies have analysed. International maritime industry has many different pathways and options to fully decarbonise the sector. Therefore, a multidimensional answer is necessary. Although grounded in a complicated legal framework, decarbonisation in a long-term, should be assisted from a clear and efficient strategy that will allow the sector to reduce emissions effectively.

LNG is the major solution to replace marine diesel oil (MDO) and heavy fuel oil (HFO), and that will reduce carbon emission in a cost-effective way. Now LNG is cheaper than MDO and HFO but there is not enough infrastructure around the globe and the development of infrastructure will have significant CAPEX. The study shows that LNG cannot be used independently to cover the 50% reduction of emissions. Efficiency measures should be implemented. Biofuels have a potential when are used in combination with other fuels and are an economically viable solution.

In case that target cannot be achieved with low cost efficiency measures, more radical measures should be included on the decarbonization equation. For example, hydrogen fuelled ships, or the use of ammonia produced with renewables onshore could be an alternative solution to meet the IMO's target. There is no ammonia fuelled ships built until now but lead companies such as Wärtsilä, Equinor and Man Energy Solutions are in a hurry to bring ammonia fuelled ships to market. The high CAPEX for hydrogen infrastructure will leave hydrogen as secondary solution. In fact, nuclear energy could decarbonise 100% shipping, but safety and security issues will remain the main barrier for use in commercial shipping.

Applying a cap on global shipping emissions will secure that shipping development will be oriented to sustainable pathways. The carbon offset mechanism gives the flexibility to gain money from carbon taxation and invest those money to other sectors. For instance, in additional research for climate change or alternative fuels infrastructure. The pathway to decarbonisation should contain combined fuels, state of the art technologies and global policies. Those mixtures should be sustainable in short and especially in long term. LNG is an economical and secure alternative fuel that produce less emissions and can be implemented effectively by means of port dues and subsidies. Nevertheless, there is still a need for further investigation for long-term solutions such as the use of renewable energy, ammonia, hydrogen, or even nuclear power.

8. Recommendations for Future Work

This study has clarified some development scenarios of shipping by 2050. However, the CAPEX data for each energy efficiency device were not provided from a reliable source and therefore the respective analyses could not be conducted. In case that very radical solutions cannot be avoided, an extra analysis should be undertaken to calculate the costs. A new formula that will estimate the cost of averting a ton of emission (CATE) should be introduced. This formula will indicate the amount of money that should be spend in order to reduce one ton of emissions. Calculate the total cost is of great importance so that every shipowner would be able to invest for each device according to her/his needs to reach greater efficiency.

The literature review does not provide all the available energy efficiency devices such as air lubrication, waste heat recovery and additional propulsion improving devices. In case that one device is not possible to be installed, it can be replaced from an alternative device. Many measures refer only to some types of ships, and this is often stated in the description of the measures. This means that not all the energy efficiency devices are applicable to every ship. For example, on the bulk carriers with cranes, the Flettner rotors are difficult to be installed. The potential savings and related costs for each measure depend on the type of vessel and the way each vessel operates. However, a more thorough research is needed for the percentage of emission reduction that each device can provide and under what conditions. This is a limitation that may have an impact on the accuracy of the total emission reduction.

It is also important to calculate the CI of the entire fleet as well as the CI of the case study vessel. Probably calculating first the emissions from a past voyage would be a helpful step to allow the calculation of the CI. The fuel consumption is based on the data from Seanergy Maritime Corporation. The method should be applied on the case study vessel. To do that, a more accurate description of the case vessel needs to be available. A set of different engines, sizes and operating speeds should be studied in order to reach a comprehensive conclusion. Finally, a sensitivity analysis will show the best choice of ship in terms of capacity, operational speed, main and auxiliary engine, CAPEX and ROI. Also, the fleet development should be taken into account as it constitutes a key characteristic. The EEDI would be calculated at a later stage in order to identify whether the ship would comply with the target values and therefore with the IMO's regulations. This index considers the potential energy usage of the vessel based on the engines mounted, the measures for improving performance and also the size and capacity of the vessel. Towards 2025 the restrictions will slowly become more stringent. To calculate the EEDI value, first the characteristics of the main engine should be determined, i.e. the auxiliary engine and shaft motor, the energy efficiency electrical and mechanical technology, and finally the transport work (Appendix 3: EEDI formula - four key parts).

