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TOTAL COST OF OWNERSHIP IN MARINE PROPULSION WITH ALTERNATIVE FUELS

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Abstract

In this master thesis, a total cost of ownership (TCO) model was developed regarding the marine propulsion with different alternative fuels for a Panamax dry bulk carrier throughout its lifecycle. The fuels involved were the conventional as a basis, biofuels B24 and B30 instead of VLSFO, LNG, methanol, LPG, ammonia and liquified hydrogen. Initially, the total cost of ownership was separated into capital expenditures (capex) and operational expenditures (opex) with subsequent divisions. Following that, the global and European regulations that require the reduction of greenhouse gases emissions and the adaptation of alternative fuels and the characteristics of the latter regarding production, emissions and properties were analysed. Technical specifications and details about main engines, gensets, boilers, auxiliary systems, storage and bunkering infrastructure were also assessed. With respect to the methodology section, a Panamax bulk carrier with suitable dual fuel engines were assumed and project guides and engine calculators were utilized for fuel consumption data and GHG emissions. Fuel prices were also assumed to remain fixed for the lifetime of the vessel. Capital expenditures were mostly calculated with data provided by maritime specialists and studies applied in the specific details of the assumptions made in the dissertation. Operational expenditures were formed also with data collected from maritime annual reports, however for some fuels and in certain sections some reasonable estimations were made using the LHV of the fuels for their consumption since ammonia and LH2 marine engines are not available yet for the energy output and size needed. For the estimations about other operational aspects also the availability, hazardousness, properties and current market of the fuels in combination with advises from maritime specialists were made. Additionally, after evaluating the CII rating of each fuel for the panamax bulk carrier the lifecycle capex and opex were calculated and analyzed. The results could not be straightforward since a promising TCO was sometimes associated with a low CII rating which led to an inevitable swift to a greener fuel. Subsequently, a comparison was conducted at last taking into consideration both the straight capex and opex and the environmental ratings of the vessel.

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1 Introduction

1.1 Purpose of this thesis

This thesis aims to create a total cost of ownership model for the operation of ships with alternative fuels in the wake of increasing environmental concerns, stringent regulatory frameworks and demand for compliance, and the pressing need for sustainable solutions. The vessel used for the analysis was a panamax dry bulk carrier, and the fuels that were evaluated were conventional (VLSFO) / drop-in Biofuels, LNG / drop-in biogas, methanol, ammonia, LPG and hydrogen focused on liquified storage. The approach followed calculated both Capital Expenditures (CapEx) and Operational Expenditures (OpEx) throughout the lifetime cycle of the vessel for every different fuel in comparison with conventional. Different aspects were taken into consideration such as technical for engines and systems purchase, maintenance and operation as well as fuel tanks and their different needs, environmental with the corresponding regulatory compliance and taxes, fuel particularities and safety systems distinct costs. Global market in fuel prices and bunker infrastructure and further parameters that were considered significant for the TCO analysis of a ship powered by a different alternative fuel. The whole approach though, had a subjective element in terms of the ship's voyages so for that to be more quantitative, a scenario analysis was employed—a method that examines diverse scenarios based on various assumptions, leading to more effective decision-making and ultimately a more structured evaluation of the total cost of ownership based on realistic data. Aiming for a more up-to-date and realistic, for a shipping company, approach, some information and data were gathered from maritime specialists involved in the analysis. Thus, it became possible to compare the TCO of a panamax bulk carrier of similar range with different alternative propulsion systems and find the most cost effective and still compliant fuel in the long term.

1.2 Shipping, Decarbonization and Maritime Organizations

Shipping and delivery of goods by sea is essential for global commerce and the world economy, with more than half of the monetary value and at least 80% of the total volume of international trade being transported through maritime channels with that percentage expected to rise in the following years[1]. That means that the global fleet will increase in the following years with an anticipation of 60% expansion for the next three decades [2]a forecast that also follows the past years increase of fleet. (see Figure 1: Thousands Deadweight Tonnage and Annual percentage change & Figure 2: Growth of shipping forecast for further details).

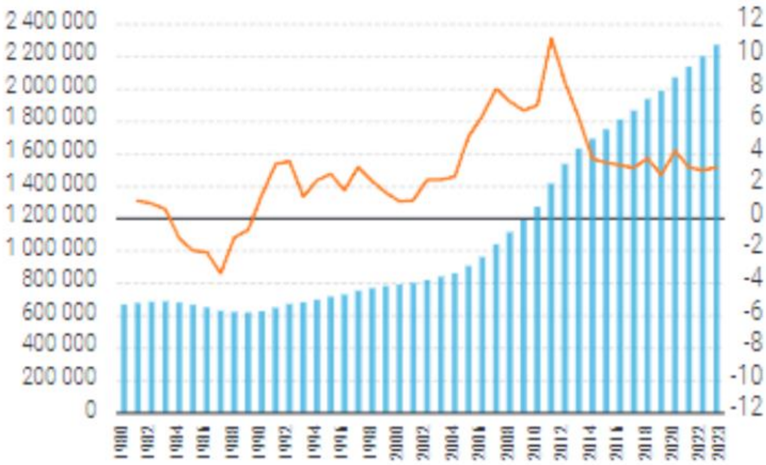

Figure 1: Thousands Deadweight Tonnage and Annual percentage change [3]

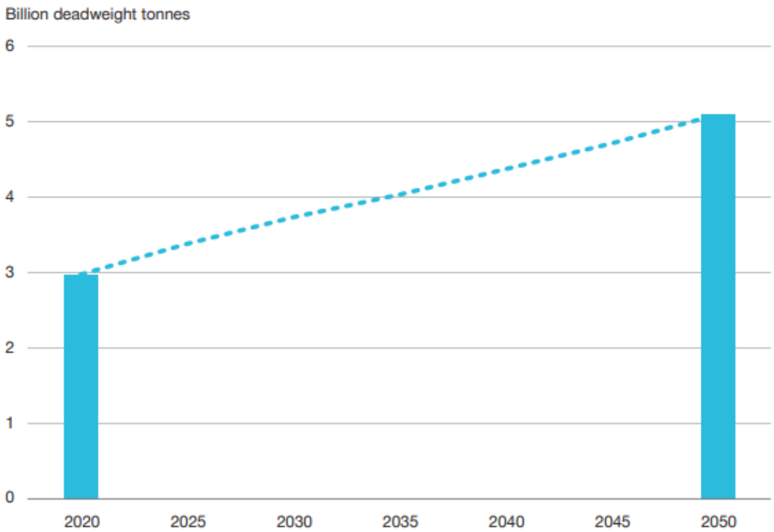

Figure 2: Growth of shipping forecast [2]

Thus, since maritime shipping is not going to stop expanding and given that it is heavily reliant on fossil fuels such as HFO, it is clear that the impact it has on the environmental pollution is not negligible and will dramatically rise. Specifically, the global maritime shipping sector is currently responsible for approximately 3% of the total greenhouse gas emissions worldwide [4] with that percentage only going higher if no actions are to be taken.

The shipping industry is receiving growing regulatory pressure to significantly reduce emissions in order to comply with the Paris Agreement which points out a limit on the total increase in global warming to 1.5°C. To bring this outcome it is important that greenhouse gas emissions will start shrinking until 2025 and by 2030 a 43% reduction has to be witnessed[5],[6].

The following expectation of well-to-wake emission compared to Paris Agreement is shown in Figure 3: CO2 overshoot[2].

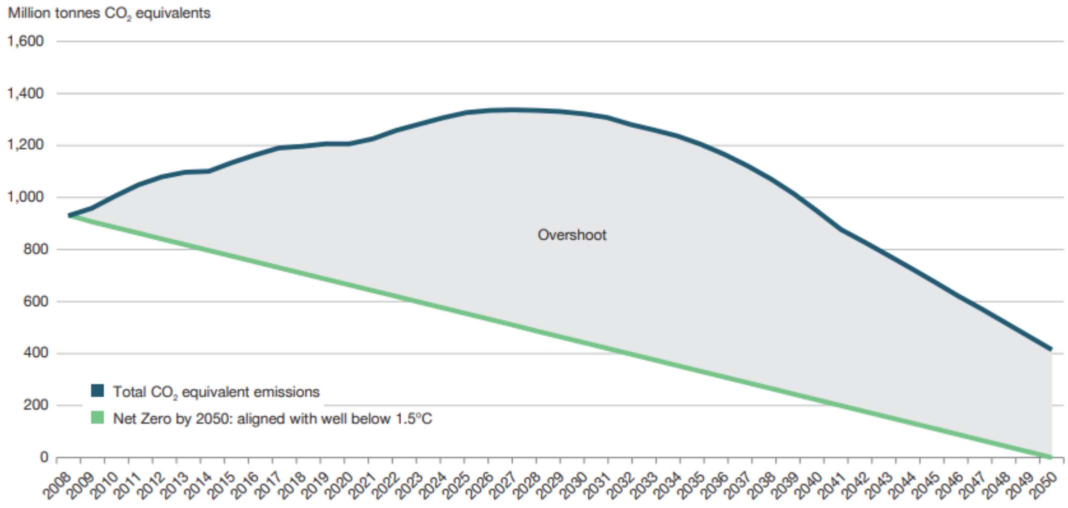

Figure 3: CO2 overshoot [2]

The International Maritime Organization (IMO) has been leading the initiatives to tackle environmental issues and diminish the environmental impact of the industry. The updated IMO GHG Strategy outlines an increased shared goal to achieve nearly zero greenhouse gas (GHG) emissions from global shipping by approximately 2050[7]. It also commits to promoting the adoption of alternative zero and near-zero GHG fuels by 2030 and establishes the following indicative milestones for the years 2030 and 2040 according to the 2023 IMO GHG Strategy:

- At least 20% reduction of the total annual GHG emissions from international shipping by 2030, aiming for 30% compared to 2008.
- At least 70% reduction of the total annual GHG emissions from international shipping by 2040 with a goal of 80%, compared to 2008. [7]

At the same time, the European Union is also actively pushing the marine industry to comply with regulations and enhance environmental sustainability, safety, and overall operational standards. A comparison regarding the standards about CO2 emissions reduction that IMO and EU are pressing for as per January 2023[8] can be shown in Figure 4: CO2 Reduction Timeline

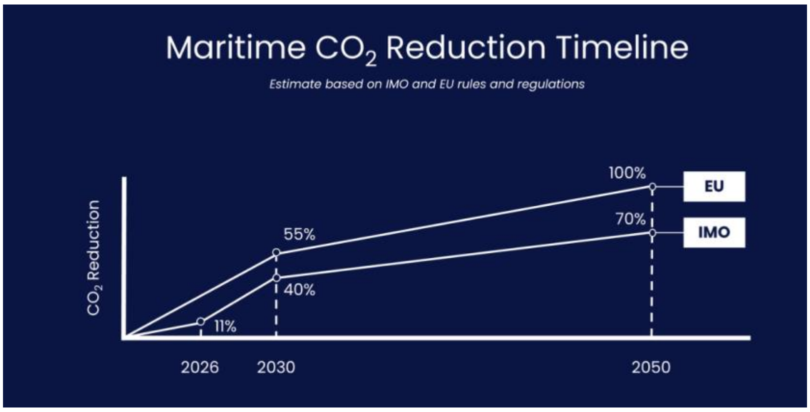

Figure 4: CO2 Reduction Timeline from IMO and EU [8]

Further details regarding the compliance on regulations and how these are expected to affect the maritime industry taxwise or according to the vessels acceptance were discussed in the 2.1 Regulatory Compliance section.

1.3 Total Cost of Ownership

The Total Cost of Ownership (TCO) serves as a purchasing tool computing all expenses incurred throughout the lifespan of the asset involved. TCO as a methodology assesses costs from the viewpoint of the side making the asset purchase, in this case the maritime company[9]. A Total Cost of Ownership (TCO) analysis may not yield precise real-world numbers as some calculations were made via different scenarios and estimations on fuel prices that might differ according to various external factors that cannot be predicted. Covid-19 is a representative example on the effect it had on last years' forecast about the fuel prices; however, the TCO serves as a valuable investment tool for comparing various options by evaluating the total costs of each option. Thus decision-makers can make informed choices based on a comprehensive understanding of the financial commitments involved[10].

The frequency of maintenance and service requirements is influenced by the operational practice of the machine, posing a potential challenge in the Total Cost of Ownership (TCO) model. Nevertheless, the TCO model frequently offers valuable insights for implementing preventive maintenance strategies and avoiding unforeseen breakdowns that can incur high costs. In general, it is crucial for a TCO model to incorporate the equipment's usage hours to facilitate a comparison with the annual cost[10].

The sections that were involved as well as the general approach that this dissertation followed for the TCO analysis are presented into the following two categories below:

1.3.1 Capex

This part involves the initial investment in assets that have a long-term use. As a significant component of TCO it includes all the costs associated with acquiring, shipping, installing of all the vessel's systems and equipment which vary according to the alternative fuel and the main engine that the ship is using due to their different technical particularities.

The CapEx analysis encompasses the initial investment and associated upfront costs over the ship's lifecycle, particularly focusing on the following components:

Main Engine and Generator Sets

This includes the initial investment in acquiring the main engine and the generators for the ship. It covers the base cost of the engine itself and any additional components for its installation as well as possible modifications to the ship's structure for the engine and the exhaust gas system and piping.

Fuel Injection Systems

Costs related to acquiring and installing fuel injection systems for the main engine and generator sets. Different fuels have varying properties and combustion characteristics that significantly determine the technology of the selected fuel injection system and ultimately the total cost for the CapEx calculation. The system must meet all the needs of specific pressure, air and fuel mixing. As dual-fuel operation that is used in most cases necessitates introducing both pilot fuel for initiating combustion and the main fuel, into the combustion chamber and different valves are employed for injecting the secondary fuel and pilot fuel it is obvious that the complexity and subsequently the cost for these systems increases and varies depending on the fuel characteristics and properties. Fuel injection systems differ greatly on every occasion and their complexity affect drastically the TCO.

Auxiliary Supply Systems and Boilers (Heat Exchangers, Vaporizers & Pumps)

The cost of heat exchangers is crucial because certain alternative fuels of those analyzed require specific temperature conditions for efficient combustion. Vaporizers are essential for converting liquid or cryogenic forms of alternative fuels into vaporized or gaseous states suitable for combustion while different requirements in pressurized injection determine the choice of pumps. The cost of pumps capable of handling these pressures can be a decisive factor. Additionally, boilers used for steam production can have a different cost according to the fuel they have to handle. Certain safety features and different characteristics call for a specific usage of cryogenic or corrosive resistant materials. An example can be seen on LNG fueled ships which need to handle boil off gases or have durability at cryogenic temperatures Thus, total cost of ownership, is directly affected.

Fuel Tanks

Alternative fuels such as LNG, LPG, Ammonia and Hydrogen need to be stored in well insulated tanks to maintain the low temperatures or high pressures needed. Specialized cryogenic storage tanks are needed in these cases. For instance, LNG storage tanks are typically double-walled and vacuum-insulated to minimize heat transfer increasing dramatically the cost of tank purchase and installation. Another crucial factor is the different energy density per unit volume of each fuel and the vaporization rate of the fuels that are stored in liquid phase (while gaseous in ambient conditions) with low temperature or high-pressure utilization. Taking these into consideration, in order to achieve a specific range for the ship the volume of the tanks has to swift accordingly for each case affecting the total cost considerably.

1.3.2 Opex

On the other hand, the Operational Expenditures (OpEx) analysis focuses on the costs that incur after the initial purchase and onward. In the TCO framework, OpEx analysis provides valuable insights into the long-term financial implications and efficiency of an investment. The key aspects that were developed in the current thesis are presented as listed:

Fuel Price

OpEx is closely tied to the cost of the fuel itself throughout the whole life cycle of the ship. Fluctuations in fuel prices directly affect the day-to-day operational expenses related to fuel consumption and their prediction can turn out to be of great complexity. In the framework of this thesis the price of each fuel that was chosen is corresponding to the current situation of the market and is subject to change in the near future. This possible fluctuation was approached with some different scenarios based on a forecast and feedback from the maritime sector.

Bunkering

Another aspect closely connected with the fuel price to be discussed that was involved in the TCO is how regular should the bunkering for each type of ship take place throughout its trip. This is equal with the range of the ship and highly affected by consumption of the engine and systems, the energy density of the fuel and the volatility of it. Fuels like methanol though with really low energy density limit the ship’s travel range without bunkering to only some weeks meaning that bunkering has to be well supported by suppliers.

Regulatory taxes

Fees for non-compliance with regulations from the European Union and the International Maritime Organization. As it was mentioned in the Maritime Organizations section in introduction the growing need for decarbonization and the promotion of sustainability lead the authorities and the regulatory bodies to set limits in Greenhouse Gases Emissions especially over CO_2, NO_x and SO_X or Methane. Deadlines are already established for the permitted emissions meaning that over this period the ship and the shipping company will have to pay taxes per ton of CO2e and at the same time they won't be accepted in certain regions and ports if the ship is not corresponding to a specific rating. Therefore, over the whole life cycle each ship with different alternative fuel system will have to pay a different total cost for emissions for not complying with the regulations which will obviously be much lower compared to the conventional fuel (in the case no action is taken). The regulations that are currently into force were extensively analyzed in the 2.1 Regulatory Compliance section.

Maintenance and service

The choice of the fuel that is going to be combusted can have significant implications for the ship's engines, systems, and overall maintenance requirements. The properties of each fuel such as the corrosive characteristics and the distinct viscosity play a key role on the wear of the engine, pipelines, pumps and injection systems. Impurities, contaminants and cat fines that exceed the permitted levels in the fuel used which can depend on the fuel's production methods can lead to increased wear and tear on engine components, necessitating more frequent maintenance. Of high importance regarding the maintenance framework is also the storage conditions (temperature, pressure) which are a result of the fuels properties and the need for higher volume. The temperature and pressure shifts from the tank to the combustion chamber have a profound connection with the fuel injection system and the supply pumps wear, thus occasional service is needed. This parameter also incorporated the drydocking costs for every ship throughout its life-cycle.

Wages and cost of training

This parameter may vary according to the ship's propulsion system, the fuel and their complexity. Different needed knowledge over the engine and the auxiliary systems demands sea farers specific training provided by the maritime company while the risk of some fuels (e.g. toxicity of fuels like ammonia and methanol) influence and can significantly change their payments.

Port Dues Tariffs throughout the vessel’s life cycle:

For different alternative fuels, ports are likely to have a different handling approach and operation on low carbon fuels or carbon free fuels is already supported and awarded by ports which offer reduced port taxes per stay depending on the fuel used within the port. Port dues charges are in general determined by the size of vessel in Gross Tonnage (GT), the length of stay and the purpose of the call meaning that different taxes were applied for bunkering operations and for cargo loading and discharging procedures. Port tariffs for each fuel and vessel were provided by specific port authorities and their regulations as it was further analyzed in 3.2.7 Port and ultimately affected the opex of the vessel and the TCO.

Off-hire periods

Delays in ports due to the ship’s special features may cause an off -hire period for which the charterers may suspend the payments to the shipowner company according to the contract of each occasion. For example, an ammonia fueled ship could take much longer for bunkering due to port’s regulations that have to be followed for the shake of safety against toxicity. That results in more off-hire days when the maritime company doesn’t receive freight rates. Nevertheless, this is an aspect which is defined in each contract and can vary greatly depending on the details of it regarding the periods that are expected to affect the shipping company and result in any loss in freight. Additionally, determining specific off-hire periods costs requires the incorporation of revenue in the TCO analysis in order to affect the shipping company in a loss of daily income which was not the purpose of this master thesis. Therefore, off-hire periods were mentioned for a thorough understanding but were not included in the methodology.

Insurance Costs

Insurance costs were also a part of the operational expenditures that was affecting the total cost of ownership on a different scale based on the fuel being used for propulsion. As it is further discussed in 3.2.9 Insurance Costs this variation in insurance prices arose from the different risk of failure in the systems and the machinery of each vessel due to higher dangers from the fuel and their properties themselves as well as the lack of knowledge and insecurity regarding completely new to the maritime scene fuels like ammonia and hydrogen.

Lubrication

It was anticipated that annual lube costs, either referring to the main engine lubricants, turbocharger lubricants or cylinder oil would meet an increase in the region of 5% in 2023 and then continue to rise approximately 1.7% annually according to a forecast for the period 2023-2027 corresponding to a compound annual growth rate (CAGR) of 2.4% from 2022 to 2027[11]. As new engines emerge, and different fuel properties are linked with different lubrication needs it is inevitable that the total lubrication oil costs would change on each occasion affecting the TCO. For instance, extended use of VLSFO in the last years resulted in a specific preference and selection of 40 base number (BN) cylinder oil instead of 70 or 100 BN.

2. Theoretical background

2.1 Regulatory Compliance

As mentioned above in "1.2 Shipping, Decarbonization and Maritime Organizations" in the regulatory framework of shipping the main active authorities are the International Maritime Organization (IMO) and the European Union (EU). This section analyzes the active regulations that affect with taxation and limitations on operation the entire shipping industry.

2.1.1 IMO

Carbon Intensity Indicator (CII)

The Carbon Intensity Indicator (CII) is a key component of the International Maritime Organization's (IMO) efforts to address greenhouse gas emissions from shipping. The CII for a vessel quantifies the average carbon dioxide emissions per unit of transportation workload. An evaluation can be conducted by contrasting the achieved annual operational CII (Attained CII) with the stipulated annual operational CII (Required CII) for a particular ship, leading to the assignment of a rating[12]. The CII considers the emissions from a tank-to-propeller perspective, meaning that only what is emitted from fuel combustion on board is calculated. The following correlation (Equation 1) describes the concept of CII:

$$CII = \frac{Annual\ fuel\ consumption \times CO2\ Emission\ Factors}{Annual\ distance\ travelled \times Capacity} \times Correction\ factors \quad (1)$$

Where:

- Capacity in DWT or GT

The CII rating mechanism entered into force on January 1, 2023, and it is mandatory for all the shipowners and the vessels to gather all the necessary data for the annual CII report which will provide the corresponding rating from A to E, with A being the indicator for major superior rating and E indicating inferior performance level [12], [13].

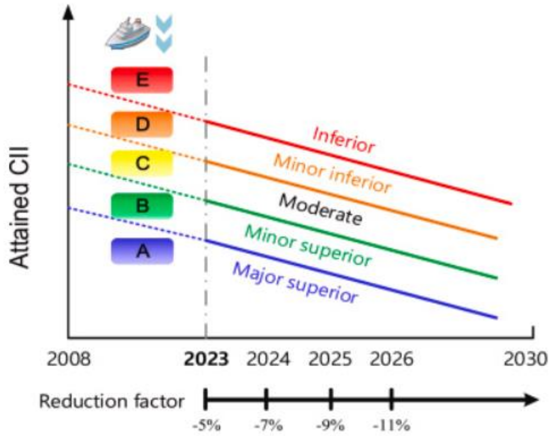

Figure 5: CII Rating scale [12]

The rule mandates that a ship with a D rating for three continuous years or an E rating must present a corrective action plan to ensure adherence to a minimum C rating. This implies that over a third of global ships are at risk of not meeting the CII requirements. Additionally, the CII baseline incorporates a reduction factor relative to the 2019 reference line, starting at 5% in 2023 and increasing by 2% annually until 2026. Consequently, a ship currently holding a C rating might face a downgrade to a D rating the following year if emissions reduction measures are not implemented[12], [13]. The CII regulation does not stipulate any straightforward taxations yet that can be estimated for the TCO but only the obligation for compliance. This obligation though, in the frames of this thesis was translated as compliance with one specific rating throughout the lifetime cycle of the ship. By doing so, a need for implementation of blended in fuels like biofuels B24 and B30 arises in order to maintain the same vessel's speed.

EEXI & EEDI

From the same date and on (1st January 2023), the Energy Efficiency Existing Ship Index (EEXI) is also active and oblige shipowners for compliance. EEXI requirements apply to all the ships above 400 GT that do not follow the EEDI concept. It assesses their energy efficiency during their operational phase and in order to comply with the regulation the attained EEXI has to respond to the following formula 2:

Attained EEXI ≤ Required EEXI (2)

A timeline of the EEXI regulation is presented in the figure below:

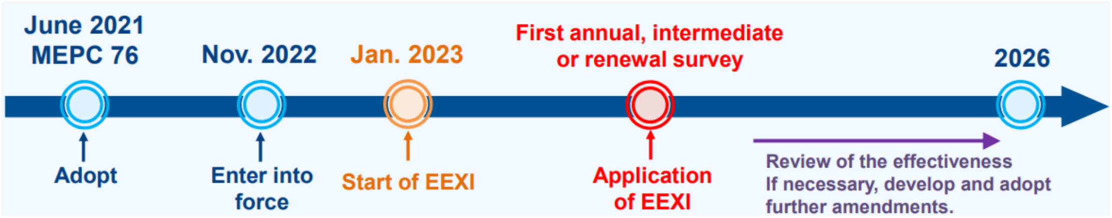

Figure 6: Timeline of EEXI regulation [14]

For new buildings the Energy Efficiency Design Index is corresponding to the Energy Efficiency Existing Index during the design phase of the ship and entered into force on 1st January of 2013 and is mandatory for most of the ships built after that date.

The general concept for these regulations can be described with Equation 3 below with the only differences for EEXI and EEDI in some parameter's definition:

$$EEXI\ [g/ton \cdot mile] = \frac{CO_2 Conversion\ factor \times SFC\ [g/kW{\cdot}h] \times Engine\ Power\ [kW]}{Capacity\ [ton] \times EEXI\ Speed\ [knots]} \quad (3)$$

In this case EEXI or EEDI demonstrates the CO_2 emissions in grams from a ship during the transportation of 1 ton of cargo for 1 nautical mile [14].

The responsibility for the calculation of the EEDI lies upon the shipyards that have undertaken the construction of the ship which has then to be accepted and verified by the classification societies[15]. Since the analysis is mostly referring to newbuildings or at least buildings with a construction year later than 2013 considering that the technologies for the fuels involved are unarguably advanced, it should be mentioned that the regulation that is applicable refers to the EEDI form and responds to the following alternative correlation [14]:

$$\text{Attained EEDI} \leq \text{Required EEXI}$$

In the case that the ship doesn't comply with the EEXI requirements then some measures should be taken. These can be:

- Engine Power Limitation (EPL) resulting in vessel's speed reduction. This can be attained by a device limiting the injection of fuel and the maximum engine power.
- Implementation of an energy saving system with a small impact of roughly 1-3% when used with no further contribution.
- Reduction of the carbon dioxide footprint by using low carbon fuel or further implementation of a higher percentage of biofuel or biogas within the combustion of VLSFO or LNG respectively.

The last method of complying with the requirements is the one which is going to be used when the regulation of required EEXI is not met with the attained EEDI and therefore affect the TCO with a more expensive total fuel price. Even though the prementioned regulations aim in the reduction of the greenhouse gases from the maritime sector by setting standards and affecting the energy efficiency of the ship, they don't directly stipulate any taxation for the TCO but the obligation for compliance has an impact on the analysis through secondary means.

Emission Control Areas (ECAs)

IMO has also established regulations towards limitation of SO_x and NO_x emissions with the introduction of Emission Control Areas. The regulation within ECAs request a sulfur content of 0.1% m/m fuel regarding the SO_x emissions and operation on TIER III instead of TIER II that is mandatory outside of these areas. ECAs currently include the Baltic Sea, the North Sea, the North American East and Western seas i.e. the Canadian coast, most of US and the US Caribbean). The Mediterranean Sea is also set to become an ECA with that coming into effect on 1st May of 2025[16]. Other potential ECAs are also set to cover Japanese and Australian waters. The accepted global sulfur content within and outside Emission Control Areas as established from 2020 and on is shown in the table below.

Table 1: Sulfur Percentage withing and outside ECAs

Maximum Sulfur Content of Fuel (% m/m)	
Sulfur ECAs (SECAs)	Global percentage
0.1%	0.5%

The way to achieve such low percentages accepted withing SECAs is either by using the alternative marine fuels that were discussed in this thesis corresponding to zero or close to zero sulphur content or by using Very Low Sulphur Fuel Oils and its biofuels blends with a content of 0.5% in sulphur for global voyages and use of ULSFO within ECAs, typically Marine Gasoil (MGO).