9. References

Agarwal, R., Rainey, T.J., Steinberg, T., Rahman, S.M.A., Perrons, R.K. and Brown, R.J. (2020). LNG regasification – Effects of project stage decisions on capital expenditure and implications for gas pricing. *Journal of Natural Gas Science and Engineering*, [online] 78, p.103291. Available at: https://www.sciencedirect.com/science/article/pii/S1875510020301451

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A. and Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, [online] 182, pp.72–88. Available at: https://www.sciencedirect.com/science/article/pii/S0196890418314250?fbclid=IwAR1q6dUJAEOZetPIyLhC8M_61j85RPRwgVkIUataNtNhPgYXGXt2UqTvrEk

Bilgili, L., Celebi, B. and Mert, T. (2015). *ESTIMATION OF SHIP EXHAUST GAS EMISSIONS*. [online] Available at: http://www.universitypublications.net/ajs/0401/pdf/DE4C437.pdf

Bordogna, G., Muggiasca, S., Giappino, S., Belloli, M., Keuning, J.A. and Huijsmans, R.H.M. (2020). The effects of the aerodynamic interaction on the performance of two Flettner rotors. *Journal of Wind Engineering and Industrial Aerodynamics*, [online] 196, p.104024. Available at: https://www.sciencedirect.com/science/article/pii/S0167610519306245

Boulougouris, E., Banks, C., Incecik, A., Turan, O. and Lu, R. (2015). A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping. *Ocean Engineering*, [online] (110), pp.18–28. Available at: https://www.sciencedirect.com/science/article/pii/S0029801815003558

Bullock, S., Mason, J., Broderick, J. and Larkin, A. (2020). Shipping and the Paris Climate agreement: A Focus on Committed Emissions. *BMC Energy*, [online] 2(1). Available at: https://link.springer.com/article/10.1186/s42500-020-00015-2#:~:text=Climate%20change%20and%20committed%20emissions,1.5%20%C2%B0C%20%5B1%5D

Camós Noguer, A., Olsen, S.M., Hvilsted, S. and Kiil, S. (2017). Field study of the long-term release of block copolymers from fouling-release coatings. *Progress in Organic Coatings*, [online] 112, pp.101–108. Available at: https://www.sciencedirect.com/science/article/pii/S0300944017301297

Chang, X., Sun, S., Zhi, Y. and Yuan, Y. (2018). Investigation of the effects of a fan-shaped Mewis duct before a propeller on propulsion performance. *Journal of Marine Science and Technology*, 24(1), pp.46–59.

Chu Van, T., Ramirez, J., Rainey, T., Ristovski, Z. and Brown, R.J. (2019). Global Impacts of Recent IMO Regulations on Marine Fuel Oil Refining Processes and Ship Emissions. *Transportation Research Part D: Transport and Environment*, [online] 70, pp.123–134. Available at: https://www.sciencedirect.com/science/article/pii/S1361920918309155?fbclid=IwAR0RGiQ6niCqiSTcsZY8xs3lPYEwGp-7DRCLZ-K7C5T43WL1K2qEHUdMGGg.

DNV GL (2017). *Maritime Forecast to 2050 - Energy Transition Outlook 2017*. [online] DNV GL. Available at: https://eto.dnvgl.com/2017/maritime

Gonyo, S.B., Goedeke, T.L., Wolfe, K.E., Jeffrey, C.F.G., Gorstein, M., Poti, M. and Dorfman, D.S. (2019). An economic analysis of shipping costs related to potential changes in vessel operating procedures to manage the co-occurrence of maritime vessel traffic and whales in the Channel Islands region. *Ocean & Coastal Management*, [online] 177, pp.179–187. Available at: https://www.sciencedirect.com/science/article/pii/S0964569118303399.

Green Ship Technologies IMarEST and Science & Innovation Network (SIN). (n.d.). [online] Available at: https://www.imarest.org/reports/682-green-ship-technologies/file.

Held, G. (2016). *Introduction to Light Emitting Diode Technology and Applications*. [online] *www.taylorfrancis.com*. Auerbach Publications. Available at: https://www.taylorfrancis.com/books/9780429133848.

Horvath, S., Fasihi, M. and Breyer, C. (2018). Techno-economic Analysis of a Decarbonized Shipping sector: Technology Suggestions for a Fleet in 2030 and 2040. *Energy Conversion and Management*, [online] 164, pp.230–241. Available at: https://www.sciencedirect.com/science/article/pii/S0196890418302152#b0010.