Another solution that is met, is using scrubbers onboard by spraying sea water at most cases where sulphur oxides are being absorbed in water (wet scrubber) and then returned to the sea in open loop scrubbers where the acidic water formatted from the sulfuric acid can easily be neutralized. Heavy Fuel Oil could also be used with constant operation of scrubbers throughout the whole voyage of the ship, although it is rather unprofitable.

The regulation within ECAs towards the limitation of nitrogen oxides (NOx) is somewhat different and takes into consideration the revolutions of the marine engine. From 1st January 2016 it demands operation on TIER III within these areas, the so-called NECAs. A presentative diagram regarding the three TIERS and how the NO_x emissions are associated with the engine speed is shown below in Figure 7 [17].

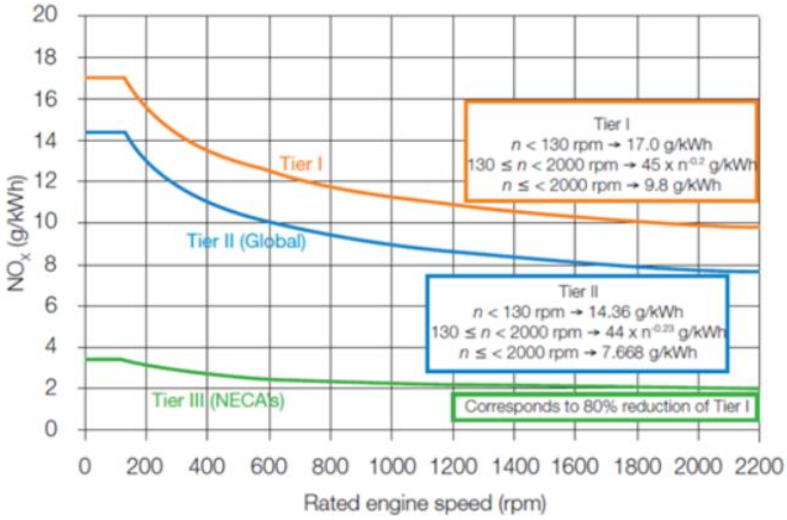

Figure 7: IMO NOx TIER Emissions Standards [17]

For all the fuels and the related engines involved, TIER II is achieved without any further modification but that's not the case for TIER III. Reaching TIER III limits lead to the need of technologies such as Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR). The former is considered an after-treatment method as utilizes urea injection in the exhaust gases resulting in a NO_x reaction while the latter is reducing the initial engines NO_x emissions by a recirculation process of the exhaust gas stream. For every engine with the fuels discussed the installation and operation of one of these two systems is mandatory for TIER III compliance withing ECAs.

2.1.2 European Union

The European Union on the other hand has set some more quantifiable regulations that include taxation in the case of not meeting their limits.

<u>EU ETS</u>

One such regulation is the EU ETS (Emissions Trading System) which is a mechanism aiming once again for greenhouse gas emission limitation by establishing a specific limit that can be accepted. The regulation stipulates that every shipping company will have to be registered in the EU with an administering authority. By the 31st of March of each year from 2025 and on each company is obliged to deliver consolidated emissions data which will be linked with the MRV (Monitoring, Reporting, Verification) reports for the previous year to the authorities. The emissions from maritime that are subject to the EU ETS are 100% of the emissions on trips and ports within the European Union (EU) or the European Economic Area (EEA) and 50% of the emissions from voyages entering or exiting the EU/EEA as presented in Figure 8 below:

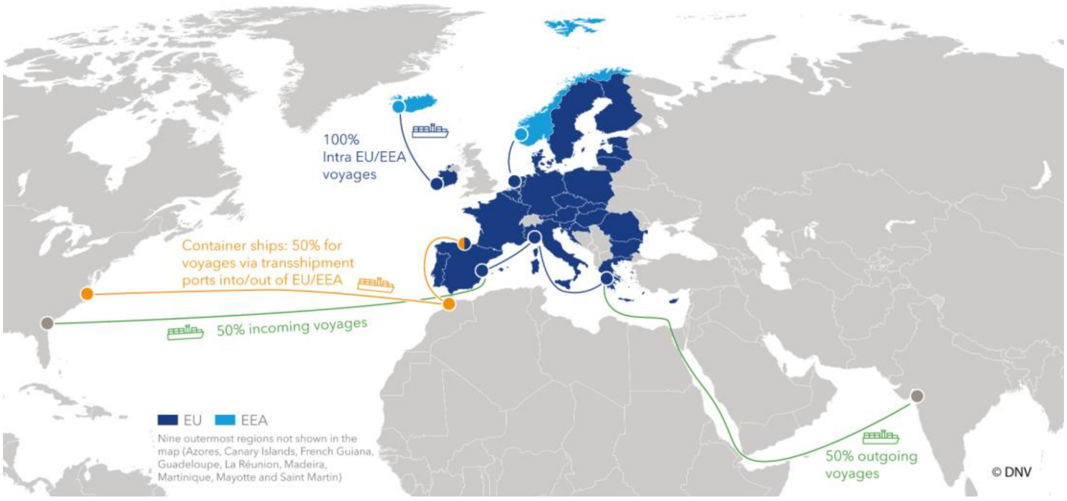

Figure 8: CO2 Emissions involved in the EU ETS [18]

Surrendering the EU Allowances which permit all the shipping companies covered by the EU ETS for a certain amount of CO_2 emissions is essential by the 30 September of each year. EU Allowances can be traded or bought and sold in auctions or the market and have to be enough to fully account for the company's CO_2 emissions. When a lack of compliance is noticed by not delivering the EU Allowances within the deadline, companies will have to pay a penalty of 100 euros per ton of CO_2 emitted which is prone to. Aside from CO_2 emissions though the EU will include in ETS, beginning in 2026, also methane (CH_4) and nitrous oxide (N_2O) emissions which will be integrated into taxation converted into CO2 equivalents with a Global Warming Potential approach. Non-compliance from one ship may yield non-compliance of the entire fleet and in the case of consecutive failure by the company for two (or more) periods their ships may face a prohibition from engaging in trading activities within the EU [18]. As far as the EU Allowances are concerned each of these provides the company with the right for emission of:

- one tonne of carbon dioxide (CO2),
- or one tonne of CO_2 equivalents of other powerful greenhouse gases i.e. methane (CH_4) and nitrous oxide (N_2O). The GWP equivalent factors of CH_4 and N_2O are 28 and 298 respectively meaning that 1 tonne of CH_4 is equal to 28 tonnes of CO_2.

The European Union Emissions Trading System (EU ETS) operates under a set limit, or 'cap,' on the quantity of emission allowances available. Companies can obtain the pre-mentioned emission allowances within this cap, and they have the flexibility to trade them as necessary. The cap is reduced annually, guaranteeing a decline in overall emissions[19].

Fuel EU

The EU targets for progressive reduction of greenhouse gas emissions with the package ‘Fit for 55’ which aims for 55% CO_2 reduction by 2030 compared to 1990. A part of it, apart from the EU ETS, is the FuelEU Maritime which is a regulatory framework designed to facilitate the shift towards a more sustainable and low-carbon shipping industry. Effective from January 1, 2025, this regulation seeks to boost the utilization of renewable and low-carbon fuels, contributing to a greater proportion of these environmentally friendly options in the fuel composition of international maritime transport within the European Union (EU). According to the FuelEU regulation ships engaged in trade inside the EU borders or the European Economic Area (EEA) are obligated to maintain an annual average Greenhouse Gas (GHG) intensity of energy consumption on board below a specified threshold. This intensity is measured as GHG emissions per unit of energy (gCO2e/MJ)[20]. The regulation also mandates the use of onshore power supply (OPS) in ports and shipyards where available[21].

The calculation of GHG emissions in FuelEU follows a comprehensive approach from well-to-wake, encompassing emissions associated with fuel extraction, cultivation, production, and transportation. Additionally, it considers emissions resulting from the energy consumed on board the ship until exited from the exhaust system[20]. The area and the effect it will have on each voyage within, entering or exiting the EU or EEA regarding the energy used is equivalent to the EU ETS with application on the 100% and 50% of energy respectively as before.

Ships failing to adhere to the prescribed limits on the annual average Greenhouse Gas (GHG) intensity of on-board energy consumption should face a penalty. This penalty, referred to as the 'FuelEU penalty,' aims to discourage non-compliance, align with the degree of violation, and eliminate any economic benefits associated with non-compliance. The intention is to maintain fair competition within the sector. The calculation of the FuelEU penalty should be based on the quantity and cost of renewable and low-carbon fuels that the ships were expected to utilize to meet the Regulation's stipulated requirements[21].

The FuelEU Penalty can be calculated with Equation 4 [21]:

$$\boldsymbol{FuelEU\ Penalty} = \frac{|Compliance\ Balance|}{GHGIE_{actual} \times 41000} \times \mathbf{2400} \quad (4)$$

Where:

- The FuelEU Penalty is in EUR
- $GHGIE_{actual}$ is the average of the whole year of the GHG intensity of energy used on-board a ship
- 41000 is in MJ and equivalent to 1 metric ton of VLSFO
- 2400 is the amount in EUR per metric ton of VLSFO
- |Compliance Balance| is in grams of CO_2 and calculated by the formula:

$$|\textbf{Compliance Balance}| = |(GHGIE_{target} - GHGIE_{actual}) \times \left[\sum_{i}^{nfuel} Mi \times LCVi + \sum_{k}^{c} E_k\right] \quad (5)$$

Where:

- $GHGIE_{target}$ is the GHG intensity limit of the energy used on-board a ship
- LCVi the lower calorific value of fuel i
- Ek Electricity delivered to the ship per OPS connection point k [MJ]

It was needed to be mentioned that FuelEU, even though it should be taken into consideration for a more holistic approach by the maritime sector, since it includes well to wake emissions which deviates from the approach this thesis can have in order to be closely comparable with the sectors analyzed and specific taxes are not yet constituted, it won't be included in the regulatory taxes for the Opex evaluation.

Ultimately, regulations from IMO are affecting the TCO analysis of the alternative fuelled ship indirectly with the obligation of incorporating either biofuels blend in with the conventional fuel resulting in higher fuel price or different propulsion system. Regardless, the regulations from the European Union are both going to have a considerable impact on the choice of the fuel of the future but in the context of this analysis ETS forms the main calculations for the EU regulatory taxes.

2.2 The Fuels Involved

Aiming to attain the desired reductions in CO2 emissions, it is essential for the maritime sector to complement the adoption of energy-efficient measures with the incorporation of alternative marine fuels. Even though the transition towards the use of alternative fuels has started seeming like a one way street in the pursue of a more sustainable future, it is no secret that the options are not yet totally mature due to lack of experience and performance data, direct and indirect costs, accessibility and bunkering infrastructure, safety and specific crew training reasons as well as technical barriers originated from fuel properties such as energy density and their restrictions. In the present thesis the alternative fuels that were discussed are the conventional VLSFO /drop-in Biofuels, LNG/ drop-in Biogas, LPG, Methanol, Ammonia, and Hydrogen. It is important to be mentioned that for marine propulsion, the combustion of all these fuels takes place in dual fuel internal combustion (IC) engines as pilot fuel is also needed to be injected in the combustion chamber for the ignition of the gas for every alternative fuel engine involved except of course for the case of conventional fuelled vessel by VLSFO/MGO and biofuels/MGO. It should be mentioned, that in the cases of VLSFO and LNG the idea of drop-in biofuel and drop-in biogas refers to the utilization of the alternative fuel without requiring any major modification to the dual fuel engines or systems for their smooth operation thus they can be used simultaneously as a percentage of the fuel to lower the ship's emissions.

Below a more comprehensive review of each of the fuels above is presented aiming for a better understanding of their properties that were closely associated with most of the aspects that were discussed in the thesis.

2.2.1 Very Low Sulfur Fuel Oil / Drop-in biofuels B24 & B30

It was regarded as the basis of the analysis for the comparison of the Total Cost of Ownership calculated for all the alternative fuels involved. VLSFO is a residual marine fuel which is classified in accordance with ISO 8217 which defines the fuels specifications and is produced either through refining processes or blending of heavier fuel oil with distillates. Regarding the use of VLSFO it has become really popular recently in maritime as it has a content of 0.5% in sulphur and its utilization seems appealing as it relieves the shipping companies from the obligation of installing scrubbers to their ships while stocked with a distillate like Marine Gasoil or ULSFO for combustion within Emission Control Areas which were discussed in the 2.1 Regulatory Compliance section. The supply chain of VLSFO is already well developed and the technical background mature as the fuel has been in the industry for some years with a spike in its use after 2020 when it emerged as a solution for compliance with IMO 2020 regulations. The fuel compared to High Sulfur Fuel Oils has a lower viscosity, lower density and a higher net specific energy while keeping cat fines percentages of Al and Si at low levels[22]. Even though it helped limit the sulphur oxide emitted from maritime by 70% since 2020, its combustion is not in compliance with the arising regulations towards near zero Greenhouse Gases emissions.

The fuel is assumed to have penetrated deep into the maritime industry the last years resulting in a greater understanding of its characteristics and properties, thus the analysis was focused more on the alternative fuels rather than VLSFO even though the basic concepts were discussed, and the total cost of ownership was calculated also for ships with VLSFO propulsion systems. For the ship using VLSFO, pursuing compliance with a certain CII rating, it was considered useful to utilize drop in biofuels as blend in with whatever this comes with in terms of fuel price. The Internal Combustion Engines used for the calculations of the total fuel consumption are fully compatible with a biofuel blend with VLSFO which is a drop-in fuel and can effectively lower the emissions from combustion of pure VLSFO. The drop-in biofuels mostly used in shipping are B24 and B30 which correspond to 24% and 30% respectively of UCOME (used cooking oil methyl ester) blended with VLSFO.

2.2.2 LNG

LNG is a liquid mixture of several gases, mostly made up of methane (CH_4), whose mass concentration can range from 70 to 99 percent, depending on where the natural gas comes from and of course the way it was produced. Some hydrocarbons that are frequently present in LNG include butane (C_4H_{10}), propane (C_3H_8), and ethane (C_2H_5). There may also be trace amounts of other gases, such as nitrogen (N_2)[23]. Natural Gas in its liquified form is odourless, colourless and has neither corrosive nor toxic characteristics[24]. The volume required for natural gas is decreased to roughly 1/600 of its initial volume after it is liquefied at a temperature of around -162°C. By doing so, the energy density of the gas (MJ/L) is highly increased to even though it still corresponds to approximately 60% of the volumetric energy density of diesel. Under such conditions, LNG is kept in tanks where heat penetration causes boil-off gas (BOG) formation which is one main characteristic of the fuel. The BOG is either re-liquified or consumed by the engines to keep the pressure in the LNG tank within allowable bounds [23].The management of the Boil-Off gas is subject to the IGF Code which considers the methods of consumption, reliquefication, pressure accumulation or cooling as the only acceptable. As the most used alternative fuel currently, it has become quite abundant due to a rise in its production, and its bunkering infrastructure has been developed and is still improving, with more than 200 operational bunkering stations worldwide and fuel readily accessible in the majority of large maritime hubs. The use of the fuel has spread globally in the shipping industry, given that, as of October 2023, approximately 900 vessels in the seas had the capability of operating using LNG and another 900 newbuild had been ordered [25]. Nevertheless, the supply infrastructure is still insufficient compared to the global fleet needs when speaking for catholic adaption. Moreover, it is of great interest and should be noted that LNG, although a promising short-term option as an alternative fuel it isn't regarded as a suitable substitute for the 2050 environmental goals in its initial form mainly due to the high impact it has in global warming because of the methane slip (described below). On the contrary, it can be considered a great transitional alternative towards zero emissions targets while gaining technological knowledge in cleaner non-fossil fuels[24]. It has the potential though of achieving really low emissions that can get close to zero with a shift to biogas by a blending procedure with complete compatibility with LNG as a drop in fuel. Thus, by shifting the percentage of biomethane used together with the natural gas, CO_2 emissions can be minimized and compliance with the selected CII rating attained. A necessity for this to be achieved is the elimination of the methane emissions[26]. BioLNG though has not been given a lot attention in that extend in order to gather data for calculations therefore it was not taken into consideration in the methodology section like B24 and B30 biofuels.

From a greenhouse gas emissions perspective, an LNG-Fuelled vessel has some considerable advantages when compared to the conventional fuel. The table below presents the estimated reduction (%) of GHG Emissions:

Table 2: LNG Fuelled Vessels GHG Emissions Reduction [Data [27]]

Category	Reduction (%)
EEDI	20
CII	20 (approx.)
NO_X	80
SO_X	Net zero
PM	Close to net zero

As presented in the table above, the NO_x emissions are significantly reduced but still compliance with TIER III requirements necessitates the use of either EGR or SCR in the exhaust gas system.

Methane Slip in LNG Engines

An important downside factor to be taken into consideration when dealing with liquified natural gas is the methane slip, particularly now under the prism of regulatory compliance and the EU putting pressure on the shipowners with the EU ETS including also methane (CH_4) emissions from 2026 and on, as mentioned in the 2.1.2 European Union section earlier. The term "methane slip" describes the unburned methane found in the exhaust emissions of internal combustion (IC) engines. The concentration of methane in each case differs significantly depending on the engine load, engine design, and combustion type (Diesel or Otto cycle). Since methane has a higher Global Warming Potential (GWP) than other greenhouse gases (GHGs), it is a main cause for concern. Numerous studies have been conducted on life-cycle greenhouse gas emissions, and the outcome is usually presented on a 20 or 100-year GWP basis. On a 20-year basis, methane emissions are predicted to be 84 times more severe than CO_2, and on a 100-year basis, they are expected to be 28 times more intense[23].

Methane slip can be caused by three main factors:

- Incomplete combustion: This usually happens when the phenomenon of flame quenching takes place near the walls of the cylinder which are the coldest parts during engine operation resulting in flame extinguishing while in lower temperature and pressure. At low engine loads the phenomenon is more intense and the methane slippage higher. Additionally, incomplete combustion can be noted in both Internal combustion engine cycles, Diesel and Otto but is more intense and noticeable in the latter as it corresponds to lower pressure gas injection.
- Scavenging leakage and losses: It occurs when the mixture of methane and air flows through the exhaust as it happens when the fuel is injected into the chamber before the exhaust valves are closed. This is affected by the timing of fuel injection and of course the percentage of successful scavenging during the simultaneous purging of the exhaust gas in two stroke engines which are the ones involved.
- Trapped methane within crevices of the combustion chamber: The unavoidable existence of crevices or dead volumes in general inside the engines chamber highly increase the chances of the fuel not being fully burnt and therefore resulting in a possible escape of methane through the exhaust.

It is interesting though that the amount of methane leakage is greatly linked with the technologies used from the engines manufacturers as it was discussed later in the 2.3.1 Main Engines section.

2.2.3 LPG

Liquified Petroleum Gas is mostly a mixture of propane and butane with a low content of other light hydrocarbons in a liquid form. Its production is mainly focused on the separation of these lighter hydrocarbons from the heavier ones during the production of natural gas. During the natural gas extraction roughly 10% of its volume is a mixture of propane, butane and isobutane which reflects the composition of LPG. This method corresponds to 60% of the total LPG production. The other 40% is a result of oil refining as it is a co-product during the processes of atmospheric distillation, cracking and reforming[28].

The liquification of the fuel, which is in gaseous state at normal conditions, happens at relatively low pressure in the range of 2 to 5 atm and regular temperature. The systems used for LPG are usually the same as LNG with some changes depending on the circumstances. The heat value ranging 46-51 MJ/kg measuring the energy density of LPG is higher than other petroleum products and as an alternative is regarded more promising than LNG in terms of storage facilities and bunkering infrastructure but still quite limited[24], [29]. It has a low flash point which raises safety concerns and measures that have to be taken on ship, a downside which is supplemented by the fact that LPG has a higher density than air and it's heavier leading to difficulties on leakage detection[24].

Regarding the environmental advantages from the use of LPG as a maritime fuel, its low C/H ratio leads to a lower CO_2 profile with up to 18% lower emissions than conventional fuel. Additionally, the content of sulfur in LPG reaches almost net-zero ensuring in that way that this is going to meet all the sulfur emission requirement from SECAs even with stricter modifications on the regulation. Furthermore, NO_x emissions are decreased by 10 -20 % and the particulate matter (PM) emissions virtually comes to zero. The contribution of LPG as a marine fuel in the EEDI is in the region of 15% as it's the case for CII but can vary a lot according to the technologies used on ship [30]. The following table gathers the anticipated environmental advantages of LPG as mentioned for LNG:

Table 3: LPG Fuelled Vessels GHG Emissions Reduction

Category	Reduction (%)
EEDI	15 (can vary)
CII	15 (can vary)
NO_X	10-20
SO_X	Net zero
PM	Close to net zero

In general, when compared to LNG, LPG has the benefit of being more widely available with more terminals and supply points, having less expensive infrastructure, as well as more cost-effective installation. It is regarded again as a transitional fuel towards 2050 regulations.

2.2.4 Methanol

In the continuous journey of the maritime sector towards a carbon free future, methanol has been regarded as an alternative fuel that can be used from marine engines. Also referred to as methyl alcohol, methanol (CH3OH) is a clear, light and simple form of alcohol that has flammable characteristics. The two large categories associated with methanol's production are fossil based and renewable methanol. In a further extent these can be classified in accordance with the methods of production as followed:

- Brown methanol: Produced from coal and has a carbon intensity which is 5 times higher than grey methanol.
- Grey methanol: Produced from natural gas, a fossil fuel feedstock.
- Blue methanol: Made using carbon capture technology with blue hydrogen meaning that hydrogen is produced from natural gas reforming and carbon capture and storage.
- Green methanol: Made either from biomass or CO_2 that has been captured from renewable sources in combination with green hydrogen which is produced by renewable electricity[31].

The problem stands on the fact that most of methanol produced today comes from natural gas resulting in a high total GHG emissions profile from well to wake with the CO_2 impact equal or even higher than diesel. This, on the extend of this research is an issue when taking into consideration the FuelEU regulation which is going to consider not only the tank to wake emissions but also the origins of the fuel the shipping company has chosen. The above indicates facing 2050 regulations blue and mostly green methanol are the real alternatives. From a tank to wake perspective though methanol when compared to a conventional marine fuel offers a 7% reduction of CO_2 emissions, almost net zero SO_X emissions (more than 99% of VLSFO) and a cut of NO_x by up to 60% while the potential of green methanol having a carbon free impact is very promising [32].

Methanol has a considerably low volumetric energy density (approx.15-16 MJ/L) with a high stoichiometric fuel/air ratio and a lower viscosity than diesel. One main advantage of CH_3OH is the fact that it remains in liquid form while in ambient temperature and pressure which encourages easier transportation and storage although some modifications are needed (discussed later) while this also relieves from the need of technologically advanced fuel injection systems and pumps[24],[33]. On the other hand, it requires additional precautions to achieve optimal combustion and prevent seal leaks as a consequence of its extremely low viscosity when compared to conventional fuels like HFO and diesel. This feature also raises the need for better lubrication inside the combustion chamber. Methanol has a low flashpoint of 11-12^{o} C which corresponds to a lower-level temperature than accepted by SOLAS resulting in additional necessary adjustments. Thus, it is regulated by International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IMO IGF) on low flashpoint fuels which stipulates many of the essential safety measures on the use of methanol aboard ships [33].Additionally, the fuel is regarded as volatile and has a flammable nature but still corresponds to approximately half of the volatility of LPG. It's important to be mentioned that methanol is both corrosive and toxic on inhalation, exposure or skin contact, but it is suggested that from a technical perspective this hasn't resulted in any major issue as the toxicity level is rather low, still though proper ventilation system implementation is a necessity. Similar to LPG, Methanol is also heavier than air so in case of leakage the fuel will reach the lowest levels but its dilution in water is quick and the dangerous concentration levels are avoided. Nevertheless, further safety precautions are needed, and compatibility must be taken into account when choosing materials for tank coatings, pipework, seals, and other components due to its corrosiveness[34], [35].

2.2.5 Ammonia

Ammonia (NH_3) has recently made its way into the shipping industry and has gained great interest as a possible solution towards net zero or close to zero carbon emissions. It is a compound of Nitrogen (N_2) and hydrogen (H_2) with N_2 being widely available and able to be captured from the atmosphere. Ammonia is categorised depending on the way it is produced as followed:

- Brown (or Grey) Ammonia: It's currently representing more than 60% of the global production of ammonia and the most conventional method for this type is the Haber-Bosch process. It is though connected with high CO_2 emissions from well-to-wake. In this case the nitrogen is originated from the atmosphere and the hydrogen from natural gas or in some situations from coal or oil. The most typical source for hydrogen generation is considered to be steam methane reforming.
- Blue Ammonia: It still has a hydrocarbon feedstock origin but for this type, carbon capture and storage technology is used cutting the overall emissions and using in total less energy for the production.
- Green Ammonia: It's the only type promoting zero carbon emissions from renewable feedstocks. It is mostly generated by water electrolysis with green energy and hydrogen production and is the most promising type of ammonia given that it has no CO_2 impact from well to wake. It is though the most expensive type to be produced and is currently available in really low amounts. In order to be considered viable as a solution, great investments and unified efforts have to be made. [36]

The fuel is a colourless gas at ambient conditions with a distinctive odour and it is liquified at -33^o C which is the temperature it is transported. Its energy density is 12.9 MJ/L which is three times lower than VLSFO (35-42 MJ/L) thus higher volume is needed reducing space for onboard cargo transportation although it has a very high heat of vaporization ensuring little loss and long sea voyages. From a risk of explosion or fire perspective, it is safer than other fuels containing hydrocarbons as it has a high combustion temperature although relative safety measures have to be taken into account. The most significant safety issue that raises concern about the feasibility of adapting ammonia as a fuel for marine engines is the high toxicity of it even in low concentrations and can be threating for human life in exposure. Additionally, it has a corrosive behaviour which have to be kept in mind for storage tanks and fuel systems. Thus, it is classified as a hazardous substance and in case of leakage it can have severe impacts also for sea life that can last for several years. It is a necessity that safety practises against leakage have to be implemented and accurate handling of the fuel with ventilation systems and protective gear are required[37], [38].

From a Greenhouse Gases emissions perspective ammonia has a great advantage over other alternative fuels when dealing with tank to wake emissions due to its absence of molecular carbon. However, for a more holistic environmental approach only green ammonia should be considered as beneficial. Ammonia, then, has a net zero CO_2 impact and the only carbon emissions that have to be calculated are the ones from the pilot conventional fuel used. Sulfur oxides, carbon monoxide and particulate matter are also not emitted due to ammonia's nature. Despite that, ammonia can produce nitrous oxide emissions (N_2O) which is even more hazardous than methane and on a 100-year basis it was found to be 265 times more harmful than CO_2. Emissions are to be highly affected by the engine's technology, design and combustion approach as a complete combustion will minimize N_2O slip and NO_x emitted will have to get treated with a SCR technology with the twist that, instead of urea, it's suggested that ammonia is possible to be injected as the catalytic agent as it is presented in Figure 9 [39][38].

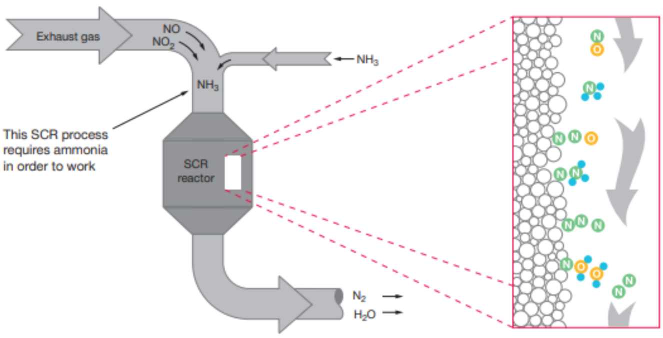

Figure 9: Selective Catalytic reduction for ammonia dual fuelled engines [39]

2.2.6 Liquified Hydrogen

Hydrogen (H_2) is clean, abundant as an element in nature and is the most basic form of fuel (when processed chemically and extracted) which can be produced by both fossil fuels and alternative resources. It can be categorised mainly in three big groups according to the production process even though there are also other categories as presented below:

- Grey hydrogen: Representing the most popular form of hydrogen, it is also the most cost efficient and it's produced from natural gas with the steam reforming process.