Hughes, E. (2015). *Third IMO Greenhouse Gas Study 2014*. [online] Available at: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

IMO (2011). *Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating thereto (Inclusion of regulations on energy efficiency for ships in MARPOL Annex VI)*. [online] Available at: http://www.imo.org/en/MediaCentre/HotTopics/GHG/Documents/eedi%20amendments%20RESOLUTION%20MEPC203%2062.pdf

IMO (2016a). *AIR POLLUTION AND ENERGY EFFICIENCY STUDY SERIES: Studies on the Feasibility and Use of LNG as a Fuel for Shipping*. [online] Available at:

http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/LNG%20Study.pdf

IMO (2020). *Fourth IMO GHG Study 2020 – Final report: REDUCTION OF GHG EMISSIONS FROM SHIPS*.

IMO (2020a). *Energy Efficiency Measures*. [online] Available at: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx.

Kachi, A., Mooldijk, S. and Warnecke, C. (2019). *Carbon pricing options for international maritime emissions*. [online] Available at: https://newclimate.org/wp-content/uploads/2019/04/Carbon-pricing-options-for-international-maritime-emissions.pdf.

Karim, M.M. and Hasan, S.M.R. (2017). Establishment of EEDI Baseline for Inland Ship of Bangladesh. *Procedia Engineering*, [online] 194, pp.370–377. Available at: https://www.sciencedirect.com/science/article/pii/S1877705817333118

Khalid, N. (2014). Efficient Energy Management: Is Variable Frequency Drives the Solution. *Procedia - Social and Behavioral Sciences*, 145, pp.371–376.

Krarti, M. (2018). *Optimal Design and Retrofit of Energy Efficient Buildings, Communities, and Urban Centers | ScienceDirect*. [online] www.sciencedirect.com. Available at: https://www.sciencedirect.com/book/9780128498699/optimal-design-and-retrofit-of-energy-efficient-buildings-communities-and-urban-centers.

Lehtveer, M., Brynolf, S. and Grahn, M. (2019). What Future for Electrofuels in Transport? Analysis of Cost Competitiveness in Global Climate Mitigation. *Environmental Science & Technology*, 53(3), pp.1690–1697.

Lloyd's Register (2014). *Working Together for a Safer World: Lloyd's Register LNG Bunkering Infrastructure Survey 2014 the Outlook of Ports on Provision of LNG Bunkering Facilities*. [online] Available at: http://lng.wpci.nl/lng/sites/default/files/2014%20Lloyds%20Register%20LNG%20Bunkering%20Infrastructure%20Survey.pdf.

Longva, T. (2019). *Forecasting the effects of world fleet decarbonization options - DNV GL*. [online] Missing Label with key: Page-Annotations-sitename. Available at: https://www.dnvgl.com/expert-story/maritime-impact/Forecasting-the-effects-of-world-fleet-decarbonization-options.html

McMillan, C. (2013). *Focus hull coatings for vessel performance*. [online] Available at: http://www.fathommaritimeintelligence.com/uploads/2/5/3/9/25399626/focus_hull_coatings_for_vessel_performance.pdf.

Michail, N.A. and Melas, K.D. (2020). Shipping Markets in Turmoil: an Analysis of the Covid-19 Outbreak and Its Implications. *Transportation Research Interdisciplinary Perspectives*, [online] p.100178. Available at: https://www.sciencedirect.com/science/article/pii/S2590198220300890#s0025.

Nowruzi, H. and Najafi, A. (2019). An experimental and CFD study on the effects of different pre-swirl ducts on propulsion performance of series 60 ship. *Ocean Engineering*, [online] 173, pp.491–509. Available at: https://www.sciencedirect.com/science/article/pii/S0029801818316780#fig1.

O'Mahony, H. (n.d.). *How a coating can cut carbon and cost*. [online] Available at: https://marinecoatings.brand.akzonobel.com/m/6b4d166d3a0c3a26/original/Intersleek-English.pdf.

Poulsen, R.T. and Sampson, H. (2020). A swift turnaround? Abating shipping greenhouse gas emissions via port call optimization. *Transportation Research Part D: Transport and Environment*, [online] 86, p.102460. Available at: https://www.sciencedirect.com/science/article/pii/S1361920920306477.

Prakash, V., Smith, T., Rehmatulla, N., Mitchell, J. and Adland, R. (2016). *Revealed preferences for energy efficiency in the shipping markets*. [online] Available at: https://u-mas.co.uk/LinkClick.aspx?fileticket=XZrD06pN9Ik%3D&portalid=0.

Psaraftis, H.N. and Kontovas, C.A. (2014). Ship speed optimization: Concepts, models and combined speed-routing scenarios. *Transportation Research Part C: Emerging Technologies*, [online] 44, pp.52–69. Available at: https://www.sciencedirect.com/science/article/pii/S0968090X14000667#s0095.