Although hydrogen does not emit any greenhouse gases from its combustion, via this method carbon emissions are emitted into the atmosphere.

- Blue hydrogen: Like ammonia, for the production of blue hydrogen the same process needed for grey hydrogen is used with the difference of carbon capture and storage technology utilization. Blue hydrogen generates greenhouses gases which are stored and need further treatment but the well to wake emissions are reduced significantly and combustion emissions are net zero.
- Green hydrogen: For this form of hydrogen, clean renewable sources are utilized during the production through the water electrolysis method with energy coming from the wind or sun. Water then is separated to hydrogen and oxygen and in the meantime no emissions are produced. Green hydrogen is the most sustainable form and can be considered emissions-free[40]. It is suggested that carbon emissions have the potential of dropping down by 6 gigatons annually from green hydrogen usage[41]. The major issue for this type though is the significant cost of the process for the production of even a small amount of the fuel making it a huge challenge to make it a feasible maritime fuel.

The above are the main three categories for fuel but the following can also be found:

- Black and brown hydrogen: Made from gasification of coal. This form corresponds to the highest emissions.
- Red, pink or purple hydrogen: Produced by electrolysis from nuclear power [40].
- Turquoise Hydrogen: Production via the pyrolysis of fossil fuels while the CO_2 which is formed is solid.

Hydrogen has a low flash point and a wide flammability range leading to ignition of a greater part of the gas but also raising some safety concerns. It is also possible to be blended with other fuels and stand for a percentage of the mixture if needed. Additionally, the boiling point reaches the extremely low temperature of -253° C making liquified hydrogen's transportation and storage a really challenging matter to be encountered. If not cooled down, for its liquification a pressure in the region of 700 bar is required. Keeping the fuel at such cryogenic conditions demands a tremendous amount of energy and boil-off is to be considered inevitable. It has a low volumetric energy density which affects the range of the ship or the size of the storage tanks. When compared to ammonia, hydrogen has a lower volumetric energy density and much lower boiling point but contrary to that drawback, hydrogen is not toxic providing a safety advantage[42].

2.2.7 Aggregated Fuel Properties

In the tables and figures below an aggregated analysis of all the fuel properties was made with data from citation. In Table 4: Volumetric Energy Density of Each Fuel, Table 7 and Table 8 data for MGO was also provided as it was necessary as a main fuel in ECAs and was also used as a pilot fuel in all the gensets.

Volumetric Energy Density

Energy density refers to the amount of energy contained within a given quantity of the fuel. Below the volumetric energy density is presented (in MJ/L) in order to be comparable with the tanks' volume of each vessel and provide a deeper understanding for the needed size of the tanks onboard in order to have a similar voyage range. The data are shown in Table 4: Volumetric Energy Density of Each Fuel and Figure 10: Volumetric Energy Density of The Fuels Involved as follows:

Table 4: Volumetric Energy Density of Each Fuel

Fuel	Volumetric Energy Density (MJ/L)
VLSFO	35-42 (38)
MGO	36.6
B24	36.7
B30	36.4
LNG	22.2
Methanol	15.4
LPG	25.3 (propane) / 27.7 (butane)
Ammonia	12.9
Hydrogen (liquid)	8.5
Note: MGO was presented for ECAs utilization and gensets' pilot fuel as analyzed later	

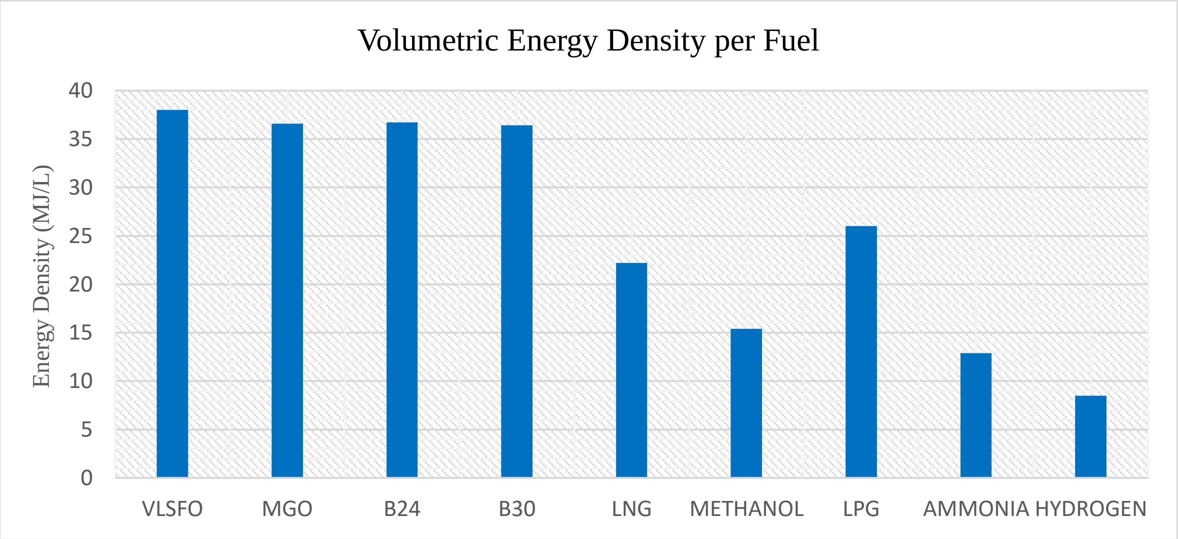

Figure 10: Volumetric Energy Density of The Fuels Involved

Flammability limits

As a fuel's property, they refer to the lower and upper concentration of the fuel in volume percentage in the air within which the mixture can be considered flammable limits and are strongly linked to the safety measures that have to be taken for every fuel and engine. Below the lower limit the concentration of the fuel in the air is not sufficient for combustion and above the upper limit its too high for the mixture's ignition. The chances of igniting the fuel and the consequent dangers and safety concerns are as dependent to the range of the limits as to the lower flammability limit of each fuel. That yields greater danger in a wider flammability range but also in a lower limit since it is possible to ignite even with a small concentration in air. The limits are shown in Table 5 and Figure 11.

Table 5: Flammability Limits of Each Fuel

Fuel	Flammability Limit (vol % in air)
Conventional (VLSFO, biofuels)	0.7-5
LNG	4-15
Methanol	6-36
LPG	2-9.5
Ammonia	15-28
Hydrogen	4-75

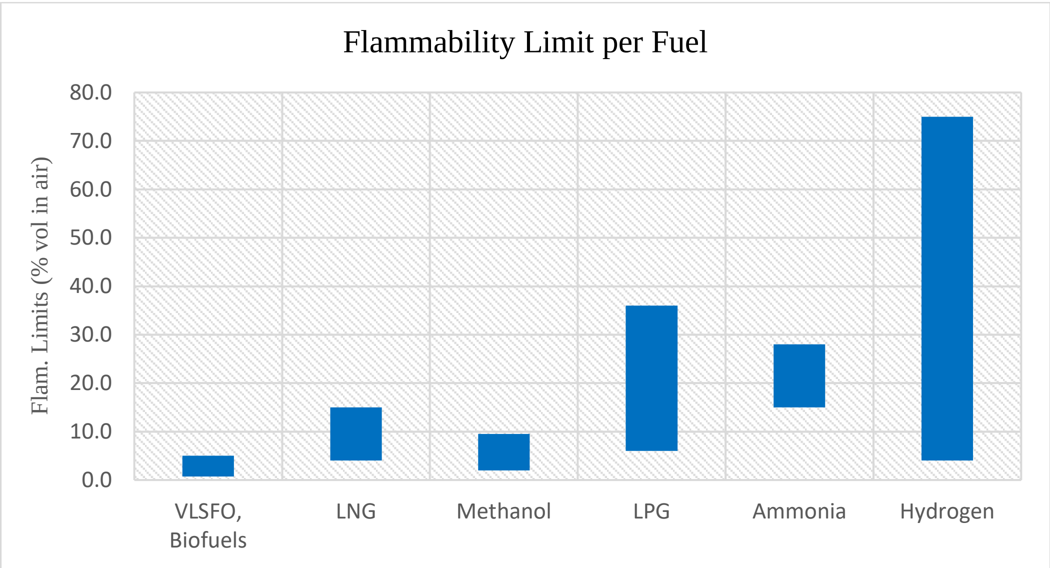

Figure 11: Flammability Limits (vol% in air) of Each Fuel

As it can be observed, hydrogen has a very wide range of lower and upper limits raising some concerns about safety while VLSFO is flammable at a really low concentration.

Liquefaction & Storage Temperature

The temperature at which every fuel can be liquified and therefore increase its volumetric density and utilize storage more efficiently is shown in Table 6 and is also indicating the storage temperature that the tanks have to withstand.

Table 6: Liquefaction & Storage Temperature

Fuel	Liquefaction Temperature (ºC) at atmospheric pressure
VLSFO	Ambient
LNG	-162
Methanol	Ambient
LPG	-42
Ammonia	-33
Hydrogen	-253

However, in the table above the temperature of fuel storage may vary as pressurised tanks are also used except for low temperatures to maintain the fuel in liquid form as it is described in section 2.3.5 Fuel Storage Tanks.

Fuel Density at Liquefaction Temperature

In Table 7 the density of all the fuels that were involved in this study were gathered and presented. For the biofuels the density of both VLSFO and the density of UCOME (880 kg/m^3) were used with the respective proportions for B24 and B30. Additionally, although MGO was not used as a whole concept, it was presented since it was the fuel used within ECAs instead of the conventional fuels and as a pilot fuel for all the gensets considered.

Table 7: Fuel Density

Fuel	Density [kg/m^3 or g/L]
VLSFO	936
MGO	860
B24	923

B30	919
LNG	465
Methanol	793
LPG	540
Ammonia	682
L.Hydrogen	70.85

Lower Heating Value (LHV) of Fuels

Lower Heating Value was a very important aspect as it shows the amount of heat or energy released from the combustion of a specific quantity of fuel. It was also used for proportional estimations regarding the Main Engine's Fuel Consumption of ammonia and LH2 data of which were not openly available. Additionally, it was used for calculations regarding the genset's fuel consumption since this part had a qualitative approach. The LHV of the fuels that are involved were shown Table 8.

The LHV was calculated using the following Equation 6:

$$\boldsymbol{LHV}\ [\boldsymbol{MJ/kg}] = \frac{\boldsymbol{Volumetric\ Energy\ Density}\ [MJ/L]}{\boldsymbol{Fuel\ Density}\ [kg/L]} \quad \textbf{(6)}$$

Table 8: LHV of Fuels

Fuel	LHV [MJ/kg]
VLSFO	41.0
MGO	42.6
B24	39.8
B30	39.6
LNG	47.7
Methanol	19.4
LPG	48.1
Ammonia	18.9
L.Hydrogen	120.0

Flash Point

Presenting the lowest temperature at which the vapors of the fuel can be ignited in existence of a flame spark, it's very decisive in safety matters and is taken into consideration when designing systems against explosion. The flash point for every case is presented in Table 9 below:

Table 9: Flash Point of Fuels

Fuel	Flash Point (ºC)
VLSFO	61
LNG	-188
Methanol	11
LPG	-105
Ammonia	132
Hydrogen	-253

As presented, cryogenic Hydrogen and LNG have the worst flashpoint conditions and are considered of great hazard thus measures for explosion prevention are taken with incorporated ventilation systems and leakage detection as described later.

Toxicity

Finally, an important property of each fuel is whether they are considered toxic both for the crew and for marine life and the data that were discussed in section 2.2 The Fuels Involved are gathered as follows in Table 10:

Table 10: Toxicity of the Fuels

Fuel	Toxicity
VLSFO	-
LNG	-
Methanol	Toxic
LPG	-
Ammonia	Highly Toxic
Hydrogen (Liquid)	-

As ammonia and in a lower degree methanol are toxic and exposure can result in severe health consequences, realize into the atmosphere and human inhalation cannot be risked. Thus, venting of the fuels in case of any pressure difference involved is not an option and the safety systems are designed respectively for that reason as it is described in 2.3.4 Safety auxiliary systems.

2.3 Specific Technical Details

2.3.1 Main Engines

In the context of this thesis an assumption was made regarding the operation of the main engines. More specifically, a usage of the main engine at a load of 75% of the maximum continuous power (MCR) was implemented for the estimation of the consumption.

When dealing with the maritime sector and large ocean-going vessels, a two-stroke main engine for propulsion is quite the one-way solution. High power-to-weight ratio due to their large stroke providing high power compared to their size and weight, their capability to burn lower grade fuels and little demand for maintenance compared to a four-stroke engine given that the ship's engine is working constantly and for weeks or months in a row are key components for the preference of two stroke engines. The combustion cycle which is also dominant in use is diesel as it has a higher efficiency than Otto cycle even though the Otto cycle has also made its way into marine main engines with the low-pressure Gas engines for LNG combustion. The focus was turned mostly into MAN Energy Solutions and WIN GD manufacturers. All the engines involved in this analysis were capable of Dual Fuel operation. In general, two-stroke engines using gaseous or liquid alternative fuels function in dual fuel mode, with the alternative fuel which is the primary fuel providing the majority of the energy and a small quantity of liquid conventional fuel referred to as pilot fuel serving as the source of ignition. Every alternative fuel engine needs a different amount of pilot fuel in order to be ignited and this affects the fuel cost and the emissions produced from the combustion. However, these engines can have three distinct operational methods:

- Typical dual fuel operation where the alternative fuel is injected at a percentage of 95 to 98% by volume and the remaining 2-5 % comes from the pilot fuel, which is a conventional fuel either residual or distillate. The pilot fuel functions as the initial source of ignition for the combustion.
- A mixture of both conventional and alternative fuel is used. This is precisely representing the operation with drop-in biofuels blended in with VLSFO and drop-in biogas/biomethane blended in with the natural gas injected when converted from LNG.
- The last method of operating a dual fuel marine engine is the fuel oil mode, entirely by using only the conventional fuel when needed in case of an alternative system's breakdown when the options for propulsion are inevitably limited.

The approach that is followed by every engine for the evaluated fuels is presented aggregated below:

Conventional

The conventional VLSFO and drop-in biofuel are combusted into dual fuel two stroke engines either by the VLSFO on its own or by blending both in a different percentage each. The diesel cycle is employed for the engines design. Injection of pure liquid fuel oil is followed by its vaporization during the compression and the following power stroke shortly after its admission.

LNG

At this point it should be highlighted that LNG is an alternative fuel that is also used with the Otto cycle in dual fuel engines. Regarding the main engines used for LNG combustion, two different gas mode combustion concepts are in the spotlight.

- low-pressure (LP) gas engines that use the Otto cycle.
- high-pressure (HP) gas engines that use the Diesel cycle.

LNG is combusted in dual fuel engines with two different concepts, both involving the conversion of the LNG to gaseous form before injection. In both cases pilot liquid conventional fuel injection is needed for the ignition of the gas fuel. The first one involves the high-pressure injection of the gas after the pilot fuel is injected just before the top dead center for the initiation of the combustion. In the high-pressure engines the Diesel combustion process is employed when using both fuel oil and gaseous LNG mode. The second concept is a low-pressure admission of gas together with air and a spark ignition with the utilization of pilot fuel injection. In this method the otto cycle is implemented. The percentage that the LNG can be blended in with drop-in biomethane (biogas) is of no significant matter for the choice of the engine. Additionally, whether a Diesel or an Otto engine is installed in the ship is directly linked with the methane emissions into the environment meaning that a high pressure diesel engine yields a much lower methane slip than the low pressure Otto engines which emit a major amount of direct methane slip. On the contrary high-pressure engines correspond to a higher capital cost of purchase due to their more demanding auxiliary systems as it is analyzed in the 2.3.3 Engine’s Auxiliary Supply Systems.

LPG

The main engines involved for LPG combustion are dual fuel and two stroke engines with the straight injection of LPG in liquid state in the correct temperature and pressure just after the conventional pilot fuel in liquid form has initiated the ignition of the mixture. The main engine family used for maritime and LPG-Fuelled large ocean ships is the MAN ME-LGIP series 14 or 15 offered by MAN which is as mentioned a diesel cycle two-stroke engine.

Methanol

Regarding the main engines for methanol combustion, once more a dual fuel combustion engine is used with a need for pilot conventional fuel at the range of 5%. A benefit of methanol is that it can be used as a fuel also in LNG dual fuel engines as both fuels are subject to the IGF code and they share the same property of a low cetane number needing a cetane enhancer for ignition (typically diesel)[33]. Likewise, an EGR or SCR system must be installed for TIER III compliance for NO_x emissions. Methanol is injected in the combustion chamber in liquid form which is the state it is stored at in ambient conditions and the diesel principles are used. The sequence of pilot fuel injection should be such that ignition has been activated prior to the methanol admission. Inside the combustion chamber a much cleaner lubrication environment is promoted but the engine wear is much more pronounced compared to the conventional fuel.

Ammonia

Ammonia engines have not yet been commercially available and there are not any respective engine running on an oceanic vessel, however engine development has started gaining interest from manufactures like MAN Energy Solutions and WinGD which expect to deliver the first dual-fuel engines running on ammonia in 2024 and 2025 respectively with on-vessel operation not before 2026. For its combustion, as ammonia has a low cetane number, an external ignition energy is needed to be given by the pilot fuel which is the only source for the carbon-related emissions. Nevertheless, except for a relatively high amount of pilot fuel needed due to ammonia's difficulty to ignite which is even higher than methanol-emphasis is also put on the engine's design in a way of favoring prevention of any N_2H emissions in the air.

Hydrogen

Hydrogen dual fuel engines are entering the industry with some differences compared to the other alternative fuel in their approach but also similarities with the LNG gas injection engines. A dual fuel 4-stroke marine engine has been recently developed from MAN-Energy-Solutions with the Otto cycle incorporating spark ignition and a supply of gas at a low-pressure within a range of 3-16 bar with 5 bar being the most common. Ignition is ensured by the injection of pilot fuel (usually VLSFO or MGO) and the hydrogen is combusted pre-mixed with air, thus air/fuel ratio is important to be controlled for prevention of knocking in the chamber. Lubrication is regarded as an issue to overcome in these engines. It should be noted that like the LNG Otto dual fuel LP gas engine, the diesel cycle is utilised when changing into fuel oil mode in case of an emergency need. This approach is currently implemented in limited range applications but is the most promising for further implementation and as a fuel for auxiliary gensets. The first approved such engine was developed from ABC (Anglo Belgian Corporation).

An option that has also been considered for hydrogen combustion is similar to the HP diesel gas injection of LNG providing a stable maximum engine output and avoidance of knocking. However, the necessity for a high injection pressure generation means a fuel supply system with cryogenic pumps able to deal with -253 ºC and the total cost of the supply system can be 5-10 times higher than the Otto LP system and much higher comparably than the HP LNG system, making it ultimately difficult to efficiently incorporate it in maritime. Thus, if dual fuel engines are to be selected for hydrogen combustion in maritime, the Otto Low-Pressure engines seem to be more dominant in the near future but it is still unclear whether a similar to LNG HP approach will be utilized [43].

Another technical approach for hydrogen combustion is the utilization of Fuel Cells in combination with the LH storage tank, the pressure build-up unit (PBU) and the vaporizer prior to distribution of the gaseous hydrogen into the fuel cell. The fuel-cells concept is being more popular and promising for short range voyages. The procedure distributing hydrogen to the fuel cell can be shown in Figure 12 [44]. However, in the framework of this thesis, fuel cell concept was not further discussed.

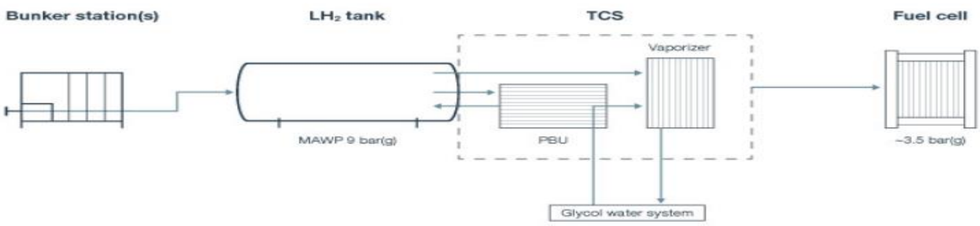

Figure 12: Hydrogen Fuel Cell Concept

Additionally, a ready for industrial use concept from manufacturers MAN Energy Solutions and Wartsila involves hydrogen blended in a percentage of 25% by volume with methane withing the gas-fuelled engines improving efficiency and limiting the methane slip from LNG. However, this is quite limited in marine applications for the moment.

2.3.2 Generator Sets

Marine auxiliary generators have not yet been fully developed for the utilization of alternative fuels. Up to date, the only alternative fuels that are ready for use in marine gensets are methanol and liquified natural gas. Biofuel derived from renewable sources can be also used as a drop in fuel blended with the conventional fuel. The conventional fuels which are used in the marine generator sets are mostly distillates divided into the following four classes: DMA, DMZ, DMX and DMB. They have the capacity though to be operated with heavier residual fuels. Two popular liquid fuels used up to 2024 for this purpose are MGO produced only from distillates and MDO, a distillate blended with HFO. These can be considered of ISO grade DMA and DMB respectfully. For the incorporation of alternative fuels in the continuously developing market towards defossilization, dual fuel and four strokes marine generator sets have started to emerge from manufacturers the past years and gain recognition among shipowners. The two distinct operations of these four stroke sets are gas mode and liquid fuel mode. When using the former, natural gas and biogas are implemented with a percentage of pilot fuel (usually MGO) injection which initiates the ignition, while, on the latter, biofuels can be used except for the conventional VLSFO, MGO or MDO with the diesel cycle. Methanol is also injected in liquid mode with the necessary pilot fuel ignition. As far as the regulation compliance is concerned, IMO Tier III is achieved on gas operation without any modifications however in fuel oil mode only Tier II is reached, and the SCR utilization is needed for Tier III NO_X regulation adherence[45].

Regarding the LNG four stroke gensets, they have the capacity of combusting the boil-off gases from the LNG vaporization inside the tank due to an inevitable pressure increase or temperature loss which is a typical efficient method instead of only using a vaporizer for the conversion of the liquid state to gaseous. As for the methanol generators, the systems used are similar to the conventional since the fuel’s properties are not that different and such gensets can also run on biofuels and conventional heavier fuel oils as they are all injected in liquid form [46]. Finally, it is soon expected that ammonia and liquified hydrogen (LH2) will also be available for marine genset operation.

2.3.3 Engine’s Auxiliary Supply Systems

A very significant aspect for the calculation of a total cost of ownership is undoubtedly all the peripherical systems for the injection, pumping, heating and preservation of the fuel in the needed pressure. When looking at the fuels involved, some similarities can be observed in the systems according to the state at which they are injected at. Hence, the systems for liquid injection i.e. conventional, methanol, LPG and ammonia follow the same concept with some different components needed for each fuel. That is also the case for gas injection including the two distinct methods for LNG combustion (Low and High pressure) as well as hydrogen when not dealt with Fuel Cells. Below, the most important parts for every concept were developed helping eventually for a better understanding of each system’s cost in the TCO analysis.

Liquid Injection Systems

Conventional Fuel

When dealing with the conventional fuel system, the main system' parts and cylinder supply procedure are presented as follows. The fuel oil is pumped from the fuel tank to the settling tank where it is heated, then centrifugally cleaned, and led to the daily service tank. A supply pump increases the pressure of the fuel roughly at 4 bar preserving the fuel in liquid state in the venting box which is responsible for releasing any gases present. A circulating pump then drives the fuel to the heater and a full flow filter at around 10 bar. One main component of the entire system is the Hydraulic Cylinder Unit (HCU) which in turn, contains the electronically controlled pressure booster for injecting the fuel and the actuator for controlling the exhaust valve. A constant pressure of the injection pumps at approximately 7-8 bar is ensured by a spring-loaded overflow valve in the fuel oil system. Additionally, the Cylinder Control Unit (CCU) is in charge of measuring the time in between injection and exhaust valve activation. When in need of using a different low-viscosity fuel like MDO or MGO, as it could be the case for gensets then the installation of a cooler is also needed ensuring a minimum of 2 cSt viscosity at engine inlet.

As far as the other liquid injection systems are concerned regarding LPG, methanol and ammonia, the systems follow a quite similar approach as the fuel oil injection. The supply system in each case displays similarities on the design with the conventional oil system with the main difference on the pumping pressure.

LPG

When dealing with LPG, which is regarded as a significantly low-flashpoint fuel, in dual fuel engines the main process for the main supply (non-pilot fuel) involves pumping the liquid petroleum gas from the low-flashpoint fuel supply system (LFSS) towards the main supply pipe where it is driven through the fuel valve train (FVT) which controls the LPG flow prior to cylinder injection and can safely isolate the engine. The FVT is preferably installed outside of the engine room but as close as possible to the main engine. The purpose of the LFSS is to prepare the fuel in terms of temperature, pressure, and purity before injection. The supply pressure is at 53 bar with a margin of ± 2 bar and operating pressure at 50 bar hence two appropriate pumps of initially low and thereafter higher pressure are used for that reason. In order to secure liquid state of the fuel, a heater/cooler is also required and utilized for preserving a certain temperature in the supply process. The number of heaters and coolers used, and the type of pumps may differ according to the manufacturer[47]. Additionally, the supply pipes for LPG are insulated and heat traced. The pilot fuel is injected with the conventional and traditional fuel oil system and the same principle explained above is followed.

Methanol

Methanol supply systems are very comparable to LPG's and some dual fuel engines from manufacturers like MAN have the capacity of running on both with a modification on the supply pressure which lies on 13 bar with a margin of ± 0.5 bar instead of 53 bar [48]. Given it has as well, a low flashpoint, monitoring of ventilation and detection systems of gas leakage are also required in combination of an implemented automatic shutdown in case of breakdown and an overfill alarm[33]. While the Low-flashpoint fuel supply system and the fuel valve train are kept the same as in LPG concept, a main difference is that there is a return piping which leads to the service tank. The methanol tank is split into two compartments, one for the supply to the engine and one for the return of the unused fuel during purging of methanol pipes. As the returned methanol brings with it a non-negligible amount of sealing oil, a drain valve is used for the removal of it and then methanol can be used[49]. In a minor reference about the methanol fueled gensets, the system for injection that was developed by MAN was the port fuel injection system (PFI) which dropped down the costs and made the procedure quite simplified. The process involves a nozzle which is injecting methanol in its liquid form outside of the combustion chamber promoting an easy installation and replacement [50].

Ammonia

Ammonia auxiliary systems similarly incorporate a Fuel Valve Train (FVT) as the connection between the auxiliary system and the main engine providing isolation of these two when needed. A nitrogen system for purging the engine, a recirculation system in order to prevent existence of ammonia in two phases which recirculates ammonia that was heated in the combustion chamber and returns it to the fuel storage tanks after separating any leftover oil from the injection valves and traces of nitrogen. The fuel supply system doesn't include any low flashpoint consideration like LPG and partially methanol since ammonia has the highest flashpoint (132^{o} C) of all. The supply from the tanks involves pumping the fuel with a high-pressure system at 80 bar which then passes through a heat exchanger and a filter for capture of possible impurities. However, the main difference that separates the ammonia system from LPG and Methanol is its handling and capture systems towards safety as described in the 2.3.4 Safety auxiliary systems section.

Gas Injection Systems

LNG

LNG, in order to be supplied and fed into the engine, must turn into gaseous state through a regasification process either for a high pressure or a low-pressure engine. The Fuel Gas Supply System (FGSS) in this case consists of a cryogenic high-pressure pump and a vaporiser and has the function of delivering the fuel to the Gas Valve Train (GVT). The configuration of the FGSS may vary depending on the manufacturer and the shipyard. Cryogenic submerged pumps (booster pumps) are needed in the storage tanks delivering the fuel to the FGSS which with the high-pressure pump raises the fuel pressure at 300 bar or approximately 16 bar for the low-pressure system and then delivers the LNG to the vaporiser for the gasification process. The function of the vaporizer is based on a heat exchanger through a plain heat increase method[51], [52].

Regarding the high-pressure system which is the most expensive due to tis technical characteristics, a closed glycol circulation system with an incorporated heat exchanger, a HP circulation pump and a gas vaporiser are used. A mixture of glycol and water acts as the heating unit and recirculates into the exchanger. The vaporizer unit is one of the most expensive parts of the FGSS and significantly increases the TCO for an LNG high-pressure engine. The glycol/water system and the high-pressure vaporiser are presented in Figure 13: Vaporizer and glycol/water recirculation for High Pressure LNG below:

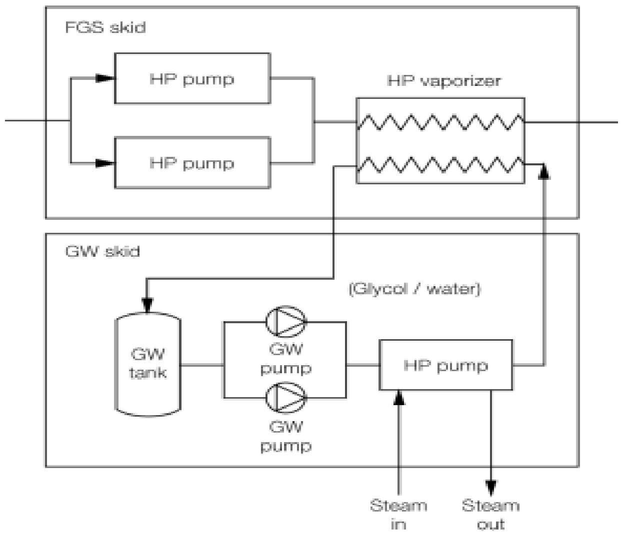

Figure 13: Vaporizer and glycol/water recirculation for High Pressure LNG [51]

When the fuel is gasified it can then be delivered to the Gas Valve Train (GVT) which, as the FVT in the liquid injection systems, isolates the auxiliary systems from the engine and delivers the gas to each cylinder for injection. The GVT for the gensets (one for each) delivers the gas at a pressure of 6 bar[51].

Boil-off gas can either be delivered and combusted straight from the main engine and gensets passing only through a BOG compressor or, if a re-liquifaction system is installed, any excess BOG can be returned into the storage tank and reused ensuring that the pressure in the FGSS remains withing acceptable limits. In this case heat exchangers and condensers are needed. BOG from LNG has a different chemical composition from the initial bunkered liquified fuel with a lower methane number resulting in the so-called “ageing” of LNG. Installing a liquefaction system ensures that the fuel composition will be kept as close to the initial composition as possible, limiting the ageing process. However, obviously it raises the capital expenditures for acquisition and installation of a more complex system[52].

Hydrogen

Regarding hydrogen combustion and auxiliary systems, only internal combustion engines were taken into consideration within this analysis even though the data available are in a preliminary level.

The auxiliary systems for the high-pressure diesel-cycle hydrogen engine are very similar to the LNG HP systems with the difference that the pump which drives the fuel to the heat exchanger has to be capable of dealing with lower cryogenic temperatures at -253 ºC.

For the Otto cycle and 4 stroke hydrogen engine the fuel supply system is simpler and less expensive as the pressure increase need is low at approximately 5 bar. Other aspects that differ from an LNG dual fuel engine refer to their safety system as described in 2.3.4 Safety auxiliary systems where the two concepts of the 2 stroke and 4 stroke engine are presented.

2.3.4 Safety auxiliary systems

The safety requirements are greatly influenced and formed by IMO with SOLAS International Convention, classification societies (IACS), Flag State Administrations and Port State Control. In this section, the safety auxiliary systems were divided into two main categories, liquid injection systems and gas injection systems due to the similarities they displayed.

Liquid Injection Fuels

The conventional fuel, as it lacks toxic features, has no need for cryogenic handling equipment and the global utilization in marine engine and technical knowledge is at the highest level, in terms of safety systems, the cost is considered to be at a base point estimated more precisely from interactions that took place with the maritime sector and representatives from shipping companies.

Regarding LPG and methanol auxiliary systems concerning safety, any leakage detection can be achieved by a ventilation system passing completely through the outer pipe of the double walled piping. An incorporated hydrocarbon sensor, either switches automatically the operation of the engine from the alternative fuel to conventional if it is activated from hydrocarbon detection on the circulated ventilation air or raises an alarm. Two separate inert gas systems, usually nitrogen systems, are responsible for purging the alternative fuel supply on the engine as well as the fuel supply pipe towards the fuel valve train (FVT) with nitrogen. A difference of the LPG system is that the separation of LPG droplets and vapour on the venting procedure in case of a systems breakdown or leakage is provided by knockout drums[47] which then provide venting with no liquid fuel into the atmosphere and the remaining liquid returns to the storage tank. Methanol on the other side cannot be vented out due to its low degree toxicity. Knockout drums are necessary as LPG vapour is highly explosive due to its very low flashpoint (-105º C) and has to be safely vented out during recirculation and at the same time ensure that the remaining liquid fuel will return to the storage tank. The fuel supply system with the required safety measures incorporated for Methanol and LPG as they are designated by MAN are provided in Figure 14 and Figure 15 respectively, below:

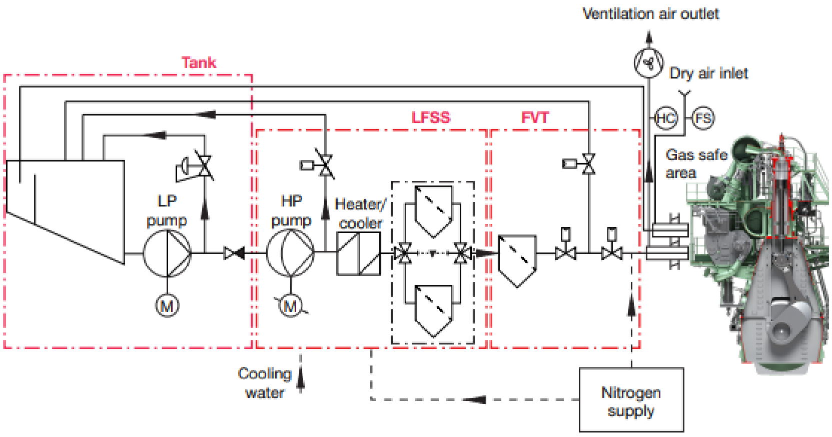

Figure 14: Methanol supply system by MAN [49]

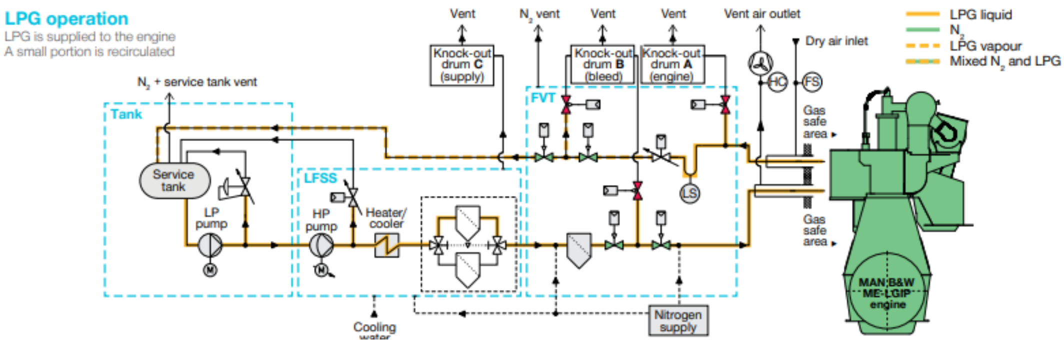

Figure 15: LPG supply system by MAN [53]

Regarding Ammonia safety systems, the double-walled ventilation piping is the same as the dual fuel engines for methanol and LPG in case of leakage. Contrary to LPG though, ammonia is highly toxic and coming into the atmosphere cannot be risked as it jeopardizes the crew and sea-life. Thus, an ammonia capture system-also called recovery and catching- is utilized in case of shutdown of the engine or leakage after passing through liquid-gaseous phase separation in the knock-out drums, ensuring that no fuel will be vented out and liquid ammonia can return in the recirculation tank and be used again. Additionally, in cases where the main engine is out of operation, any excessive boil-off from ammonia has to be combusted in boilers [38], [39]. In Figure 16: Ammonia supply system by MAN below, the total ammonia supply and safety procedure is presented.

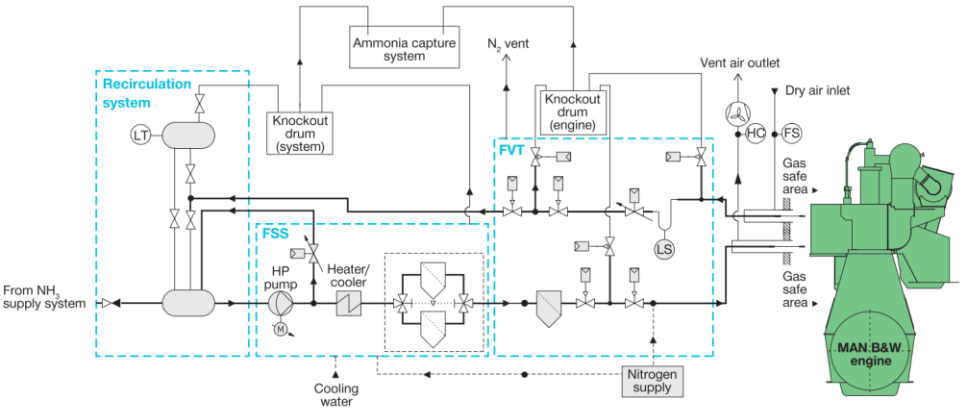

Figure 16: Ammonia supply system by MAN[39]

Gas Injection Fuels

The safety auxiliary systems for LNG dual fuel engines include ventilation piping, leakage detection and alarms are incorporated. A double walled piping is also used for the gas injection systems with the hydrocarbon sensor with an alarm incorporated being activated at a gas concentration of 30% of the Lower Explosion Limit and a shutdown signal of the engine is initiated at 60% concentration of the Lower Explosion Limit. An inert gas system is also needed for purging of the fuel systems with nitrogen. Below, in Figure 17: LNG Auxiliary System the auxiliary systems of the LNG engine are presented.

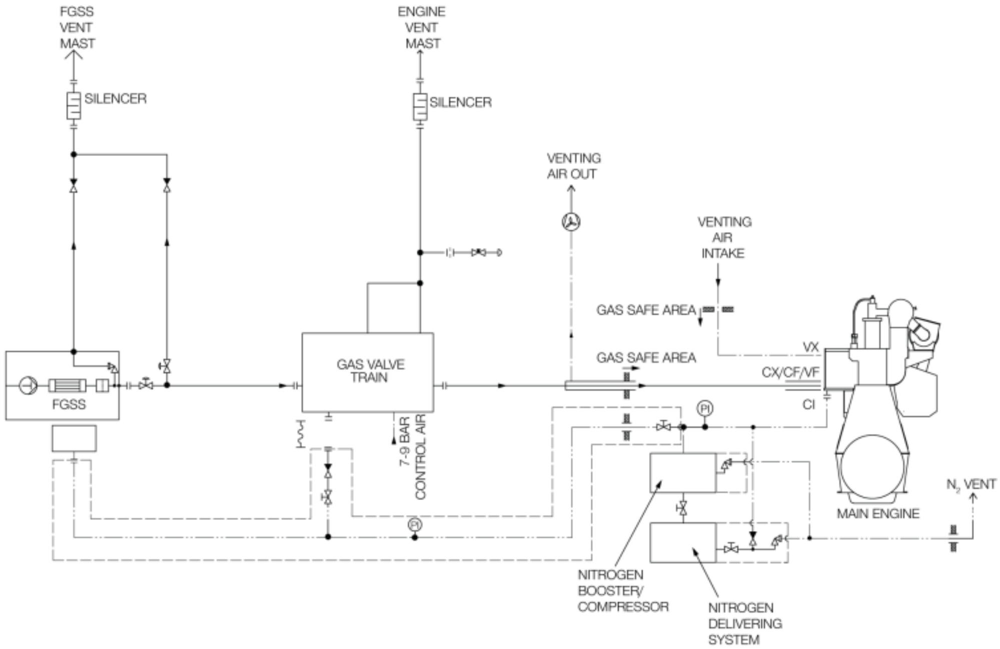

Figure 17: LNG Auxiliary System [51]

Regarding safety systems for hydrogen dual fuel engines, due to the extreme cryogenic temperatures, a pressure relief system is required that sends hydrogen to the venting system. For the Otto design, a thermal pressure relief device is also incorporated for depressurizing the storage tank in case of a temperature increase. Also, valves have to be designed and protected against the formation of ice or droplets ensuring the safe operation of the engine. Heat loss from the pumps and the piping is another concern and double wall safety is a necessity. Nitrogen purging is once more used for the fuel valve train. In Figure 18 & Figure 19 below the two concepts for hydrogen combustion in dual fuel engines are presented[43].

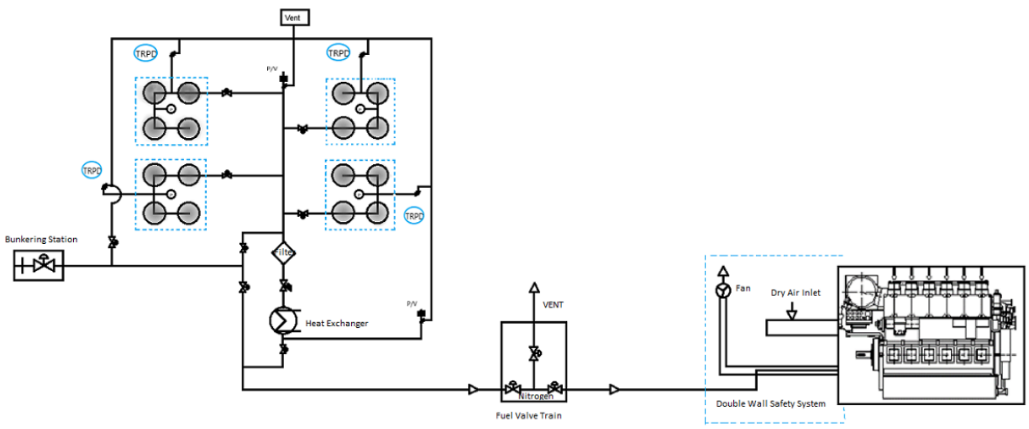

Figure 18: Auxiliary system for hydrogen 4 stroke dual fuel LP engine with Otto cycle [43]

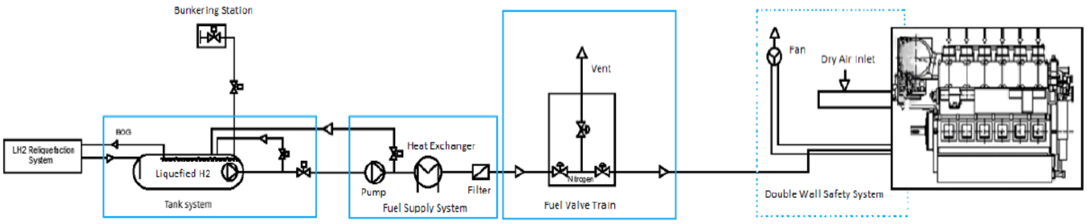

Figure 19: Auxiliary system for 2 stroke dual fuel HP hydrogen system with Diesel cycle [43]

2.3.5 Fuel Storage Tanks

An undoubted aspect affecting the TCO for an alternative fuelled ship are the fuel storage tanks and their integrated technologies. Every alternative fuel involved has its distinct properties and particularities ordering for the installation of a different storage tank onboard capable of managing cryogenic temperatures and/or high pressures. Insulation is of high importance when seeking for the lowest vaporization and boil-off. Any possible fuel leakage must be minimized and dealt with especially when toxic fuels like ammonia and methanol are stored thus careful designing and tank selection is necessary. In this section a literature review of the storage tanks chosen for each fuel was conducted presenting their features.

Methanol Storage Tanks

Methanol like conventional fuel as mentioned earlier do not need low temperatures or high pressures to be stored as they are preserved in liquid state in ambient conditions. Methanol tanks present some similarities with any regular VLSFO tank, and the latter can be easily retrofitted and adapted for methanol. However, methanol is toxic, and corrosive thus stainless steel should be utilized for the tanks. Alternatively, special coatings for methanol resistance should be applied to the tank’s interior. Methanol tanks should be surrounded by cofferdams either filled with fresh water or inerted with nitrogen equipped with gas detection systems[54]. A major issue regarding the tank size is the low volumetric energy density of methanol resulting in a need of approximately 2.5 times the size of VLSFO tanks for the same energy voyage without re-bunkering leading to less available cargo space and losses.

Liquified Gaseous Fuels Tanks

The main tank categories used for the storage of liquified gaseous fuels were initially designed for LNG and LPG containment, but their use was further extended for ammonia and hydrogen. The categorization is made as follows:

- Integrated tanks: Membrane tanks
- Independent tanks: Type A, Type B or Type C

Membrane Tanks

They are an integral part of the hull and contribute to the hull's strength as a girder. One key feature of such tanks is that their design is for a low pressure under 0.7 bar and the temperature can be kept at cryogenic temperatures (-162 ºC) in order to maintain the gaseous fuel in liquid form. A full secondary barrier around the primary barrier is also needed with two insulation layers in between. Membrane barriers are responsible for prevention of any leakage and insulation for limitation of heat exchange[52]. The required thickness of each membrane barrier and insulation layer are presented in Table 11: Membrane Barriers and Insulation LayersA cross section of a membrane tank with every barrier is shown in Figure 20: Cross Section of an Integrated Membrane Tank [55].

Table 11: Membrane Barriers and Insulation Layers

Layer/Barrier	Thickness Approx. (mm)
Primary Membrane Barrier	0.7-1.5
Primary Insulation Layer	230
Secondary Membrane Barrier	0.7-1.5
Secondary Insulation Layer	300

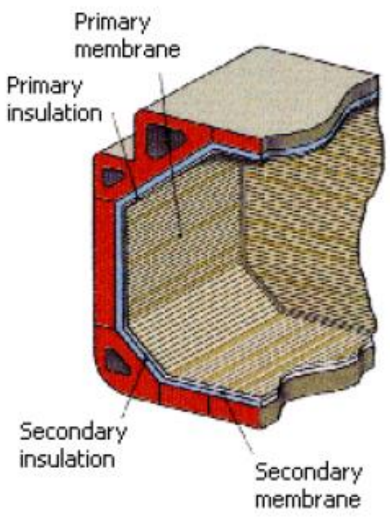

Figure 20: Cross Section of an Integrated Membrane Tank [55]

Type A Tanks

It is regarded as a Free-standing tank (independent) and has a prismatic design increasing in that way the volume efficiency. A full secondary barrier is also necessary for leakage capture and must be able to contain any leakage for a minimum of 15 days. An insulation layer and an inspection space/air gap are in between the two barriers allowing for tank expansion which is typical for a Type A tank and minimizing heat exchange and boil off. It is a non-pressurized tank with a permitted pressure of 0.7 bar like membrane tanks. Thus, the pressure developed by the boil-off gases are not to be withstood for a long period. The figure below presents a cross section of a type A tank[52].

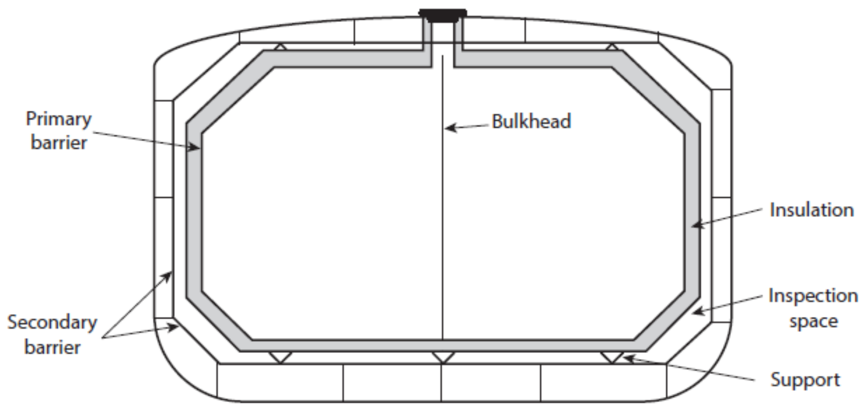

Figure 21: Cross Section of Type A Tank [52]

Type B Tanks

Independent low-pressure tanks with a maximum design pressure of 0.7 bar with a partial secondary barrier. They can have a spherical/moss design or a prismatic shape with the Moss tank being the most common, thus the one analysed, and are considered as medium volume utilization tanks. The spherical shape of it ensures that stresses are distributed evenly, and chances of failure are decreased. It has a partial secondary barrier only at the bottom of the tank for small leakage detection which is called Drip tray. This is a result of their spherical design and the fact that any possible leakage will be accumulated at the lower parts. Temperature sensors are equipped in the drip tray for liquified gas detection. A part of the tank usually half of it is over the main weather deck and at this part a weather protective layer is needed. An insulation layer covers the whole tank. A typical Type B Moss type tank is presented in Figure 22 [56].

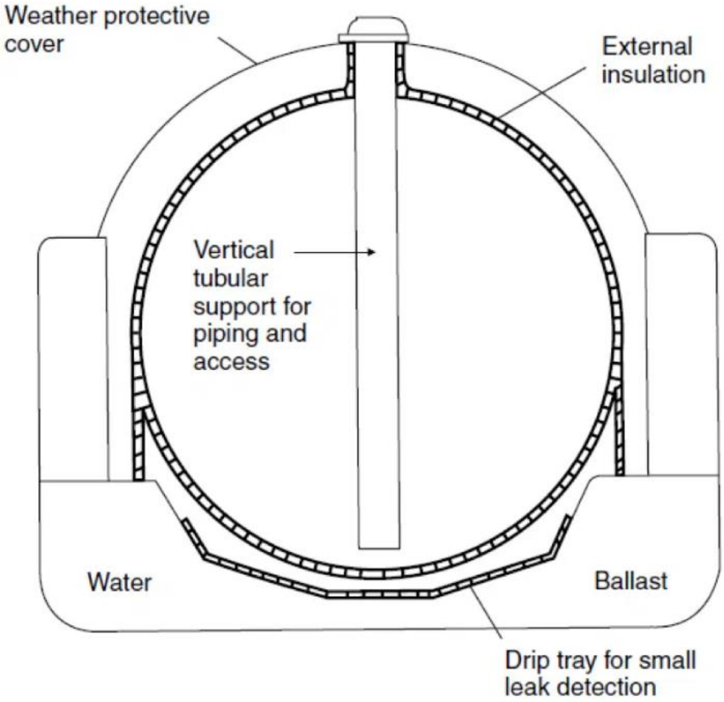

Figure 22: Type B Moss Type Tank [56]

Type C Tanks

Type C tanks are the only pressurised tanks involved in liquified gas containment with design pressures for vapour (boil-off) above 2 bar and can reach up to 18 bar for LPG and 10 bar for LNG containment[23]. They can be of cylindrical or bi-lobe (even tri-lobe) shape as presented in Figure 23 below and can also be located on the main deck for safety reasons. These, contrary to the types mentioned above, are pressurised tanks with utilization of increased pressure and low temperature. A main difference except for the pressure is the lack of a secondary barrier which reduces the infrastructure costs. However, gas sensors are installed for leakage detection in the hold space in between the tanks which is normally filled with inert gas. Despite the benefits, they offer the least space utilization and efficiency even though bi-lobe type seems to improve this issue[23], [56].

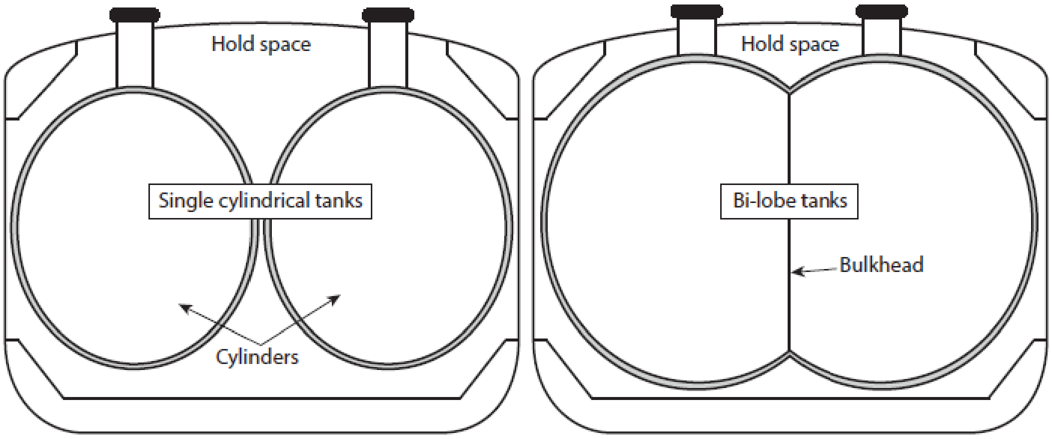

Figure 23: Type C Tanks- Cylindrical and Bi-Lobe Design [52]

Thus, the above liquified gaseous fuel tank types are utilized for LNG, LPG, ammonia and hydrogen storage and their use for each fuel is described as follows:

- LNG Storage: The most dominant design in LNG fuelled ship particularly for small scale newbuilds is the Type C pressurised tank as their construction is the most cost efficient and their design the simplest. For large deep-sea ships, membrane tanks are also widely used for highest space utilization. Type B design is also frequently met for large LNG tanks extend while type A is rarely seen.

- LPG Storage: Type A tanks are used for large LPG carriers and fuelled ships and type C tanks are also frequently met for smaller scale as they can withstand pressures up to 18 bar hence being able to hold the boil-off from LPG for a longer period while keeping the temperature at -42 ºC (-48 ºC for propane).

- Ammonia Storage: Ammonia is stored typically in tanks that are designed for LPG containment; thus, Type A and Type C tanks are used most often. The storage concepts that are considered for ammonia fuelled ships are the semi-refrigerated Type C ammonia tanks placed on the weather deck and the fully refrigerated Type A tanks placed close to the accommodation which raises some concerns and calls for further evaluation due to its toxicity and safety reasons. Special coating for the corrosiveness of ammonia should be applied on the tank walls. Additionally, ammonia's very low volumetric energy density leads to the need of large tanks possibly over cargo sacrifice[38].

- Hydrogen Storage: Liquified hydrogen as a cryogenic fuel can be stored in tanks presenting similarities with LNG like Type C tanks, but the extremely low temperature of -253 ºC calls for very well insulated tanks with insulation layers two to three times thicker than LNG tanks. Different type of tanks from composite materials have also been developed however their availability is rather low. Boil-off is also at high levels, 1-5% for each day in tank, thus a high amount of energy is needed for reliquification on board which will be provided from hydrogen itself. The high boil-off of the fuel is another reason for type C tank selection due to the vapor pressures developed which need to be withstood. In addition, since it has the lowest volumetric energy density of all the fuels involved in the study, storage tanks have to exploit a greater space on ship, otherwise refuelling is mandatory. For that reason, putting the tanks on the deck is suggested as a solution to avoid cargo reduction.

2.3.6 Availability & Bunkering Infrastructure

The making of a scenario analysis for a more realistic approach on the TCO calculation regarding the alternative fuel powered ships which was made later in the dissertation, brings the need for a better understanding of the global supply chain of each fuel and the available bunkering infrastructure which are directly affecting the ship's trip and the route it has to follow.

<u>LNG</u>

LNG has an established global availability as it has been widely used in the recent years and it's transported at an increasing rate around the world. Thus, the supply stations are also developing and bunkering can be carried out more easily with over 188 active bunkering facilities worldwide within reach from the most common trade routes and 82 LNG bunkering facilities under development as of February 2024. Additionally, 2023 was a high record year for LNG bunkering volumes for the port of Rotterdam highlighting the shift towards a greener shipping sector [57]. The standard ways for bunkering LNG are either from a port station to the vessel or from ship to ship. The latter offers a high flexibility as LNG Bunker Barges can reach at almost any destination when refueling is needed by the ship. Bunkering from a truck to ship is also possible but rarely seen[55].