Räsänen, J.-E. and Schreiber, E.W. (2012). *Using Variable Frequency Drives (VFD) to save energy and reduce emissions in newbuilds and existing ships Energy efficient solutions*. [online] Available at: https://library.e.abb.com/public/a2bd960ccd43d82ac1257b0200442327/VFD%20EnergyEfficiency_Rasanen_Schreiber_ABB_27%2004%202012.pdf.

Raucci, C., Prakash, V., Rojon, I., Smith, T., Rehmatulla, N. and Mitchell, J. (2017). *Navigating Decarbonisation: An Approach to Evaluate Shipping's Risks and Opportunities Associated with Climate Change Mitigation Policy*. [online] OurEnergyPolicy. Available at: https://www.ourenergypolicy.org/resources/navigating-decarbonisation-an-approach-to-evaluate-shippings-risks-and-opportunities-associated-with-climate-change-mitigation-policy/.

Sapkota, Y. and White, J.R. (2020). Carbon offset market methodologies applicable for coastal wetland restoration and conservation in the United States: A review. *Science of The Total Environment*, 701, p.134497.

Schinas, O. and Butler, M. (2016). Feasibility and Commercial Considerations of LNG-fueled Ships. *Ocean Engineering*, 122, pp.84–96.

Schøyen, H. and Bråthen, S. (2015). Measuring and improving operational energy efficiency in short sea container shipping. *Research in Transportation Business & Management*, 17, pp.26–35.

Schwartz, H., Gustafsson, M. and Spohr, J. (2020). Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably? *Journal of Cleaner Production*, 254, p.120069.

Sharples, J. (2019). LNG Supply Chains and the Development of LNG as a Shipping Fuel in Northern Europe. *Oxford Institute for Energy Studies*. [online] Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/01/LNG-supply-chains-and-the-development-of-LNG-as-a-shipping-Fuel-in-Northern-Europe-NG-140.pdf?fbclid=IwAR2ON376bvNojr4FLJHSZsR4TBP8tc4JzHtc4n88EBMT7cSFsHmMcOJRImg

Shell (2020). *Decarbonising Shipping: ALL HANDS-ON DECK*. [online] Available at: https://www.shell.com/promos/energy-and-innovation/all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf.

Smith, T.W.P., Bracewell, T., Mulley, R. and Palmer, K. (2015). *Stranded assets and the shipping industry*. [online] Shipping in Changing Climates 2015. Available at: https://discovery.ucl.ac.uk/id/eprint/1472835/

Stopford, M. (2009). *MARITIME ECONOMICS*. [online] Available at: https://logistics.nankai.edu.cn/_upload/article/50/93/1cf2097840e8af90af4b19979773/9ce547df-a3e1-493c-a4a3-0ebbfe0669b9.pdf.

Stopford, M. (2020). *Coronavirus, Climate Change & Smart Shipping THREE MARITIME SCENARIOS 2020 – 2050*. [online] Available at: http://webinars.capitallink.com/2020/stopford/paper.pdf.

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K. and Johnson, H. (2014). *Cost-effective Choices of Marine Fuels in a Carbon-Constrained World: Results From a Global Energy Model*. [online] Environmental science & technology. Available at: https://pubmed.ncbi.nlm.nih.gov/25286282/.

Talluri, L., Nalianda, D.K. and Giuliani, E. (2018). Techno economic and environmental assessment of Flettner rotors for marine propulsion. *Ocean Engineering*, [online] 154, pp.1–15. Available at: https://www.sciencedirect.com/science/article/pii/S0029801818301598.

Tillig, F., Ringsberg, J.W., Psaraftis, H.N. and Zis, T. (2020). Reduced environmental impact of marine transport through speed reduction and wind assisted propulsion. *Transportation Research Part D: Transport and Environment*, [online] 83, p.102380. Available at: https://www.sciencedirect.com/science/article/pii/S1361920920305678#b0085.

United Nations Conference on Trade and Development (2018). *unctad.org | Review of Maritime Transport 2018*. [online] Unctad.org. Available at: https://unctad.org/en/pages/PublicationWebflyer.aspx?publicationid=2245.