Given the above, the reliability of a fuel for propulsion purposes is straightly linked to the number of facilities available and for that reason the bunkering infrastructure global maps are presented below, with the first one showing bunkering facilities and ports and the second one bunkering vessels.

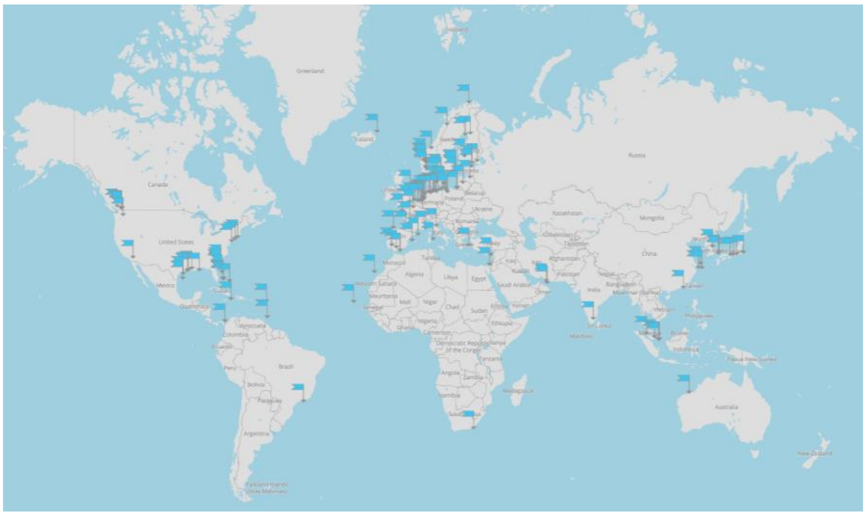

Figure 24: LNG Bunkering Facilities[58]

Figure 25: LNG Bunkering Vessels[58]

LPG

LPG is also highly used at least for LPG carriers and bunkering infrastructure seems to be developing. In the first months of 2024, more than 1000 LPG terminals were available which could operate as bunkering stations if needed raising the expectations for a well-developed LPG bunkering system in the near future. Like LNG, LPG can be also bunkered from ship-to-ship with the first such event chronologically located in 2021. Approximately 900 LPG carriers are available and could proceed to vessel-bunkering if suitably equipped [57].

There are quite a few LPG storage terminals covering the needs and demands of global market at the world's hubs and ports. However, most of them need to develop bunkering infrastructure with fuel delivery system as an addition to the already existing storage facilities. Thus, the storage terminals, the number of which (globally) and their location (Europe) are presented in Figure 26 and Figure 27, are possible to be used also for LPG bunkering.

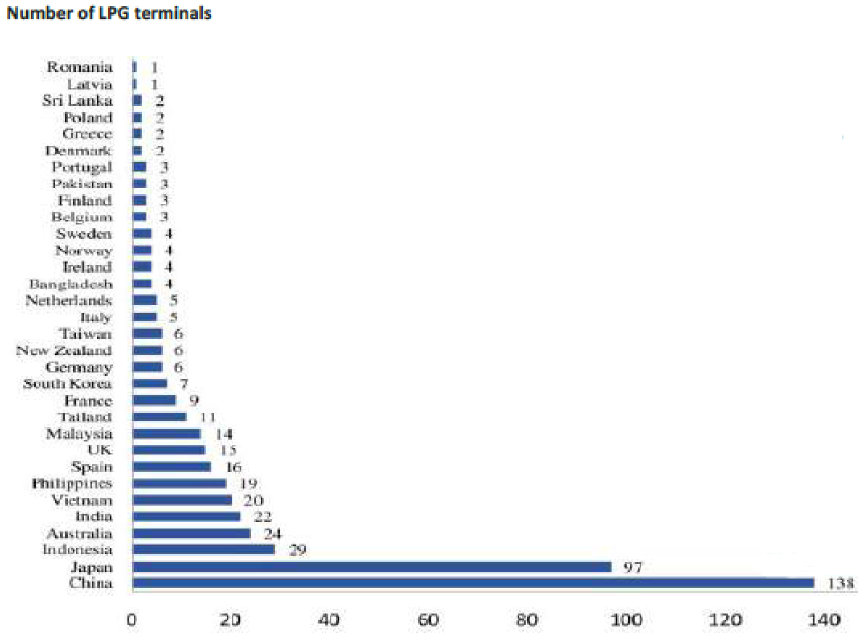

Figure 26: Number of LPG Terminals

Figure 27: LPG Import/Export Terminals in Europe [30]

Methanol

Current methanol's availability refers mostly to the amounts of grey methanol produced from natural gas resulting in a quite high possible production but not in the needed form for decarbonization. Green methanol on the other hand has a remarkably low availability; however, companies are positive in increasing their production if a demand rise is visible in the horizon.

Bunkering of methanol can be achieved from a port terminal, from bunker vessels or from tank trucks with the latter reported in Norway. The use of bunker vessels seems to be the most promising due to their flexibility and readiness. In 2024, 122 ports had the necessary facilities for methanol storage, 18 had incorporated bunkering infrastructure and 11 more being under development. The interest in adapting methanol was highlighted from 200 newbuilds dual-fuel methanol ships and ports like the Maritime and Port Authority of Singapore which was ready to be developed into a methanol bunkering hub. Covering the global fleet needs with renewable methanol though will take time as production is not well established yet [57],[59]. Figure 28 and Figure 29 present the current methanol storage facilities and the bunkering terminals respectively.

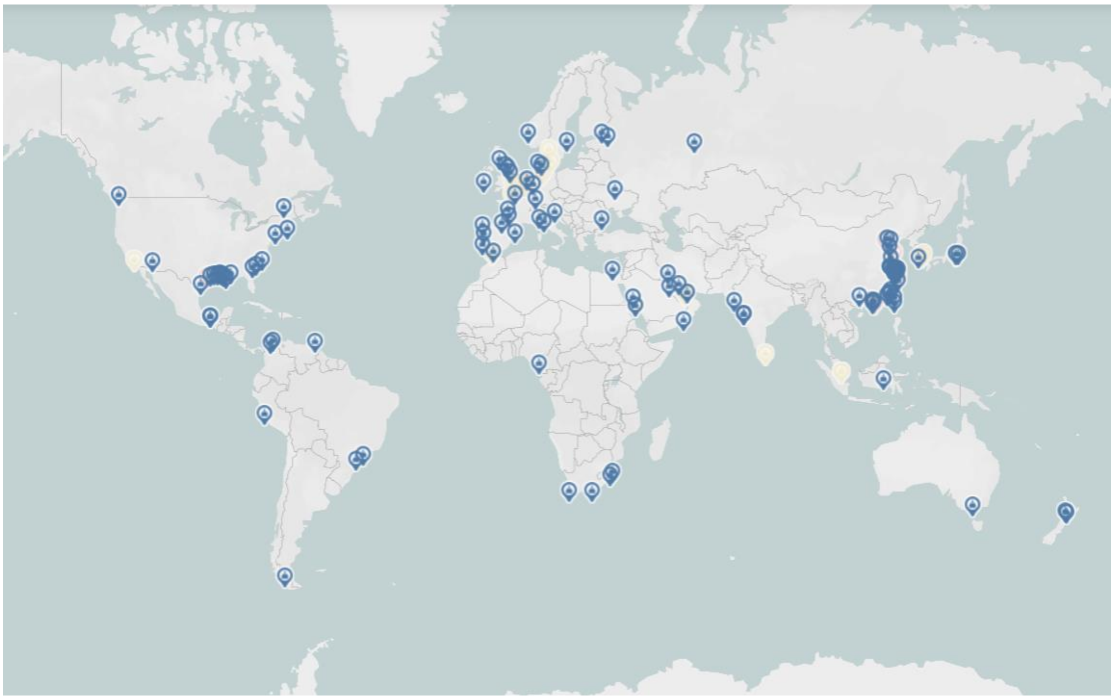

Figure 28: Methanol Storage Facilities [59]

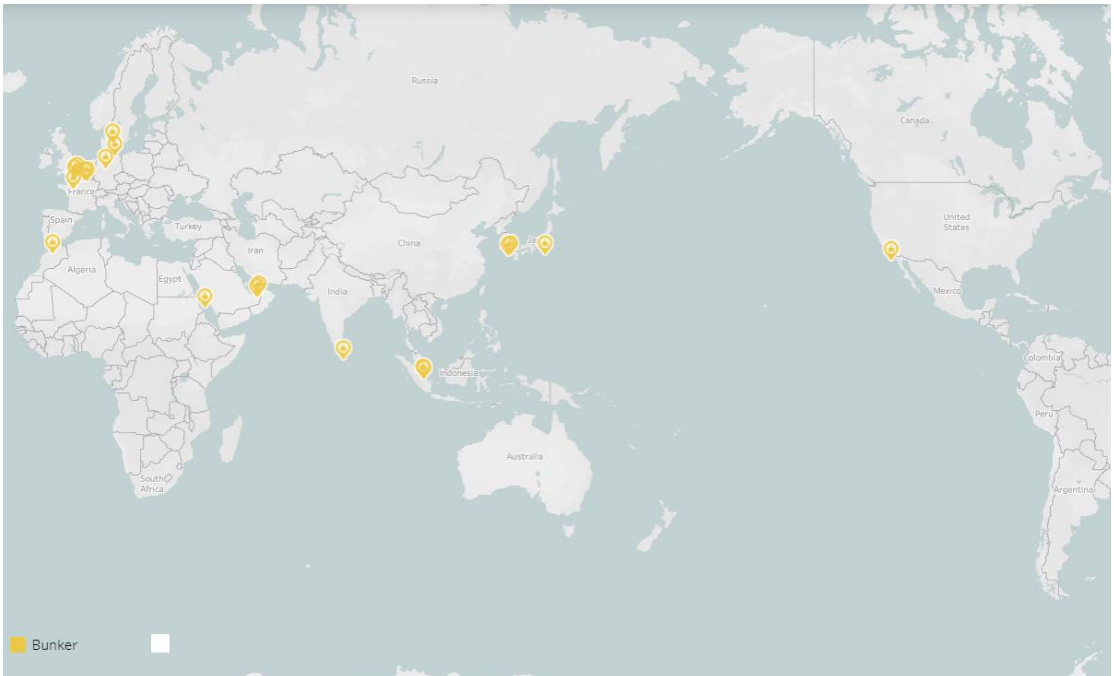

Figure 29: Methanol Existing Bunkering Infrastructure [59]

Ammonia

Ammonia up to date has only been transported as a cargo on LPG carriers since their storage tanks are also designed for LPG containment. Its availability consequently hereon refers to the readiness of ammonia in storage facilities worldwide. Its transportation is dominantly related with grey/brown ammonia which is not promising for the decarbonization journey of ship propulsion but further actions towards blue and green ammonia availability are taken and into consideration.

Bunkering of ammonia could be carried out from specialized ports but up to now there are only storage facilities in certain locations for ammonia transportation and not for bunkering. Additionally, the concerns for its toxicity and the dangers that nearby areas are exposed to in case of any leakage to the atmosphere lead to the belief that bunkering ammonia from ship-to-ship in a remarkable distance from the shore will be more sustainable and acceptable for safety reasons in the long-term. However, there are some plans and discussions as of 2023 for bunkering hubs development regarding European ports, the Panama Canal, Japan, the Gibraltar Strait and Singapore as promoted by ITOCHU Corporation (trading and investments).

To the extent of the current data and this thesis, only the Load and Discharge ports listed in 2020 for ammonia storage are presented in Figure 30 below:

Figure 30: Ammonia Storage Infrastructure [60]

Liquified Hydrogen

Hydrogen as a fuel for ship propulsion is at its very early stages resulting in a lack of bunkering infrastructure particularly when it comes to liquified hydrogen. It was not before 2022 that The Netherlands were licensed with the first hydrogen bunkering for a small vessel. Nevertheless, the necessary infrastructure is not established but ports have already been encouraged to prepare for green hydrogen bunkering facilities and develop infrastructure for liquified storage. It is expected that most of the major ports will have incorporated hydrogen bunkering systems until 2035. Bunkering of liquified hydrogen can also be carried out through shore-to-ship operations as well as from ship-to-ship.

3. Methodology & Calculations

Ship's and Main Engine's Particulars

The ships that were initially taken into consideration were dry bulk carriers as they constitute the majority of the global fleet with over 40% of the ships on sea being bulkers. The size of the vessels for this analysis were all assumed to fall in the Panamax size category which have a carrying capacity ranging from 60000 to 80000 tons Deadweight (DWT) and can pass the straits of the Panama Canal.

For the ship type selected, it was assumed a Deadweight of 80000 tons with a Contracted Maximum Continuous Rating of 11000 kW which is quite often associated with real life data. For the calculations and the comparison conducted it was considered that the vessel operated at an engine's output of 75% of its MCR as its normal continuous rating (NCR). This is also the engine's power that most manufactures provide their data at. In Table 12: Ship Type and Particulars Selection below the ship type and general particulars are gathered.

Table 12: Ship Type and Particulars Selection

Ship Type	Dry Bulk Carrier
Size Category	Panamax
Deadweight [t]	80000
Contracted Maximum Continuous Rating (CMCR) [kW]	11000
Normal Continuous Rating (NCR) [kW]	8250
Service Speed [kn]	13.5

According to the CEAS calculations from MAN Energy Solutions the data specified for the engines are shown Figure 31:

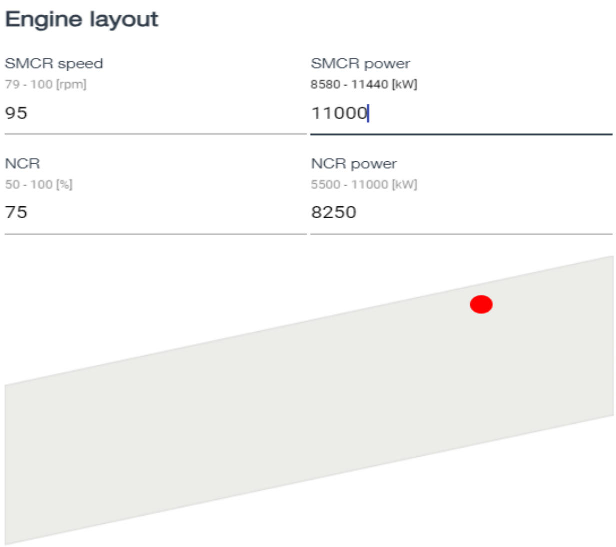

Figure 31: Engine Layout from CEAS MAN

Regarding the main engine's operation, it was assumed that the main fuel for the conventional engines would change to MGO within ECAs as VLSFO and biofuels were not compliant with IMO's SOx regulations. This swift from VLSFO to MGO was also considered for the pilot fuel regardless of the main fuel.

Gensets Power Need & Operation

As further explained later, all the gensets were assumed to operate on the main fuel considered, a fair assumption since LNG, methanol and conventional are already used and LPG, ammonia and LH2 are expected to be soon in operation. Within ECAs however the conventional fuel in gensets would change to MGO to comply with the SOx regulations. The pilot fuel used for the gensets was also MGO.

Additionally, it was estimated that the electricity for auxiliary power needs would be around 700 kWe when conventionally fueled. As far as the alternative fuels are concerned, it was estimated that a small increase in electricity needs would be necessary for pumps, boil off management and reliquification purposes, ventilation and vaporizers as well as for the safety systems apart from the lighting, cooling and accommodation needs.

The increase and the final auxiliary power needs were depicted as presented in Table 13:

Table 13: Auxiliary Power Needs and Increase from Conventional

Fuel Type	Electricity Needs Increase from Conventional [%]	Auxiliary Power Needs/Output [kWe]
Conventional	-	700
LNG High Pressure	15	805
Methanol	5	735
LPG	10	770
Ammonia	15	805
LH2	20	840

The electricity needed was assumed that it was distributed to three identical gensets as in a real case scenario, and the auxiliary power was produced from all three ensuring reliability and flexibility. More to that, with one genset out of service the power needed should be possible to be produced from the rest two generator sets as they are not working to their maximum load.

Voyage and Time on Sea

It was assumed that for the annual voyage of the ship the time on sea and at port was as follows:

- Vessel sails on sea for 80% of the year with 20% of that being within ECAs.
- Vessel remains at port for 20% of the year with only gensets operation and emissions.
- Approximate and Average Speed of 13.5 kn at Engine's NCR

Thus, the fixed data for every fuel were the following:

- 292 days on sea with Main Engine at NCR and Gensets operation
- 73 days at port only with genset operation
- Annual Distance Travelled [nm]: 94608
- Vessel's Range [nm]: 10000
- Time on sea without re-bunkering: 741 hrs or 31 days

3.1 Capex Methodology

3.1.1 Main Engines and Fuel Supply Systems Capital Costs

A great cost for the shipping company that is considered one of the leading capital expenditures paid once in the beginning of the vessel's lifetime refers to the main engine which appear to have costly different characteristics depending on the fuel used even though efforts are made to make dual fuel engines more and more adaptable for operation with different fuels without major changes. The capital costs for the main engines were feasible to be calculated in assistance with the shipping companies and their feedback as well as project guides that offered a realistic insight to the range of the ships.

The manufacturer that was taken into consideration for the main engines was MAN Energy Solutions as they provide a wide range of engine portfolio covering most of the alternative fuels selected for this analysis and for the sake of homogeneity other leading companies like WinGD were excluded.

The conventional main engine is the same dual fuel engine series but only operated in fuel oil mode as this approach is regular from the shipowners due to the flexibility it provides instead of choosing a fuel oil only engine that limits a potential future swift to operation with alternative fuels. However, it is adjusted to operate only with fuel oil initially corresponding to a conventional engine.

The Table 14 below provides the main engines that were selected from MAN for every alternative fuel:

Table 14: Main Engines Selected for the Ship for Each Fuel

Fuel Type	Engine
Conventional (VLSFO, Biofuels-B24, B30)	G50ME-C9.6 (Fuel Oil Mode)
LNG	G50ME-C9.6-GI
Methanol	G50ME-C9.6-LGIM
LPG	G50ME-C9.6-LGIP
Ammonia	Delivery in 2024 / MAN-ES Estimations
L.Hydrogen	Dual fuel Estimations

At this point it should be noted that one of the first 4 stroke dual fuel hydrogen engines combusting liquified hydrogen has very recently been designed for small applications. Major engines of the range of deep oceanic ships are to be delivered soon resulting in a very limited access to data thus conversations with the maritime sector were crucial for some realistic estimations of the engines.

The main engines capital expenditures were calculated with valuable data from the Mærsk Mc-Kinney Møller Center and help provided by maritime specialists[61]. Thus, the capital costs for the acquisition and installation of each main engine onboard excluding the capex for the fuel supply system are gathered in Table 15 below:

Table 15: Capex of The Different Main Engines

Fuel Type	Engine	Engine Cost $/kW	Main Engine Capex [M$]
Conventional (VLSFO, Biofuels)	G50ME-C9.6 (Fuel Oil Mode)	240	2.64

LNG	G50ME-C9.6-GI	490	4.62
Methanol	G50ME-C9.6-LGIM	300	3.30
LPG	G50ME-C9.6-LGIP	320	3.52
Ammonia	MAN Estimations	500	6.60
L.Hydrogen	Estimations/ 4stroke dual fuel	840	9.24

Fuel Supply Systems & Safety Systems Capital Costs

All the systems interfering in between the fuel tanks all the way to the chamber of the engine have the function of fuel transfer, pumping and filtration as well as injection. These supply systems as described earlier, vary according to the conditions they are called to deal with including temperatures, pressure and corrosiveness of the fuel and so does their acquisition and installation cost.

For a Panamax dry bulk carrier, the supply systems capital costs were calculated from data from maritime publications [[61] and with the invaluable help of maritime specialists that helped in the completion of this thesis through estimations and predictions compared to the systems of their ships. More specifically, fuel supply systems that were taken into account were pressure pumps, low pressure compressors and vaporizers, glycol water system, gas and fuel valve trains, single and double wall piping and the pump vaporizer unit.

Additionally, the capital costs of the safety auxiliary systems that have already been discussed such as ventilation systems, leakage detection systems, fire prevention and extinguishing means, pressure relief valves and fuel capture systems for the toxic ammonia were included in the supply systems as it is hard to separate the operation of each other and their costs.

The above costs were gathered in the following Table 16 and Figure 32:

Table 16: Capex of Auxiliary Supply Systems of each Vessel

Fuel Type	Fuel Supply Systems Capex [M$]
Conventional (VLSFO, Biofuels)	0.25
LNG (High Pressure)	4.76
Methanol	0.69
LPG	1.13
Ammonia	2.19
L.Hydrogen	5.67

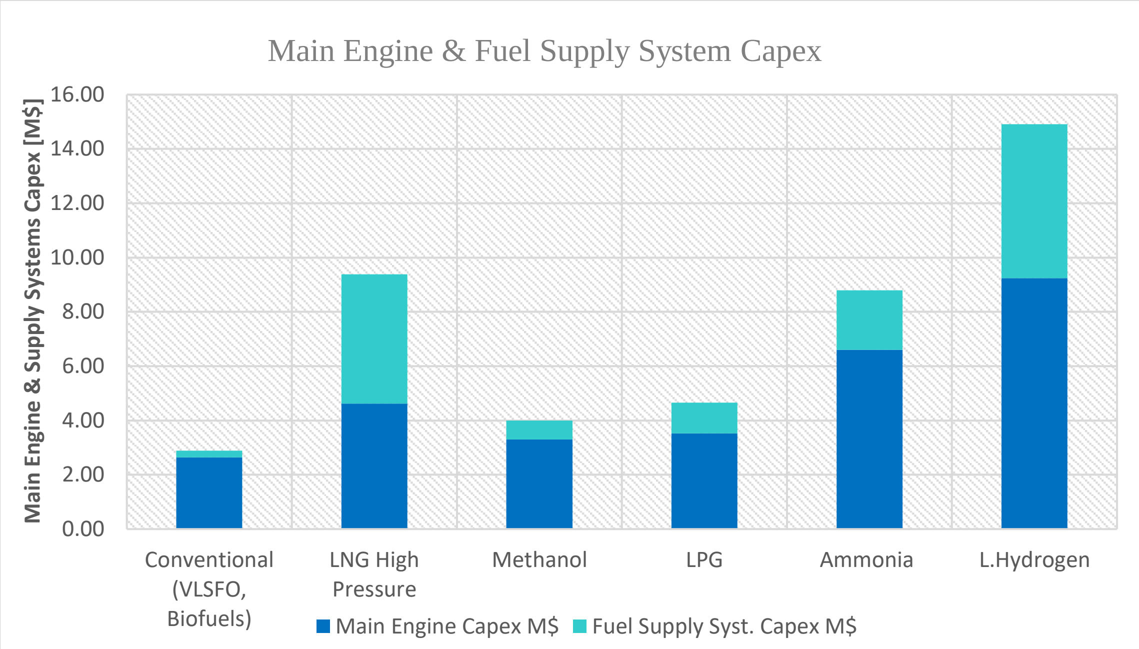

Figure 32: Main Engine & Fuel Supply System Capex

3.1.2 Gensets Capital Cost

Gensets are also highly expensive however their operation range is more limited as explained in 2.3.2 Generator Sets with the fuels used currently being the conventional (MGO, MDO & rarely VLSFO), natural gas and methanol. Thus, their capital cost could be assumed that won't vary greatly according to the main fuel rather than the fuel used separately for the gensets, a choice determined entirely by the shipowner. Based on that, a typical approach would be that an LNG fuelled vessel uses LNG also for its generators mainly coming from the boil off gas of the fuel tanks which corresponds to real life scenarios. Likewise, a methanol fuelled ship is chosen to combust methanol for both the main engine and the gensets as they are available in the industry. A similar approach was considered for LPG, ammonia and LH2 as it likely to happen really soon and this would be the sustainable line of action for environmental reasons and efficiency.

For the calculation of the gensets capital costs regarding purchase and installation, it was assumed that three generator sets were needed for a panamax size dry bulk carrier resulting in the following analysis in Table 17 for each different fuel powered vessel:

Table 17: CapEx of Gensets for Each Ship

Main Engine Fuel Type	Genset Cost [USD/kW]	Capex of three GenSets [USD]
Conventional (VLSFO, MGO, Biofuels)	250	175000
LNG High Pressure	288	211313
Methanol	300	241500
LPG	300	231000
Ammonia	300	241500
Liquified Hydrogen	325	273000
Note: LNG gensets cost were calculated as 115% of the conventional, LPG/Methanol/Ammonia as 120%, and LH2 as 130% .		

For the calculations the needed kWe for each fuel were used and the cost per kW was provided by maritime specialists. Methanol, LPG and ammonia as shown were anticipated to have similar approach for gensets operating on the last two not well-established fuels.

3.1.3 Boilers Capital Cost

The cost of auxiliary boilers that are used for steam production can vary based on the fuel used for vessel propulsion. Dual fuel marine boilers have been gaining more and more interest as alternative fuels are emerging leading to the need of handling boil-off gases. This can be made within the boiler provided it is capable of being fired with unpressurized BOG[62]. There is already a commercially ready marine boiler from Alfa Laval, the Aalborg OL designed for operation with low sulphur conventional fuels, LNG with BOG combustion capabilities as well as compatibility with methanol firing. Other alternative fuels are also mentioned as possible for operation thus the assumption that LPG could also be used for operation was made [63], [64] Ammonia is expected to have a similar approach as methanol and LPG while LH2 firing in the boiler is anticipated to have a much greater impact on the boiler's capex due to extreme cryogenic temperatures. It is important to highlight that an Exhaust Gas Economizer was used in every case but was incorporated in the capital cost of the main engines as it is accompanied most often.

The capex of each boiler was calculated through interactions with maritime specialists as 30% of the total gensets capex, as their capacity doesn't need to be very high for a panamax bulk carrier. Consequently, the capex of the boilers was presented in Table 18:

Table 18: Boiler Total Capex

Main Engine Fuel Type	Capex of Boiler [USD]
Conventional (VLSFO, MGO, Biofuels)	52500
LNG High Pressure	63394
Methanol	72450

LPG	69300
Ammonia	72450
L.Hydrogen	81900

In Figure 33 below the aggregated capex of the gensets and boilers were presented since the latter were closely linked with the cost of the former for the calculations.

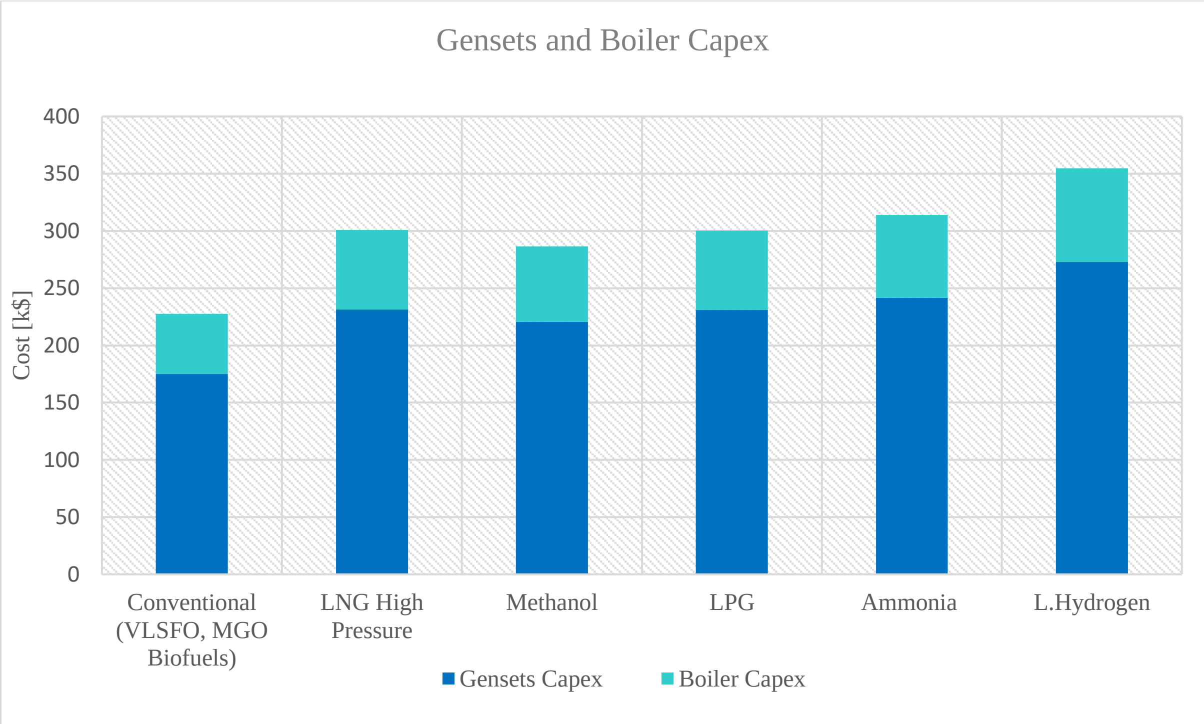

Figure 33: Capex of Gensets and Boilers

3.1.4 Fuel Storage Tanks Cost

The construction and installation of the fuel tanks for each vessel is greatly affecting the Total Cost of Ownership since alternative fuels call for quite complicated and costly insulating materials and layers with thickness depending on the storage temperature and increasing the price. Hence, cryogenic fuels like liquified hydrogen and LNG need thicker and more expensive insulation layers and toxic and corrosive fuels like ammonia and methanol need extra coatings for steel protection; otherwise, stainless steel should be used which is also raising the cost of acquisition. However, methanol is preserved liquid at ambient conditions, so the cost of the tanks is not significantly higher than the conventional compared to ammonia which also needs lower temperatures (-33ºC) to be stored additionally to its toxicity and corrosiveness.