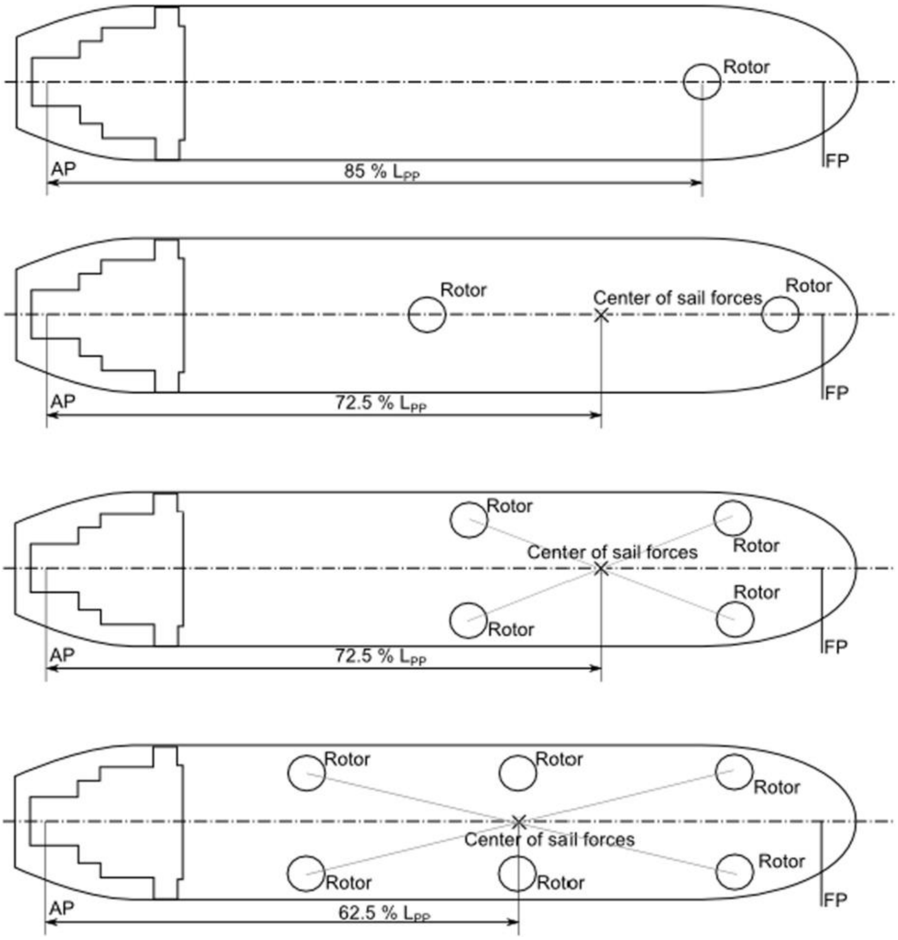
University Maritime Advisory Services and Lloyd's Register (2019). *Zero-Emission Vessels: Transition Pathways*. [online] Available at: https://www.poseidonprinciples.org/wp-content/uploads/2019/06/Lloyds-Register_Decarbonisation-Transition-Pathways_2019.pdf.pdf.

Xu, J., Yang, Y. and Li, Y.-W. (2015). Recent development in converting coal to clean fuels in China. *Fuel*, [online] 152, pp.122–130. Available at: https://www.sciencedirect.com/science/article/pii/S0016236114011636.

Zhu, D. and Humphreys, C.J. (2016). Solid-State Lighting Based on Light Emitting Diode Technology. *Optics in Our Time*, [online] pp.87–118. Available at: https://link.springer.com/chapter/10.1007/978-3-319-31903-2_5.

10. Appendices

10.1 Appendix 1: Possible Flettner rotor arrangements



10.2 Appendix 2: Seanergy Maritime Corporation data

	C5 INDEX	C5 Target
Size	177000	168000
Calendar days	365	365
Available days	360	360
Distance, Laden	3,521	3,521
Distance Ballast	3,521	3,521
Speed, Laden	12.25	12.25
Speed, Ballast	13.25	13.25
Steam days	24.26	24.26
Consumption, Laden	46	46
Consumption, Ballast	46	46
Total fuel consumption	1,113	1,113
Weather factor	5%	5%
Loading days	8.11	7.70
Turn days	1.25	1.25
Port days	9.36	8.95
Fueling days	0.90	0.90
Total voyage days	34.52	34.11
Total steaming days	253	256
Total port days	107	104
Trips per year	10.43	10.55
Port cost, loading, Australia	125,000	125,000
Port cost, unloading, China	120,000	120,000
Port cost, bunkering		-
other costs	5,000	5,000
Port fuel consumption, IFO	5	5
Total port fuel consumption, IFO	51	49
	1,165	1,162
Total Port	250,000	250,000
Total Fuel	608,844	607,372
TCE	19,000	16,950
Implied Voyage	8.81	8.81

10.3 Appendix 3: EEDI formula - four key parts