The cost for the construction of the tanks was given in USD/GJ and was strictly linked with the range the ship is considered to have, thus the fuel energy that is needed for daily operation. Aiming for a quite similar range for all the alternative fuels, it was assumed that the panamax bulk carrier involved which falls in the upper levels of the spectrum of the panamax category with a DWT of 80000 tons had a range of R=10000 nm. Considering operation of the engine at 75% of MCR the result was the following Normal Continuous Rating: NCR=8250 kW.

In Table 19 below the characteristics and values used for the calculations of the time on sea were presented:

Table 19: Vessel's Range and Voyage Days

MCR	11000	kW
NCR	8250	kW
Estimated Vessel Speed	13.5	kn
Typical Range	10000	nm
Time on Sea without Re-bunkering	741	hrs
Time on Sea without Re-bunkering	31	days

As mentioned, the total fuel consumption per day both for the alternative fuel tanks and the pilot fuel tanks was necessary to calculate the energy needed which led to the utilization of the results that were later made in 3.2.2 Fuel Consumption & Cost.

The total fuel energy needs of main and pilot fuel of each vessel were presented in Table 20 as follows.

Table 20: Fuel Energy Needs for each Vessel

Fuel	Main Fuel Needs [mt]	Pilot Fuel Needs [mt]	Main Fuel Needs [GJ]	Pilot Fuel Needs [GJ]
VLSFO	1087	0	44580	0
B24	1113	0	44310	0
B30	1118	0	44260	0
LNG	943	22	45030	1040
Methanol	2197	69	42670	1340
LPG	968	67	46610	3220
Ammonia	2323	98	43940	1850
LH2	379	22	45480	2630

For completion purposes and aiming for a better understanding of the feasibility of the tank construction the volume of the tanks was also calculated with the density of each fuel from Table 7: Fuel Density. The results were shown in Table 21 and Figure 34:

Table 21: Fuel Tanks Volume per Fuel/Vessel

Fuel	Main Fuel Volume [m3]	Pilot Fuel Volume [m3]
VLSFO	1264	0
B24	1207	0
B30	1216	0
LNG	2029	24
Methanol	2771	79
LPG	1793	73
Ammonia	3407	118
LH2	5416	41

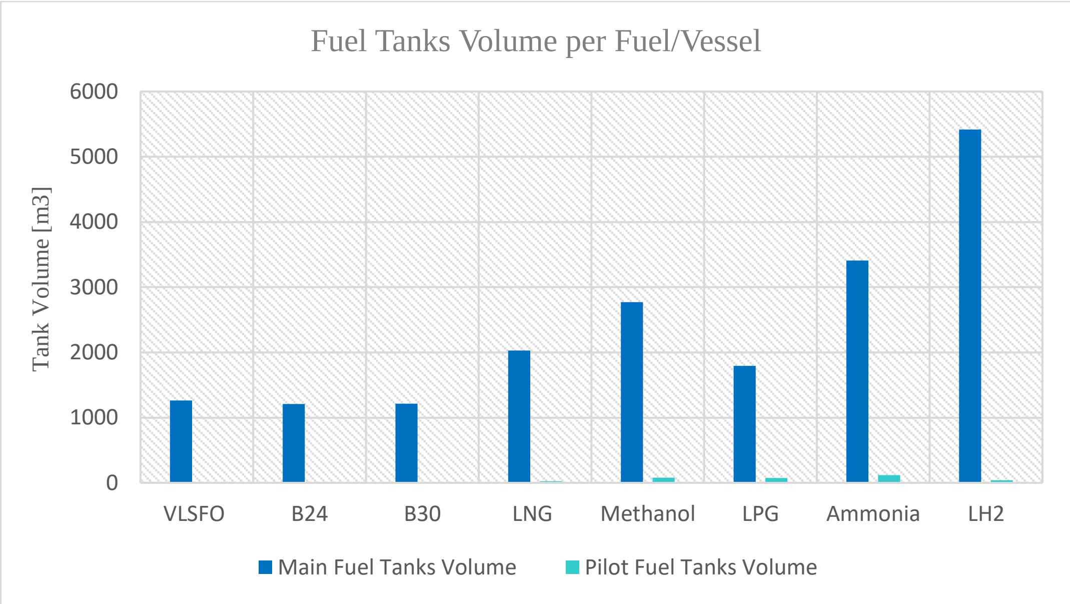

Figure 34: Fuel Tanks Volume per Fuel/Vessel

As presented above, it is important to be noted that LH2 and followed by ammonia have 4.3 and 2.7-times larger tanks in volume for the energy needed for the trips meaning that either cargo space has to be sacrificed for the same voyage or considerations have to be taken about putting the tanks on the weather deck when Type C tanks are utilized.

Table 22: Capex of Fuel Tanks Construction

Fuel	Cost of Tanks [USD/GJ]	Capex for Main Fuel Tanks [USD]	Capex for Pilot Fuel Tanks [USD]	Total Fuel Tanks Capex [USD]
VLSFO	20	891600	0	891600
B24	20	886200	0	886200
B30	20	885200	0	885200
LNG	130	5853900	20800	5874700

LPG	60	2560200	26800	2587000
Methanol	45	2097450	64400	2161850
Ammonia	75	3295500	37000	3332500
Hydrogen (liquid)	240	10915200	52600	10967800

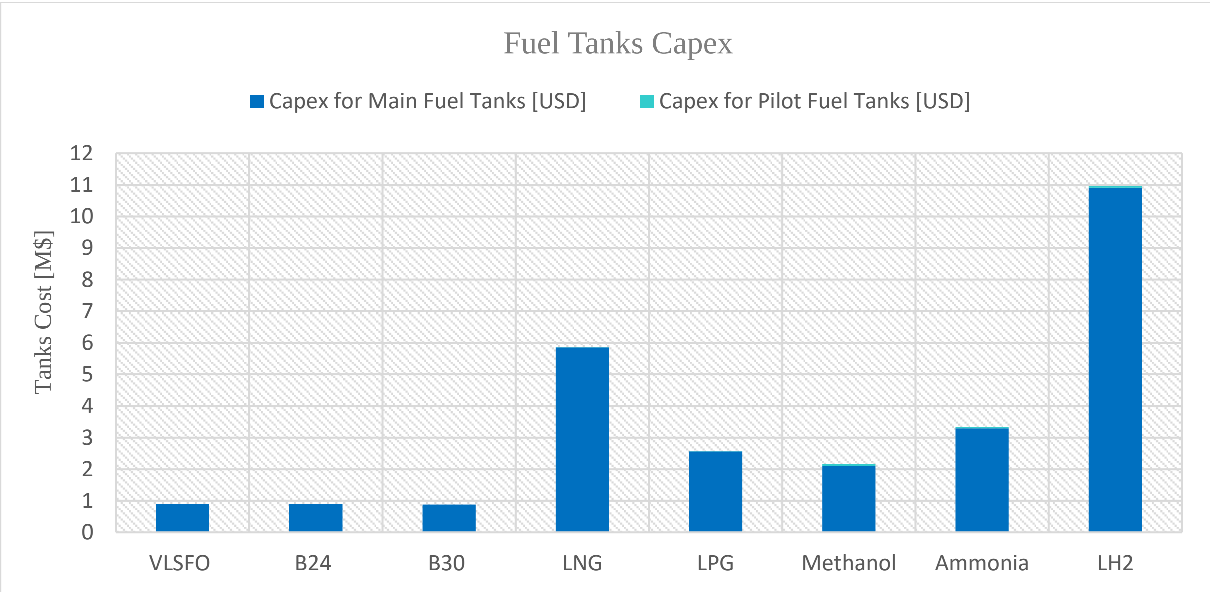

Figure 35: Fuel Tanks Capex

As it was expected, the cost for the liquified hydrogen tanks is double the price of the LNG and ten times the price of the conventional fuel since the cost per GJ is currently much higher but it is expected to reach a lower point when the fuel will be more available, and the hydrogen market further developed. Given that, and in addition to the more than 4 times larger tanks in volume than the conventional it would be rather possible that the shipowners will prompt for shorter voyages for them to be efficient and profitable or consider putting the tanks on the weather deck. However, in this thesis the range of the vessels was kept equal for comparison purposes.

Boil-Off in tanks

A parameter that should be considered when dealing with fuel storage onboard refers to the boil-off gases of the fuels stored in lower temperatures in order to be liquified. That excludes the conventional VLSFO and methanol which remain liquid in ambient conditions. However, LNG, LPG, Ammonia and Liquified Hydrogen when stored even in well insulated tanks, it is almost inevitable that a small percentage of the liquid fuel will evaporate due to the heat exchange with the outer layers of the tank. The vaporization rate is affected not only from the liquefaction temperature and excess of this value but most importantly from the vapor pressure of each fuel meaning the pressure of the vapor above the liquid at a given temperature. The higher the vapor pressure, the more volatile the fuel is leading to a greater rate of evaporation and more boil off gases inside the tank which have to be removed, reliquefied or used in gensets if this function is supported. Thus, the storage time in the fuel tanks will be shortened with a higher vapor pressure gas. Boil off gases are also of lower calorific value as the components of the gases that evaporate first are the most volatile as noted in the case of LNG where nitrogen which is an inert gas is evaporated first and then followed by methane which is the main component of LNG. The above process is illustrated in Figure 36: Illustration of the boil off gases of LNG and their composition below [65].

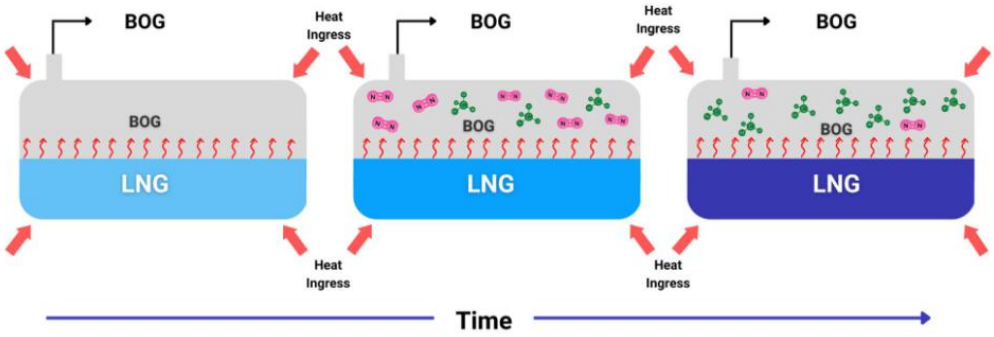

Figure 36: Illustration of the boil off gases of LNG and their composition graphic trend [65]

Ultimately, the vaporization rate of the liquified gases involved can be ranked as presented below in Figure 37: Ranked Boil Off Rate (BOR) of the Liquified Gases Involved from the highest to the lowest boil off rate (BOR). For every fuel also a typical rate of vaporization per day inside of the tank is provided from citation [43], [38]:

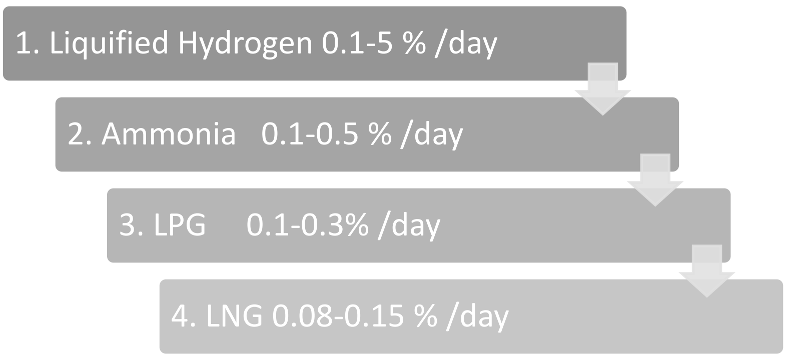

Figure 37: Ranked Boil Off Rate (BOR) of the Liquified Gases Involved

As presented in Figure 37: Ranked Boil Off Rate (BOR) of the Liquified Gases , L.Hydrogen which should be stored at -253 ºC also has an extremely high vapor pressure being the most volatile of all. LNG as shown, even though it has the second lowest storage temperature, due to lower vapor pressures it also has the lowest boil off rate.

It is suggested however that most of the boil off gases can be utilized onboard without entirely sacrificing fuel. In the framework of this analysis, it was assumed that the boil off gases were injected to the generator sets when dealing with LNG. Any excess BOG could also be combusted in the boiler for steam production. For an ammonia, LPG or LH2 fuelled ship re-liquification and recycling of the fuel took place onboard with some extra energy losses. Thus, the Boil Off Rate was incorporated in the calculations with a fuel consumption increase and more specifically in the auxiliary power needs which differed on every ship.

3.2 Opex Methodology

Aiming for a comprehensive approach in the operational expenditures of the TCO it should be assumed that the vessels involved will have a realistic life cycle in the range of 15 years which is a realistic scenario of a modern ship. In this section the extensive costs for the OpEx part of the total cost of ownership were calculated and presented as follows.

3.2.1 Bunker Fuel Prices

Regarding the total cost of the fuel which is strictly affected by the fuel price and the consumption rate, it was considered necessary to search for the recent bunker prices in order to make the research interesting for the shipping sector and the upcoming changes. The evaporation rate of liquified gases and their residence time in tanks was also taken into consideration for the bunkering frequency estimation.

Biofuels that were used as drop in fuels that were blended with conventional fuel were also considered when VLSFO was not in compliance with an adequate CII rating for market acceptance and selection from the charterers. The blends B30 and B24 are the most used and promising biofuels blends for maritime and correspond to a 30% ratio of Used Cooking Oil Methyl Ester (UCOME) mixed with 70% conventional fuel (VLSFO in this case) and 24% UCOME mixed with 76% VLSFO respectively. At this point it should be mentioned that BioLNG is also used currently with availability in approximately 70 ports as a bunker fuel and can also be used when LNG on its own is not complying with IMO’s and EU’s environmental regulations. However, due to luck of data, biomethane was not included in the calculations. The biofuels blends with their bunker prices are included in Table 23: Bunker Fuel Prices together with all the other latest bunker prices[66], [67].

Table 23: Bunker Fuel Prices

Fuel	USD/mt
VLSFO	656
MGO (For ECAs and Genset Pilot Fuel)	867
B24 (76% VLSFO-24% Biofuel)	775
B30 (70% VLSFO-30% Biofuel)	764
LNG	570
Methanol	335
LPG	350
Ammonia	530
L.Hydrogen	1300

It is import to be mentioned that ammonia bunker price was a result from the latest VLSFO equivalent prices privided from DNV which corresponded to 1150 $/t VLSFOeq. Thus, Ammonia Price [$/ton] was calculated by using the LHV of the fuels as follows in Equation 7:

$$\textbf{Ammonia Bunker Price} = 1150 \times \frac{LHV_{Ammonia}}{LHV_{VLSFO}} = 1150 \times \frac{18.9}{41} = 530\ \$/t \quad (7)$$

As it was shown, MGO was also presented since it was necessary for conventionally fuelled ships and SECA$_S$ regulations compliance demanding operation on fuels with 0.1% in sulfur content while VLSFO reaches for 0.5% complying with global (outside of ECAs) requirements.

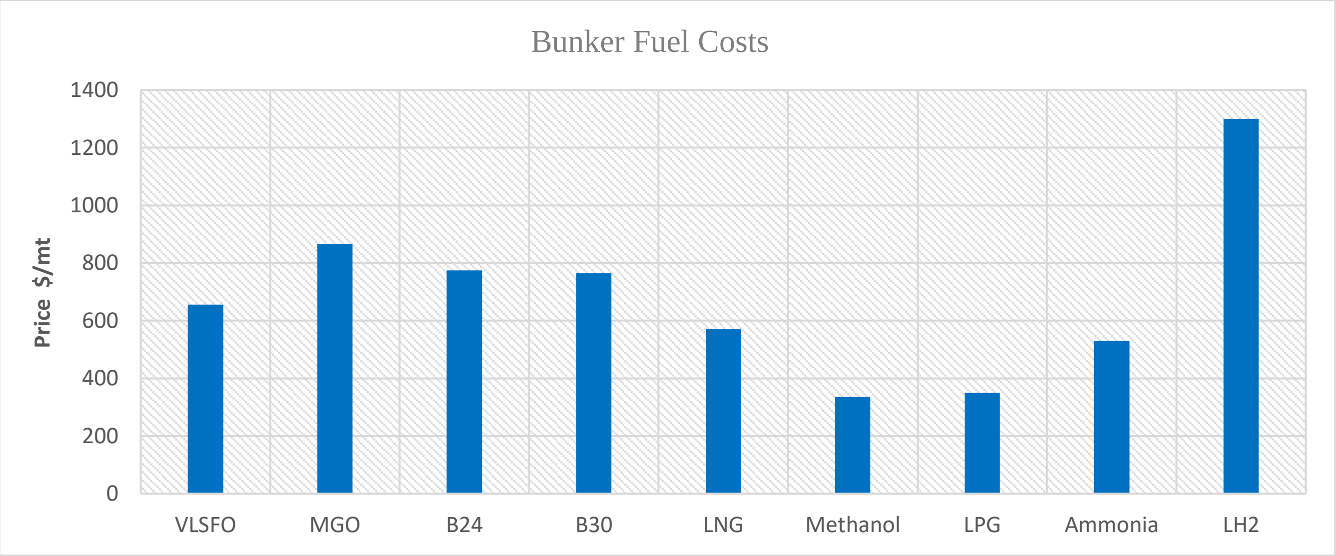

Figure 38: Bunker Fuel Costs

3.2.2 Fuel Consumption & Cost

A significant part of the Total Cost of Ownership refers to the cost that the shipping company has to pay for the total fuel and bunkering throughout the voyages in the life cycle of the ship. For the calculation of the total fuel costs a major parameter was the engine's fuel consumption for which it was considered necessary to specify the values of a typical engine that comes with every alternative fuel vessel. For that purpose, the consumption rates were taken from specific marine engine guides and leading manufacturers in the shipping sector and were calculated with the following operation concept.

Main Engine's Main Fuel Consumption & Cost

Aiming for a realistic consumption scenario, it was assumed that most of the trip's route for a panamax bulk carrier was located outside of NO_x and SO_x ECA_S which corresponded to 80% of the time of the total voyage while the remaining 20% of its voyage was within ECA_S. Thus, since the engine's manufacturers provide the technical guides and consumptions separately for TIER II and TIER III operation for NO_x compliance, the final Specific Fuel Oil Consumption (SFOC) or Specific Gas Consumption (SGC) was calculated in correspondence of every voyage giving the same results with a simpler approach proportionally as follows in Equation$\boldsymbol{SFOC/SGC_{OPERATIONAL}} = \mathbf{0.8} \times \boldsymbol{SFOC_{TIERII}} + \mathbf{0.2} \times \boldsymbol{SFOC_{TIERIII}}$ (8 8 and Table 24 :

$$\boldsymbol{SFOC/SGC_{OPERATIONAL}} = \mathbf{0.8} \times \boldsymbol{SFOC_{TIERII}} + \mathbf{0.2} \times \boldsymbol{SFOC_{TIERIII}} \quad \textbf{(8)}$$

Table 24: Main Fuel SFOC of the Engines Considered

Fuel Type	Engine	Main Fuel Consumption (SFOC/SGC) [g/kWh]	Main Fuel Consumption (SFOC/SGC) [g/kWh]
Conventional	8G50ME-C9.6 (Fuel Oil Mode)	162.7 (TIER II)/ 163.7 (TIER III)	162.9
Methanol	8G50ME-C9.6-LGIM	317.8(TIER II)/ 329.6 (TIER III)	136.38
LNG	8G50ME-C9.6-GI	136.2 (TIER II)/ 137.1 (TIER III)	320.16
LPG	8G50ME-C9.6-LGIP	141.2 (TIERII)/ 142.1 (TIER III)	141.38
Ammonia	Delivery in 2024/ MAN Estimations	333.69 (TIER II)/ 346.08 (TIER III)	336.17

L.Hydrogen	4-stroke dual fuel engine/ Estimations	54.48 (TIER II)/ 54.84 (TIER III)	54.55
Note: Since it was not possible to find specific engines for ammonia and L.hydrogen injection that would fulfill the operational criteria, their consumption was estimated proportionally with the LHV of methanol for ammonia and LHV of LNG for LH2.			

Main's Engine Pilot Fuel Consumption

All the dual fuel engines used for the analysis inject a certain amount of pilot fuel into the combustion chamber for the combustion to begin since a characteristic of most alternative fuels is their difficulty to ignite. Fuel costs are also connected with the amount of pilot fuel needed for combustion of each alternative fuel and a higher percentage of pilot fuel is needed when the alternative fuel presents a greater difficulty for ignition meaning that a higher flash point is associated with an increased need for pilot conventional fuel. Additionally, pilot fuel offers a more stable and homogenic combustion particularly in low loads engine operations. Each engine has a specified ratio for pilot fuel need given by the manufacturers in a percentage of the total energy consumption of the 100% CMCR engine power. The consumption of pilot fuel is provided in g/kWh and is given in a percentage depending on the engines used wherever they are available and applicable or by technical projects and predictions from manufacturers. The fuel that was selected for that purpose was VLSFO for 80% of a typical voyage and MGO for the 20% of the time that the ship will be within SECAs. This led to a simplified assumption for the daily consumption using 20% of MGO bunker price and 80% of VLSFO.

At this point it should be noted that an intriguing concept regarding pilot fuel oil was the case of ammonia. Initially the tests that were conducted from manufacturers and technicians led to a rather high pilot oil percentage in the range of 10-15% due to the very high flash point of ammonia as described earlier. Despite that, RnDs departments aim for a 5% use of pilot fuel ending to a similar approach as the liquid injection engine of LPG and Methanol [68]. Due to the lower volumetric energy though, the consumption for the ammonia engine was estimated even higher than methanol in order to provide the same power output as shown in the main fuel consumption table. For LH2 the same pilot fuel needs as LNG was assumed, keeping the pilot fuel amount in low levels as it is expected. The pilot fuel needs of the main engines are presented in Table 25.

Table 25 : Pilot Fuel Percentage for Each Different Engine

Fuel / Engine	Engine	Pilot Fuel Need (%)	Pilot Fuel (g/kWh)
Conventional	8G50ME-C9.6 (Fuel Oil Mode)	0	0
LNG	8G50ME-C9.6-GI	1.5	3.17
Methanol	8G50ME-C9.6-LGIM	5	10.58
LPG	8G50ME-C9.6-LGIP	5	10.58

Ammonia	MAN RnD Estimations	10-15 (initial tests), 5 (target) [69]	10.58
L.Hydrogen	Dual fuel / Estimations	1.5	3.17

Given the above, after the proportional calculations of the SFOC/SGC and SPOC for TIER II and TIER III percentages of a voyage in a daily projection, it was also possible to calculate a total daily consumption of the fuel for each vessel. The above were concentrated in Table 26 and Figure 39 by assuming a constant operation at Normal Continuous Rating (NCR) of the engine for 24hours as it is described from the Equation 9 below:

$$\boldsymbol{Engine's\ Daily\ Fuel\ Consumption} = \boldsymbol{SFOC_{OPERATIONAL}} * \boldsymbol{NCR} * \mathbf{24} \quad \mathbf{(9)}$$

Where:

- NCR: Normal Continuous Rating= 8250 kW

The case of the conventional engines and vessels was presented with the SFOC of both TIER II and TIER III as it was necessary that the main fuel would be changed from VLSFO/Biofuels to MGO within SECAs reaching for SOx compliance. Thus, main fuel consumption referred to two different fuels depending on the location of the ship and could not be presented summarised and proportionally. The Table 26 shows the fuel consumption of the main engines.

Table 26: Main Fuel and Pilot Fuel Consumptions of Main Engines

Fuel/ Ship	Main Fuel Consumption (SFOC or SGC) [g/kWh]	Pilot Fuel Consumption (SPOC) [g/kWh]	Main Fuel Consumption	ECAs MGO Consumption
VLSFO	162.70	0.00	25771680	6482520
B24	167.58	0.00	26544830	6482520
B30	168.39	0.00	26673689	6482520
LNG	136.38	3.17	27003240	0
Methanol	320.16	10.58	63391680	0
LPG	141.38	10.58	27993240	0
Ammonia	336.17	15.00	66561264	0
L.Hydrogen	54.55	3.17	10801296	0

The daily consumption of the fuels and their need for pilot fuel is also presented in Figure 39: Main Engine’s Daily Fuel Consumption for a better visual understanding:

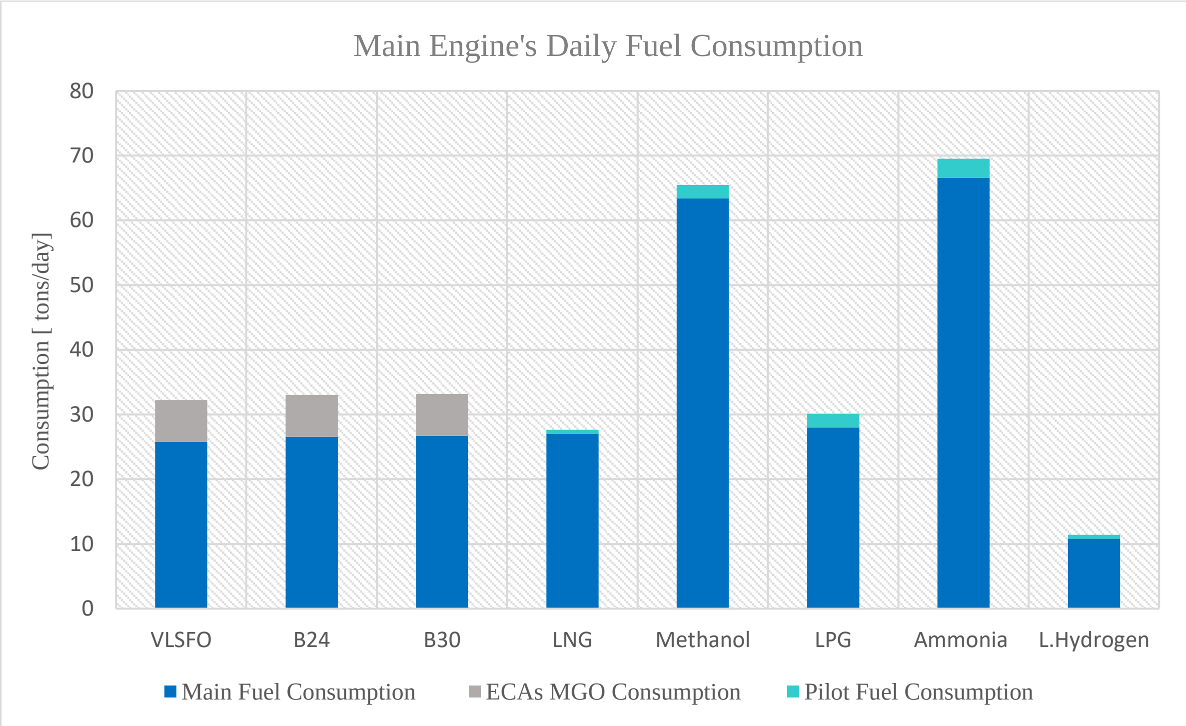

Figure 39: Main Engine's Daily Fuel Consumption

Following the above calculations, it was possible to quantify the Opex that the shipping company has to pay daily for the vessel on sea for the total fuel needed from the main engine by incorporating into the calculations the latest bunker fuel prices which are presented in $/metric ton in Table 23: Bunker Fuel Prices. Thus, the consumption is also converted in tons/day in Table 27: Main Engine Daily Fuel Cost. The daily fuel cost of the main engine was depicted in Figure 40.

Table 27: Main Engine Daily Fuel Cost

Fuel/ Ship	Engine's Main Fuel Consumption [tons/day]	Engine's Pilot Fuel Consumption [tons/day]	Engine's Main Fuel Cost [$/day]	ECAs MGO Main Fuel Cost [$/day]	Engine's Pilot Fuel Cost [$/day]
VLSFO/MGO	25.77/6.48	0	16906	5620	0
B24/MGO	26.54/6.48	0	20572	5620	0
B30/MGO	26.67/6.48	0	20379	5620	0
LNG	27.00	0.63	15392	0.0	438
Methanol	63.39	2.09	21236	0.0	1463
LPG	27.99	2.09	9798	0.0	1463
Ammonia	66.56	2.97	35286	0.0	2074
LH2	10.80	0.63	14042	0.0	438

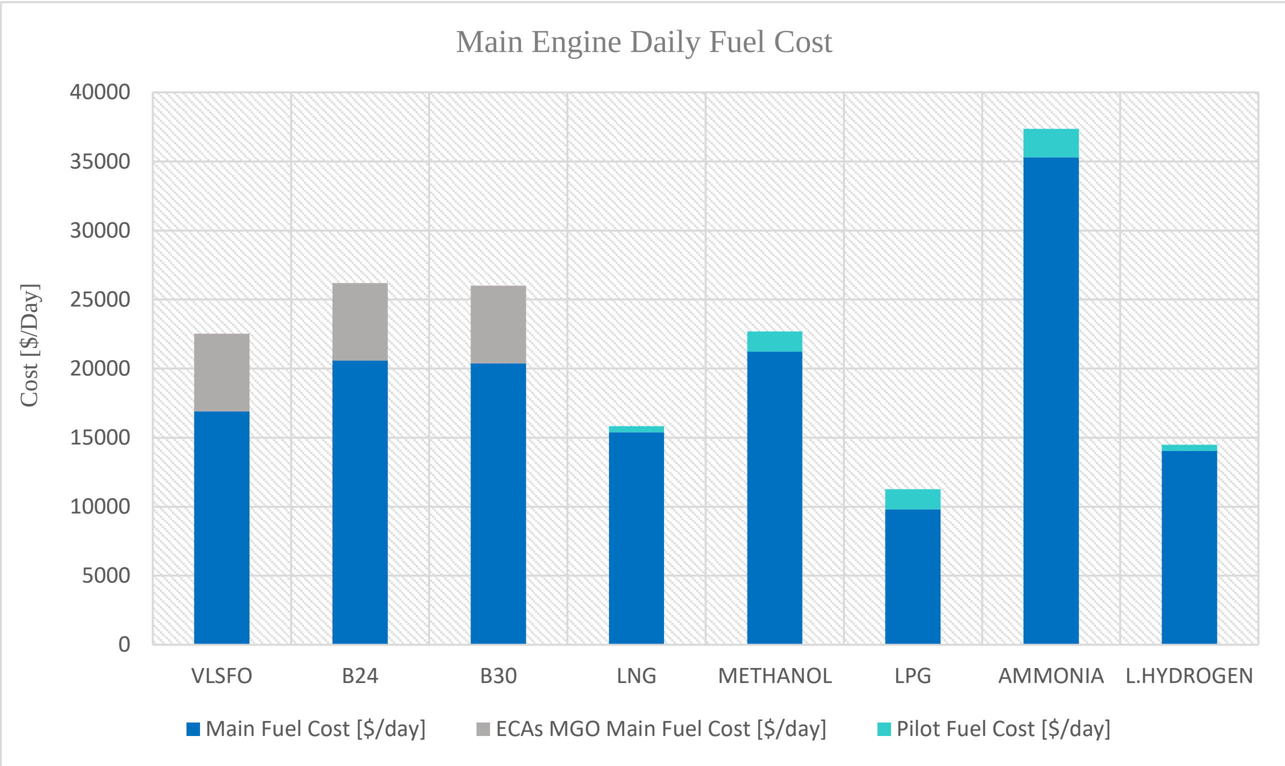

Figure 40: Daily Cost of Main Engine's Fuel

Genset Fuel Consumption & Cost

In order to calculate the fuel consumption of the gensets the efficiency of the generator was needed and was selected at the typical value of 40%. This was necessary to find the fuel energy input since the formula for the efficiency (η) of the generator was given from Equation $\boldsymbol{\eta} = \frac{\boldsymbol{Electrical\ Power\ Output}}{\boldsymbol{Fuel\ Energy\ Input}} \rightarrow \boldsymbol{Fuel\ Energy\ Input} = \frac{\boldsymbol{Power\ Output}}{\boldsymbol{\eta}}$ (10 :

$$\boldsymbol{\eta} = \frac{\boldsymbol{Electrical\ Power\ Output}}{\boldsymbol{Fuel\ Energy\ Input}} \rightarrow \boldsymbol{Fuel\ Energy\ Input} = \frac{\boldsymbol{Power\ Output}}{\boldsymbol{\eta}} \quad \textbf{(10)}$$

Thus, the Fuel Energy Input for each case was formed as presented in Table 28 based on the auxiliary power needs that were presented earlier in Table 13. Additionally, in the same table the need for pilot fuel input, which was described as a percentage (2% of total energy for LNG, LPG and LH2 and 5% for methanol and ammonia) was also shown.

Table 28: GenSet Fuel Energy Input

Fuel Type	Total Fuel Energy Input [kW]	Total Fuel Energy Input [MJ/h]	Main Fuel Input [MJ/h]	Pilot Fuel Input [MJ/h]
Conventional	1750	6300	6300.0	0.0
LNG	2010	7230	7085.4	144.6
Methanol	1830	6580	6316.8	263.2
LPG	1920	6910	6771.8	138.2
Ammonia	2010	7230	6868.5	361.5
LH2	2100	7560	7408.8	151.2
Note: Fuel Energy Input converted in MJ/h by multiplying with 3.6 for better utilization				

Reaching to the fuel consumption it was assumed that apart from conventional low sulfur diesel, LNG and methanol, also LPG, ammonia and LH2 could be used from the gensets in the near future meaning that the fuels used for main propulsion were also used for the generators. Regarding the conventional fuelled ship, the main fuels that could be used for the gensets where VLSFO, MGO, MDO and biofuels. On the other hand, MGO was the indicated pilot fuel by MAN ES gensets guides [70].

Using the Fuel Energy Input, it was possible to calculate the fuel consumption (L/h) using the volumetric energy density of each fuel from Table 4. By using the fuel density from Table 7, the main fuel and pilot fuel [MGO] consumption [g/h] was calculated. The above were presented in Table 29. Finally, a conversion to a daily fuel consumption (tons/day) by assuming operation for 24h and projecting the time in ECAs of a vessel during a voyage in daily time thus in daily consumption of MGO as main fuel for the conventional (20%) and 80% of VLSFO, B24 or B30. Ultimately, the genset fuel's daily cost was calculated by incorporating the bunker prices from Table 23. The genset's consumption and fuel cost were presented in Table 30, Figure 41 and Figure 42. The calculation for the fuel's consumption was made using the Equation $\boldsymbol{Fuel\ Consumption}[\boldsymbol{tons/day}] = \frac{\boldsymbol{Fuel\ Energy\ Input}\ [\boldsymbol{MJ/h}]\times \boldsymbol{Fuel\ Density}\ [\boldsymbol{g/L}]\times \mathbf{24}}{\boldsymbol{Volumetric\ Energy\ Density}[\boldsymbol{MJ/L}]\times \mathbf{10^6}}$ (11 below:

$$\boldsymbol{Fuel\ Consumption}[\boldsymbol{tons/day}] = \frac{\boldsymbol{Fuel\ Energy\ Input}\ [\boldsymbol{MJ/h}]\times \boldsymbol{Fuel\ Density}\ [\boldsymbol{g/L}]\times \mathbf{24}}{\boldsymbol{Volumetric\ Energy\ Density}[\boldsymbol{MJ/L}]\times \mathbf{10^6}} \quad (11)$$

Table 29: Genset Estimated Fuel Consumption

Fuel Type	Genset Main Fuel Consumption [L/h]	Genset Pilot Fuel Consumption [L/h]	Genset Main Fuel Consumption [g/h]	Genset Pilot Fuel Consumption [g/h]
VLSFO/MGO	166/172	0	155179 / 148033	0
B24/MGO	172/172	0	158248 / 148033	0
B30/MGO	173/172	0	159049 / 148033	0
LNG	319	4.0	148410	3398
Methanol	410	7.2	325274	6184
LPG	260	3.8	140645	3247
Ammonia	532	9.9	363125	8494
LH2	872	4.1	61755	3553

It is interesting that Liquified Hydrogen though needing the least amount per mass due to its high energy density [MJ/kg] it still comes with the highest volumetric consumption since it has the lowest volumetric energy density [MJ/L] meaning that a large volume of fuel must be consumed, and this leads to fuel tank size increase and potentially sacrificing cargo space.

Table 30: Genset's Fuel Daily Consumption & Cost

Fuel Type	Genset's Main Fuel Consumption [tons/day]	Genset's Pilot Fuel Consumption [tons/day]	Genset's Main Fuel Cost [$/day]	Genset ECAs MGO Main Fuel Cost [$/day]	Genset's Pilot Fuel Cost [$/day]
VLSFO/MGO	2.98	0.71	1955	616	0
B24/MGO	3.04	0.71	2355	616	0
B30/MGO	3.05	0.71	2333	616	0
LNG	3.56	0.09	2030	0	71
Methanol	7.81	0.16	2615	0	129
LPG	3.38	0.08	1181	0	68
Ammonia	8.72	0.21	4620	0	177
LH2	1.48	0.09	1927	0	74
Note: FUEL/MGO values resulted from an 20% operation on MGO for SECAs compliance and 80% on VLSFO or Biofuels					

Below the calculated genset's daily fuel consumption and daily fuel cost were presented also in Figure 41 and Figure 42 respectively.

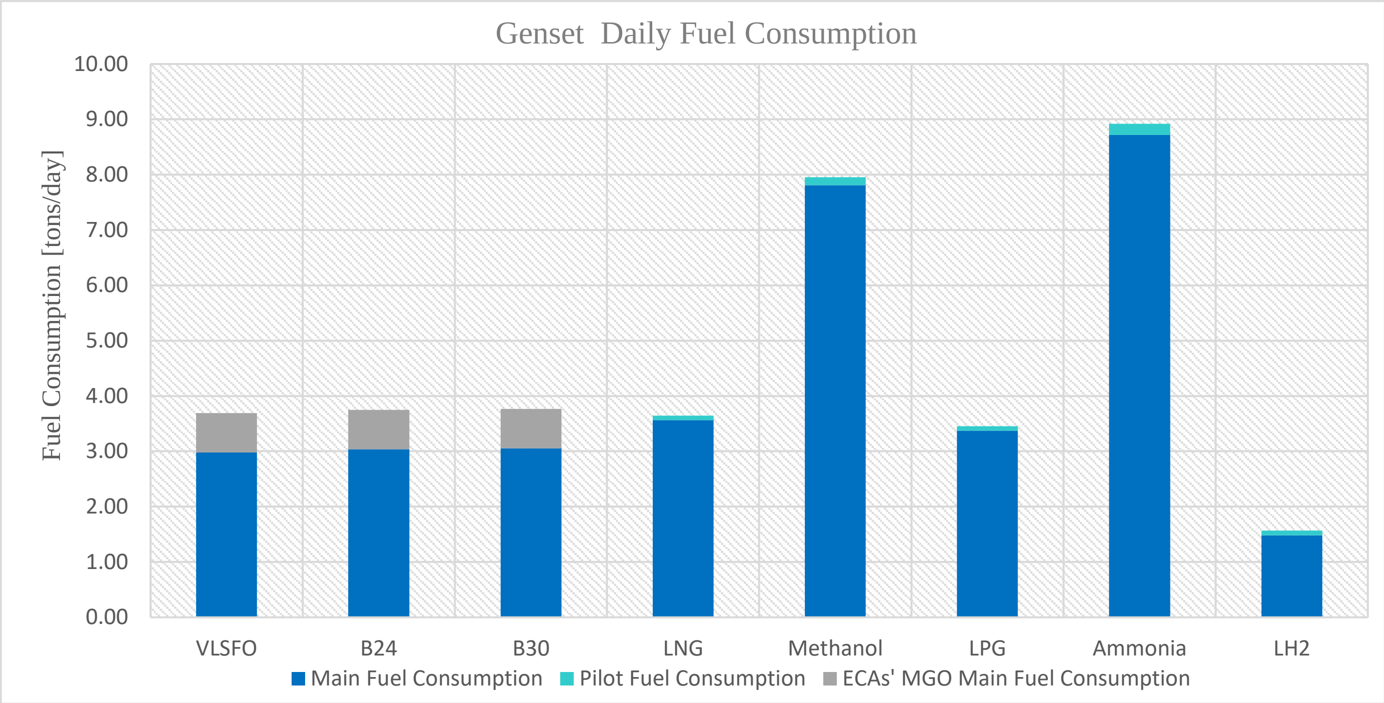

Figure 41: Genset's Daily Fuel Consumption

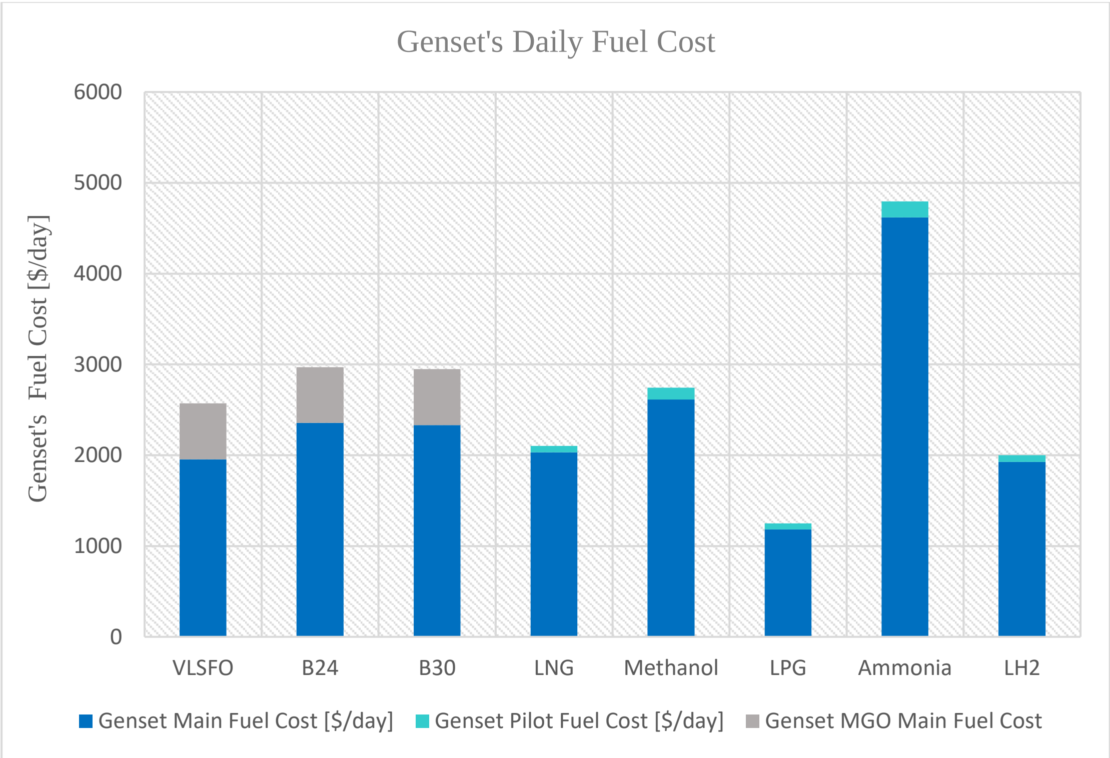

Figure 42: Genset's Daily Fuel Cost

Boiler Fuel Consumption

For the fuel fired marine boilers as it was previously mentioned, an exhaust gas economizer was used in addition to the boiler, recovering waste heat from the main engine's exhaust gases by preheating the feedwater of the boiler and ultimately limiting the fuel consumption of the boiler. As the efficiency of the boiler is increased in that way and fuel needed significantly reduced, the consumption of the boilers was considered a side factor and was not included in the calculations of this thesis.

Total Fuel Consumption

Conclusively, the total daily fuel cost from the main engine and the generator sets were presented aggregated below in Figure 43:

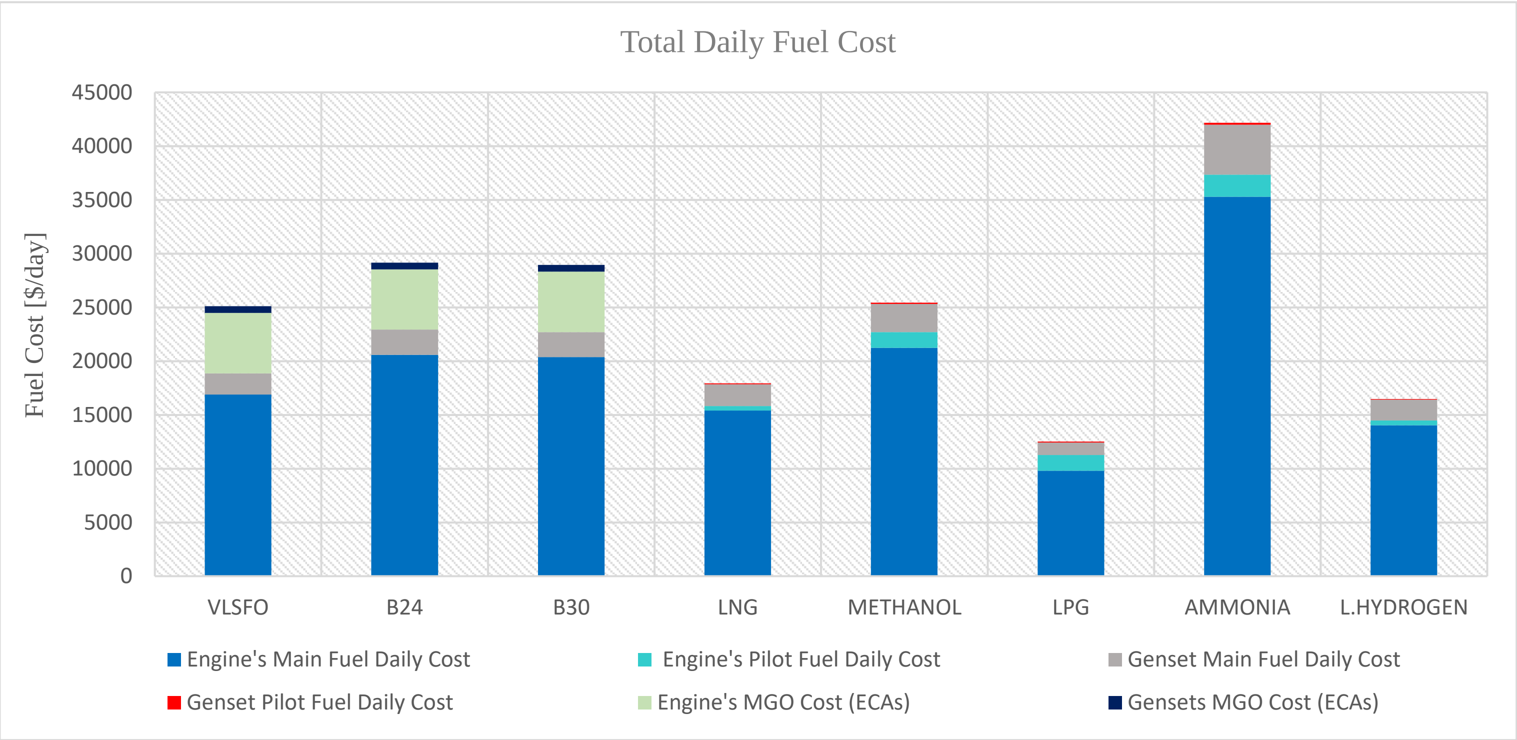

Figure 43: Total Daily Fuel Cost

3.2.3 Lubrication

It was anticipated that annual lube costs, either referring to the main engine system and cylinder oil, turbocharger lubricants or hydraulic oils would vary when dealing with different dual fuel engines particularly due to different viscosities of the fuels discussed. Methanol and liquified hydrogen have a low viscosity as mentioned earlier leading to an increased need of lubricating oils. Additionally, corrosive fuels like methanol and ammonia are likely to need additives in their lubricants more system protection. The data for the daily cost of lubricants were collected from annual maritime reports and forecast and mainly focused on newbuilds with a DWT profile similar to the one discussed in this thesis (80000 tons) [11]. Some estimations were also made taking into account that methanol and ammonia would need more cylinder oil due to much higher amounts (tons) of fuel injected into the engines for the same energy output as from Table 26 and Table 29. LH2 was not expected to have a significant difference from LNG in lub costs as there are already available engines operating with LNG and hydrogen blends, therefore was taken equal. Therefore, the daily lubrication costs were presented in Table 31 and Figure 44.

Table 31: Lubricating Oils Cost

Ship/Fuel	Lubricating Oils Costs (USD / day)
VLSFO	400
B24	400
B30	400
Methanol	600
LNG	510
LPG	510
Ammonia	660
Hydrogen	510
Note: Methanol's lub cost was selected to have a conservative increase by 1.5x compared to the conventional lub needs while ammonia lub cost was selected to be 1.1 times higher than methanol's.	

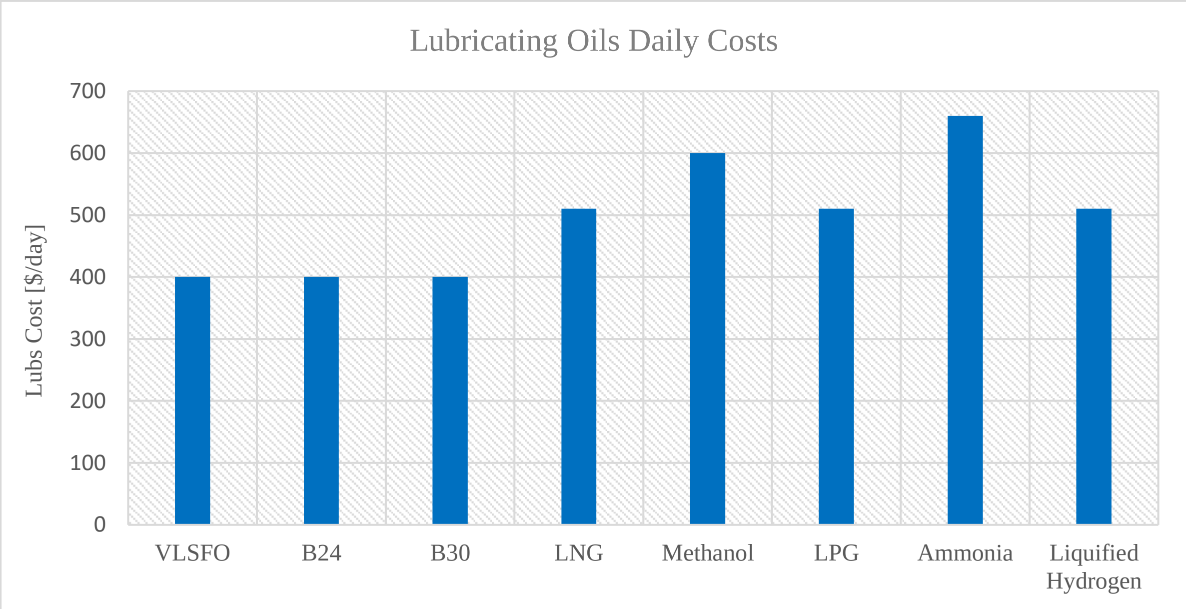

Figure 44: Lubricating Oils Daily Costs

3.2.5 Maintenance & Repair (M&R) and Drydocking

Maintenance and Repair in general is an operational expenditure that can be categorised as scheduled or unscheduled and can typically account for 15% of the total Opex of each ship. Additionally, data indicate that depending on the vessel type costs can vary due to different needs from the engine, safety reasons particularly when dealing with toxic and highly explosive fuels which call for a perfect operation of capture and ventilation systems as well as higher costs from the shipyards for scheduled intermediate or full dry-docking surveys. Unscheduled maintenance and repair refer to minor or major accidents such as collisions or systems failure. Thus, the Opex in this section was calculated in assistance with maritime specialists and data from maritime operating costs reports [11]. The costs regarding the maintenance of the main engine, generators, boilers, and ER auxiliaries were the ones changing from vessel to vessel while costs for maintenance of cargo & ballast system, electrical systems, pipes, valves & hydraulic systems, deck machinery, navigation equipment and life saving and fire fighting equipment were included but not changed on each vessel.

Regarding the biofuels B24 and B30 it was assumed that maintenance and repair was not affected compared to the conventional fuel as the engine is also the same and most of the fuel's composition is still VLSFO. Since some of the fuels are being used in marine engines still at a low scale and data were hard to be collected while ammonia and hydrogen for internal combustion engines of a high-power output are still at a research level, LPG, methanol, ammonia and hydrogen maintenance costs were inevitably qualitative and calculated as an expected percentage of the conventional fuelled vessel. These costs are presented Table 32 and Figure 45 with the dry-docking surveys excluded.

Table 32: Repair & Maintenance Costs [$/day]

Ship / Main Fuel	Fixed Maintenace & Repair Costs [$/day]	Main Engine [$/day]	Boilers [$/day]	Generators [$/day]	ER Auxiliaries [$/day]	Total Maintenance & Repair [$/day]
Conventional (VLSFO, Biofuels)	106	43	4	41	16	210
Methanol	106	51	5	49	19	231
LNG	106	64	10	64	61	305
LPG	106	53	6	51	20	236
Ammonia	106	77	8	73	28	293
L.Hydrogen	106	127	20	127	122	503

Note: Conventional and LNG costs were calculated from Drewry [11]. Methanol costs were calculated increased by 20% from the conventional, LPG costs 25% and Ammonia 80%. LH2 was increased by 200% compared to the LNG costs.

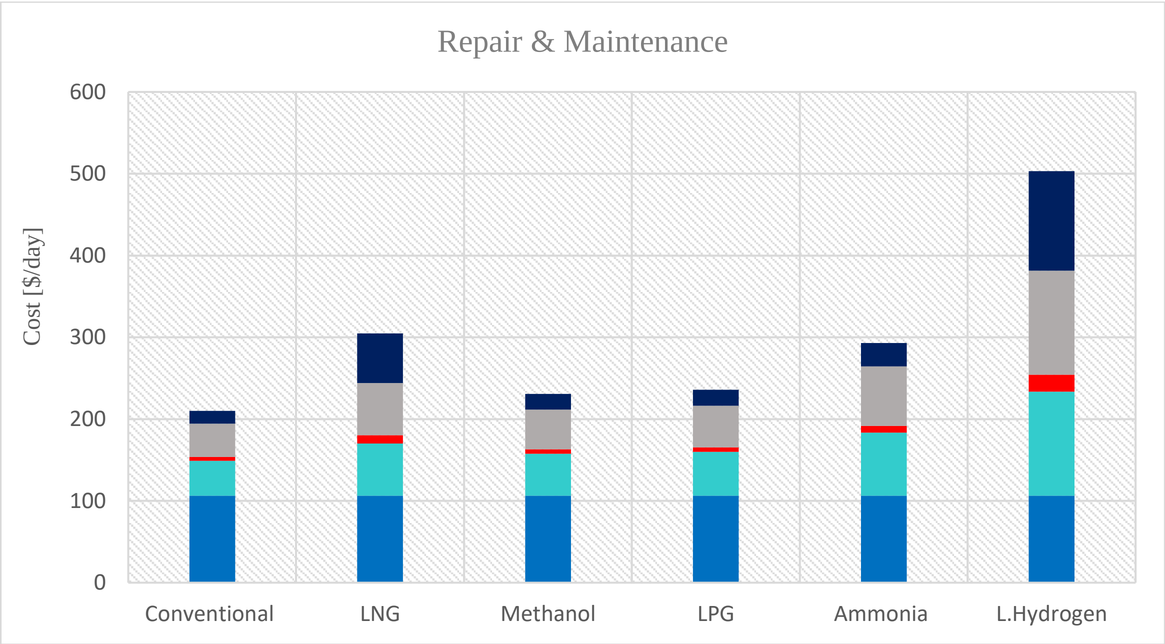

Figure 45: Repair & Maintenance Costs [$/day]

Drydocking Cost

Indicative costs for drydocking were again collected from Drewry annual report ship's operating costs [11]. General and fixed survey costs were the base for all vessels indicated from a panamax conventionally fuelled dry bulk carrier. The fixed costs that were not subject to change depending on the fuel included general drydocking services, underwater repairs, hull maintenance, hull outfitting, life saving and fire fighting equipment survey, survey of electrical controls and accommodation needs. Costs that were taken as variables were associated with the machinery and the valves & piping as presented from drewry. Data about LNG and LPG fuelled vessels were also collected while methanol, ammonia and LH2 were calculated qualitatively as a percentage of the given costs. A factor of 1.1x Conventional, 1.8x Conventional and 2x LNG was used for methanol, ammonia and LH2 respectively.

The drydocking costs for intermediate surveys every 2.5 years were presented in Table 33 and Figure 46.

Table 33: Intermediate Survey Drydocking Costs [USD]

Ship / Main Fuel	Fixed Costs [USD]	Machinery [USD]	Valves & Piping [USD]	Intermediate Drydocking [USD]
Conventional (VLSFO, Biofuels)	409150	115250	51860	576260
Methanol	409150	126775	57046	592971
LNG	409150	150442	67702	627293
LPG	409150	146120	65750	621020
Ammonia	409150	207450	93348	709948
L.Hydrogen	409150	300883	135403	845436

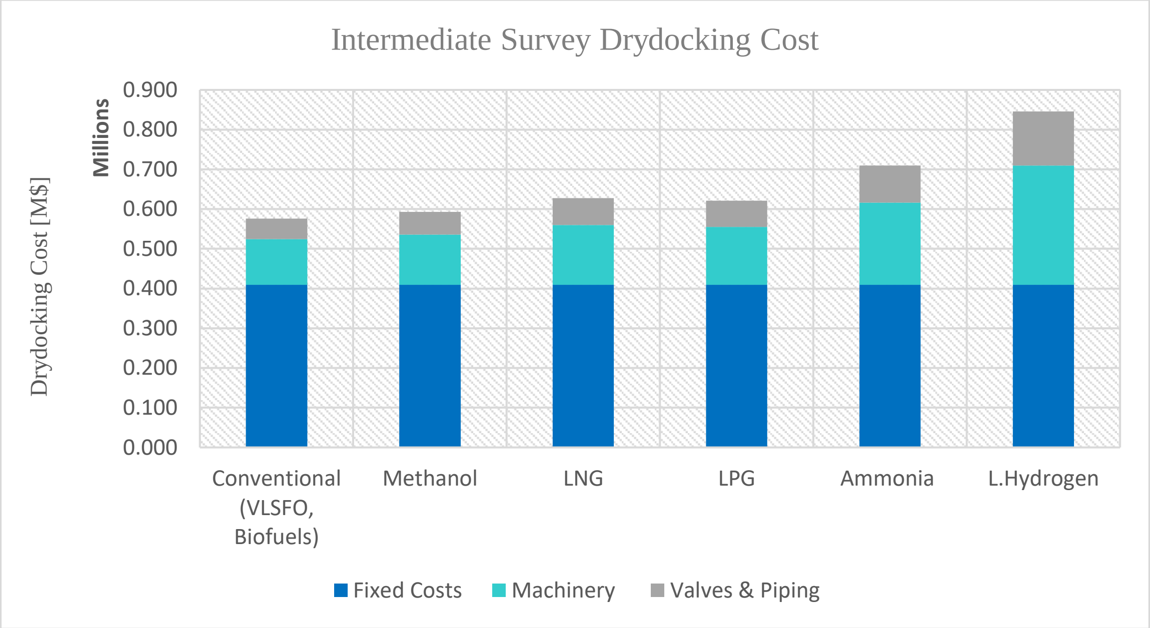

Figure 46: Intermediate Survey Drydocking Cost

The drydocking costs for full surveys every 5 years were presented in Table 34 and Figure 47 below:

Table 34: Full Survey Drydocking Costs per Fuel/Vessel

Ship / Main Fuel	Fixed Costs	Machinery	Valves & Piping	Full Drydocking [USD]
Conventional (VLSFO, Biofuels)	619080	174390	78470	871940
Methanol	619080	191829	86317	897226
LNG	619080	227640	102440	949160
LPG	619080	235980	106190	961250
Ammonia	619080	313902	141246	1074228
L.Hydrogen	619080	455280	204880	1279240

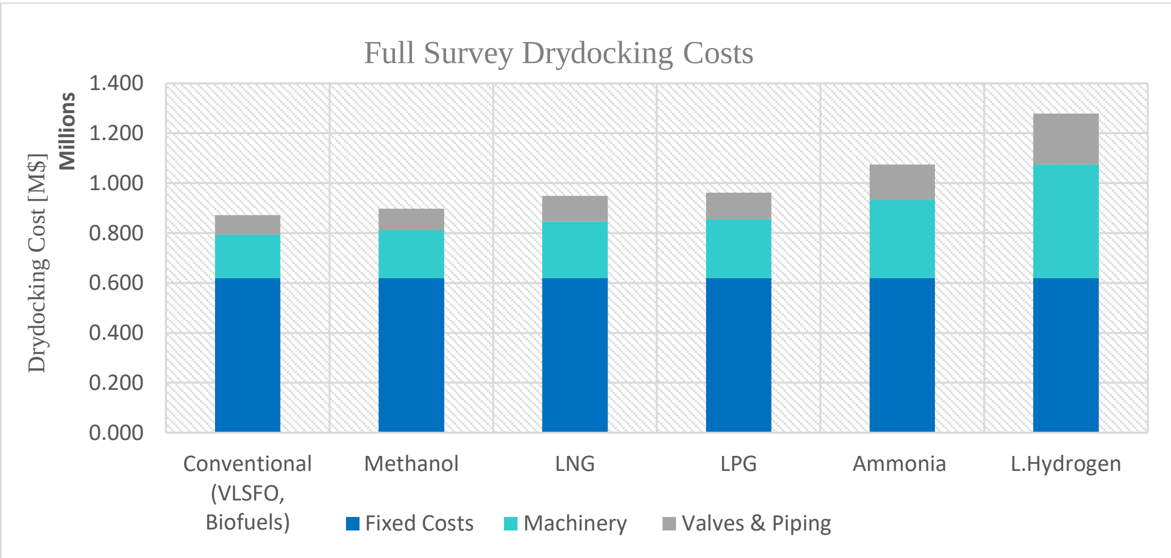

Figure 47: Full Survey Drydocking Costs

3.2.4 Emissions & Environmental Taxes

In the framework of this thesis the main regulation that resulted in straightforward fees for emissions was the EU ETS which was analyzed in section 2.1.2 European Union. FuelEU is still in a preliminary level and is expected to consider well to wake emissions which in the scale of this thesis were not possible to be calculated. As far as the EEDI rating was concerned since newbuilds were the vessels involved since new technologies and fuels were discussed, the indicator was fulfilled and no fees came out of it. From a CII perspective, since compliance is obligatory, a specific rating was considered and maintaining that was associated with either a lower vessel's speed which was not accepted for this analysis or a change in biofuels instead of the conventional VLSFO which as presented earlier have a higher bunker cost but reduce the regulatory & environmental taxes and offer a higher sustainability.

Regarding EU ETS as mentioned earlier in the respective section, the EU ETS will soon include except for the CO_2 emissions, also methane (CH_4) and nitrous oxide (N_20) equivalents being evaluated from their global warming potential, starting in 2026. The approach that was followed incorporated all the above greenhouse gases with the assumption that all of the tons emitted were paid with the relative allowances. It is worth mentioning though that the limit of the allowances will be gradually lowered resulting in an inevitable integration of alternative fuels. The following equivalence shows the impact each gas has on the environment on a 100-year basis indicated by the Global Warming Potential (GWP).

- CH_4 → 28 x CO_2 (mass)
- N_2O → 298 x CO_2 (mass)

Determining the cost of emissions and consequently the total price of EU Allowances that each ship will be obliged to deliver raised the need of quantifying the total emitted amount of CO_2, CH_4 and N_2O from each vessel and engine from a tank-to-wake approach and then multiplying with the above factors to turn every gas into CO_2e.

Methane Slip

As discussed, methane can be emitted from LNG engines and these were the only engines where methane emissions were noticed. Below, the engine's methane slip was provided by MAN Energy Solutions CEAS Engine Data report in g/kWh for different engine loads[71]. The slip provided was at engine's NCR (8250kW) which is under analysis at 75% load. Additionally, it is suggested that gensets emit a higher percentage of methane slip and could be responsible for a greater total amount of CH4 slipped than the main engines. As the gensets were selected to operate on a quite high engine load a 5% slip was selected but it could go up to 7 or 8% on lower loads[72]. The methane slip of the High pressure LNG engine and gensets was depicted in Table 35.

Table 35: Methane Slip of LNG High Pressure Engine

Fuel/Engine	Methane Slip CH_4	CH_4 Slip (tons/day)
LNG / 8G50ME-C9.6-GI	0.23 (g/kWh)	0.046
Gas Gensets	5 % of total LNG Input	0.178
Total		0.224

CO_2 Emissions

Defining the CO_2 emitted from each engine required the CO_2 content of each fuel as well as the fuel consumption of each engine. Below in Table 36 the CO_2 emissions factor of each fuel from its combustion was found[73],[74].

Table 36: Emissions CO_2 Factors

Fuel	CO_2 Emissions Factor [t CO_2 / t fuel]
VLSFO/MGO	3.114
B24	2.499
B30	2.345
LNG	2.75
Methanol	1.375
LPG (Propane)	3.00
Ammonia	0
L.Hydrogen	0

Consequently, the CO2 emitted from every main engine and from the gensets for each vessel was calculated according to the main and pilot fuel needed per day for the operation of the vessel as depicted in Equation 12:

$$CO2Emitted = CO2Factor_{MainFuel} \times Consumption_{MainFuel} + CO2Factor_{PilotFuel} \times Consumption_{PilotFuel} \quad (12)$$

The total CO2 emissions were gathered in Table 37.

Table 37: CO2 Emitted from Main Engine and Gensets [g/day]

Fuel/Main Engine	CO2 Emitted from Main Engine [tons/day]	CO2 Emitted from Genset [tons/day]	Total CO2 Emitted [tons/day]
VLSFO/MGO	100.440	13.810	114.250
B24/MGO	82.531	11.266	93.798
B30/MGO	77.755	10.618	88.373
Methanol	76.213	10.049	86.262
LNG	93.687	11.196	104.883
LPG	90.503	10.369	100.872
Ammonia	9.249	0.635	9.883
L.Hydrogen	1.955	0.266	2.220

As it is shown, the ammonia and hydrogen engines emitted a much lower amount but still not negligible due to the pilot fuel consumption needed for the ignition of the fuel.

N_2O Emissions

Nitrous Oxide (N_2O) was assumed to be formed only from little slippage of ammonia from unburnt NH_3 from the main engine. Any other formation of N_2O was considered negligible and was not assessed. Any N_2O emission levels though would be lower than the safety limits for alarms activation. The levels of N_2O emissions according to recent studies were not expected to exceed 0.06 g/kWh for the ammonia engine[75]. The selected level was 0.05 g/kWh as a realistic scenario towards the higher limit for a conservative approach due to safety reasons and the NCR of the respective engine was considered. It should be noted that both the main engine and the gensets were considered, assuming that in the near future an ammonia genset will be available. The kWe needed for the auxiliary power on an ammonia fuelled vessel were used. The total N_2O emissions were presented in Table 38.

Table 38: Nitrous Oxide Emissions from the Ammonia Main Engine

Fuel/Engine	Nitrous Oxide (N_2O) (g/kWh)	N_2O (tons/day)
Ammonia	0.05	0.011

GHG Emissions in CO_2 Equivalents

Using the GWP_{100} factors for the greenhouse gases CO_2 equivalence of 28 and 298 that were mentioned it was possible to present the gases emitted from the main engines and involved in EU ETS in the aggregated Figure 48.

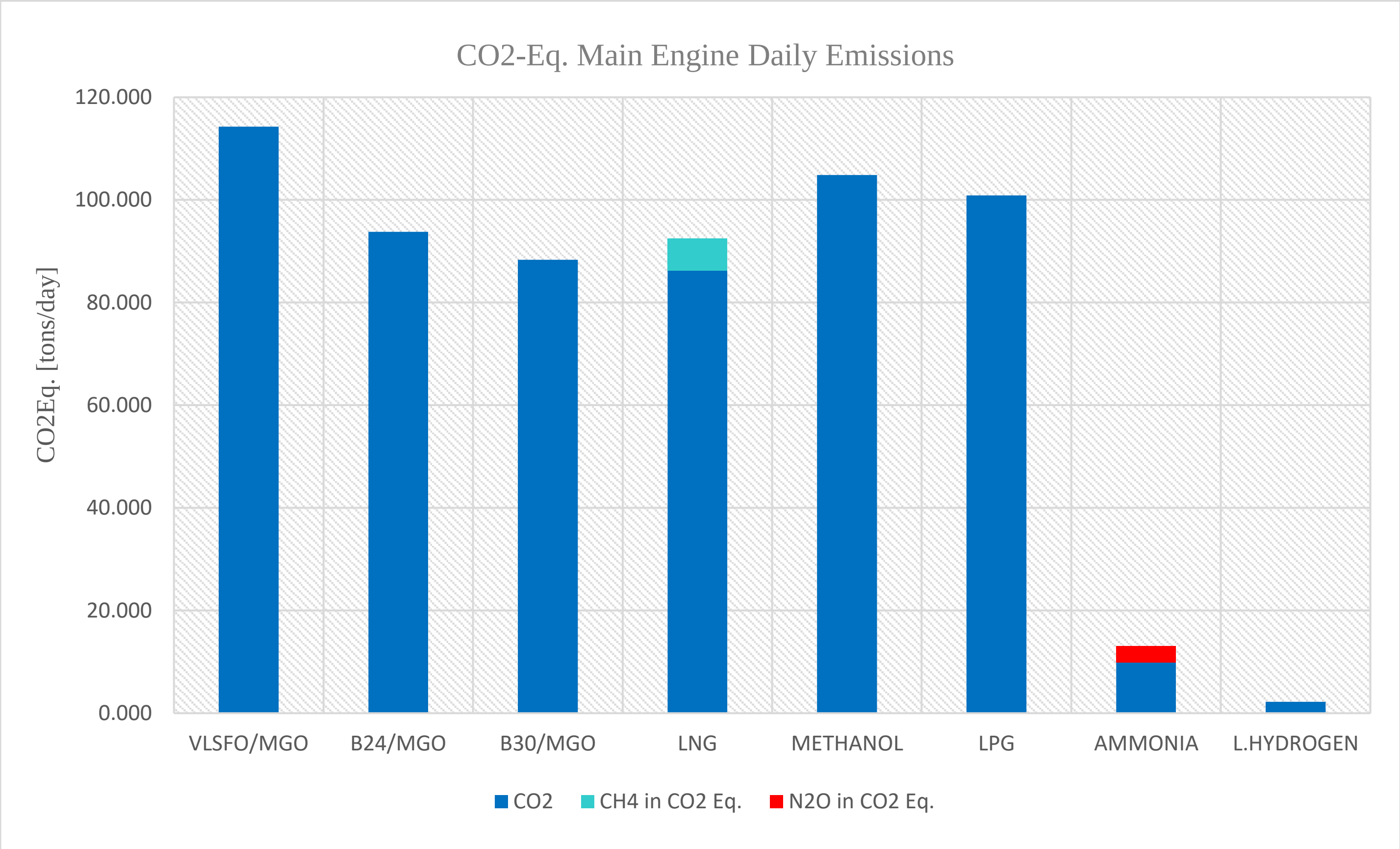

Figure 48: CO_2-Eq. Total Emissions [g/day]

EU Allowances Cost

The cost of EU Allowances has been following the rule of demand and supply but also defined in a great way from the pressing need of lower emissions and higher sustainability leading in a gradual increase. The way the EU ETS Allowance's cost has been changing through the past years up until today's price can be seen in Figure 49: EU ETS Allowance Cost ($/Ton) Fluctuation [76]. The latest price was formed at 65.85 $/ton while reaching an all-time high of 109.12 $/ton around 2021. It is expected though to be increased in the following years as the price is straightly affected by the decision of the European organizations to provide a specific number of allowances each year. An Allowance price of 100$ was selected towards the higher level of the spectrum.

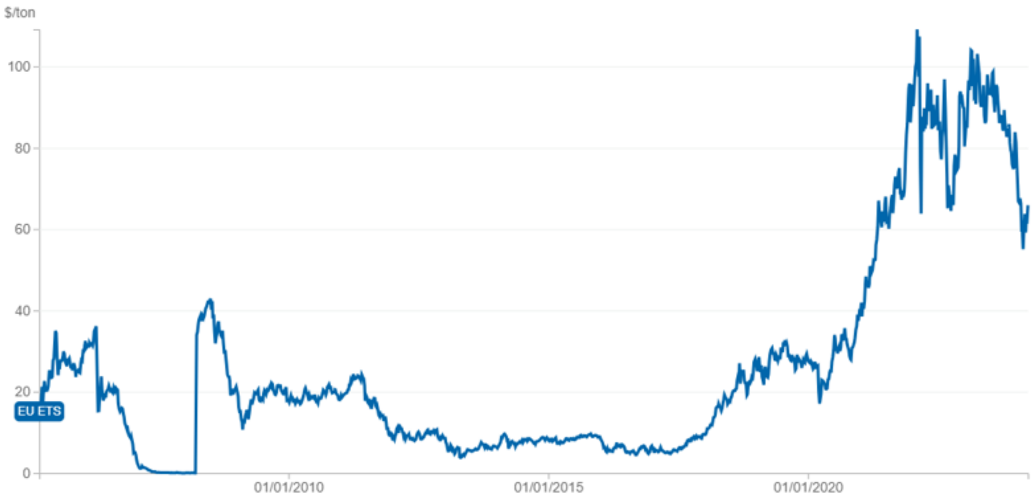

Figure 49: EU ETS Allowance Cost ($/Ton) Fluctuation [76]

For the exact calculation it was necessary to separate the ship voyages into three different categories as explained in 2.1.2 European Union which were the following:

- Intra EU/EEA Voyages including 100% of the emissions consequently 100% of the allowances:

The cost of the equivalent allowances was depicted in Table 39 and Figure 50 as follows:

Table 39: Allowances Cost for Intra EU/EEA Voyages

Fuel	CO_2 Eq. [tons/day]	100% Allowances Daily Cost [$/ day]
VLSFO	114.250	11204
B24	93.798	9202
B30	88.373	8671
Methanol	104.883	10488
LNG	92.524	9252
LPG	100.872	10087
Ammonia	13.121	1312
LH2	2.220	222

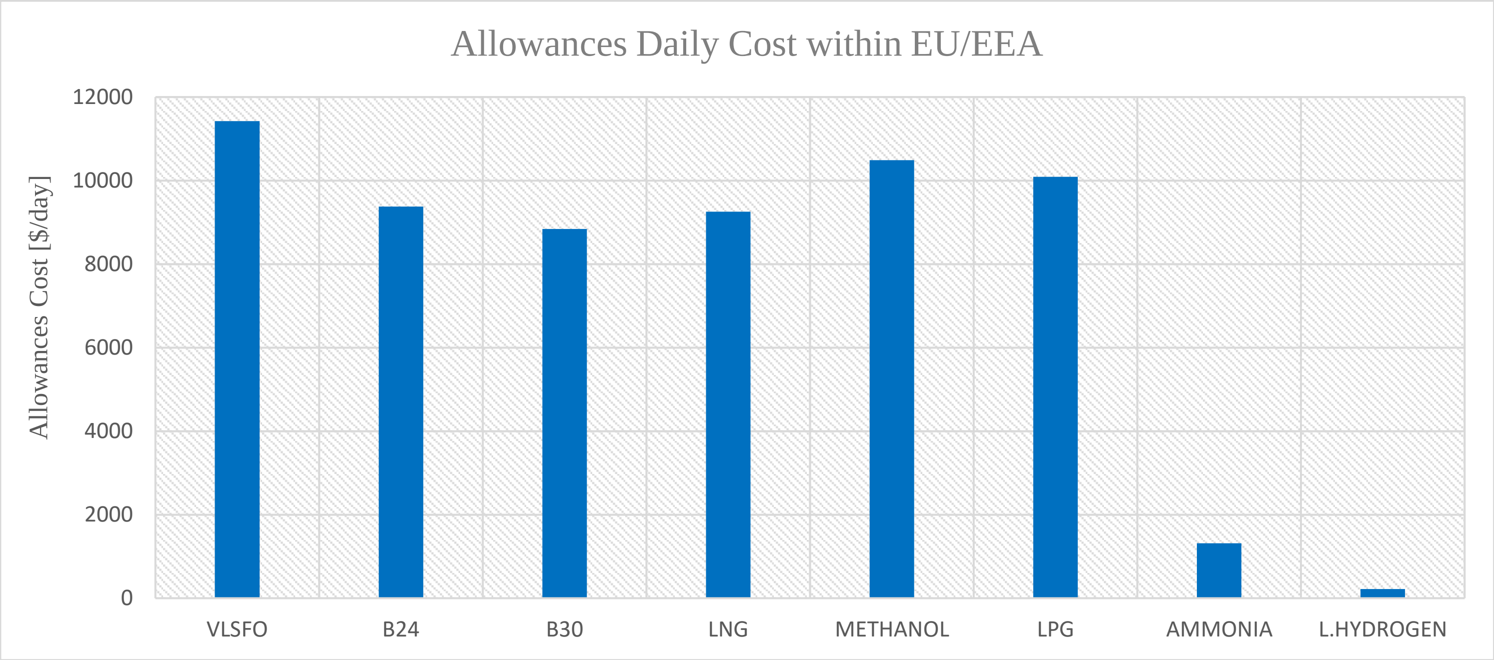

Figure 50: Allowances Daily Cost for Intra EU/EEA Voyages

- Entering/Exiting EU/EEA Voyages including 50% of the emissions consequently 50% of the allowances:

The cost of the equivalent allowances was depicted in Table 40 and Figure 51 below.

Table 40: Allowances Cost for Voyages Entering/Exiting EU/EEA

Fuel	CO_2 Eq. [tons/day]	50% Allowance Total Cost [$/ day]
VLSFO	114.250	5712
B24	93.798	4690
B30	88.373	4419
Methanol	104.883	5244
LNG	92.524	4626
LPG	100.872	5044
Ammonia	13.121	656
LH2	2.220	111

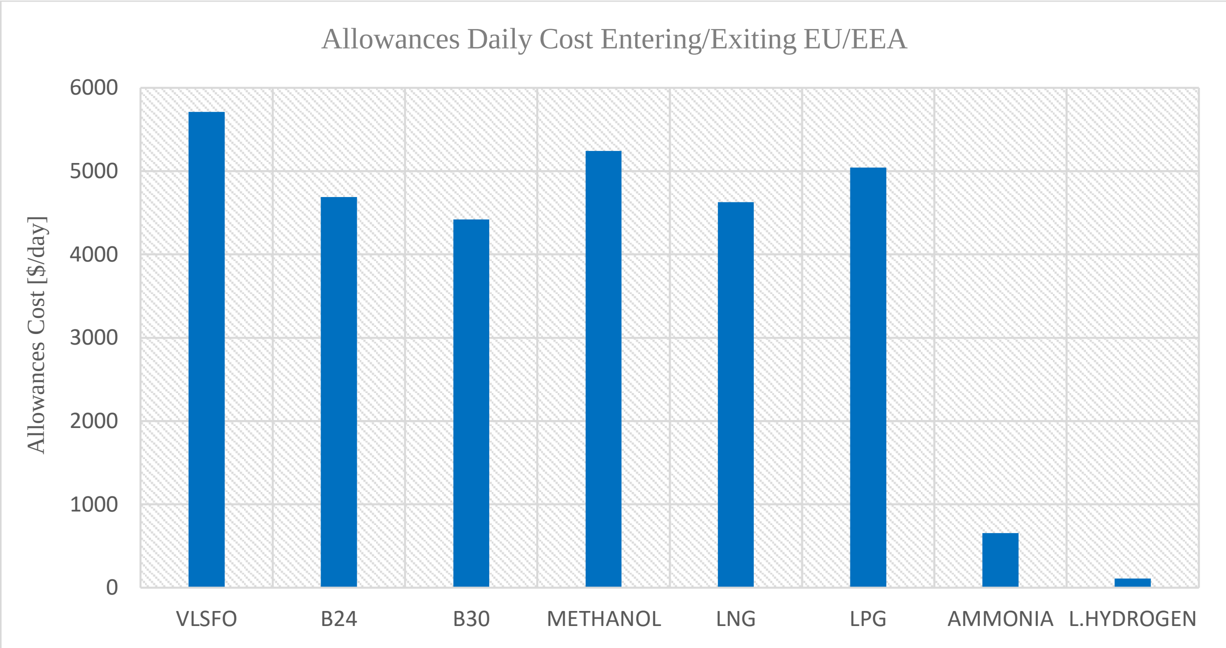

Figure 51: Allowances Daily Cost for Voyages Entering/Exiting EU/EEA

- Outside of EU/EEA Voyages:

  The EU ETS was currently not involved for trips outside of the European Economic Area, consequently no allowances were supposed to be paid thus significantly reducing the Opex for any ship operating at this range. However, more regulations are expected to straightly affect voyages outside of the EEA in the near future but are still to be announced.

IMO & NO_x Emissions

For the engines selected, NO_X emissions were ensured to be within limits of TIER II for every load and operation without any extra technology while TIER III within $NECA_s$ was covered with the use of EGR (Exhaust Gas Recirculation) or SCR (Selective Catalytic Reduction). More specifically, the NO_x reduction technology and system that is applied is affected by the kind and the size of the engine and vessel but on a certain degree it is also up to the choice of the shipowner whether an EGR or an SCR will be used. In the case of the selected main engines both of the technologies were available for installation. It should be noted that SCR was the selected technologies for the CEAS Engine calculations. This led to the subsequent consumption of urea in a water-based solution which is injected into hot exhaust gases in order to convert NO_X into nitrogen gas and water vapor. For the ammonia fueled vessel instead of urea, ammonia can be injected as the catalytic agent in the SCR reactor providing the same result whilst the ammonia consumption for the catalytic reduction could be considered negligible.

It was consequently concluded that NO_X compliance affected the TCO on the one hand with the cost of acquisition and installation of the SCR system which comes with the main engine, and it was incorporated into the calculation for the engine's capex and on the other hand with a higher fuel consumption and fuel cost when in TIER III operation within NECAs. For the gensets suitable for the size of the ship analyzed, fuel oil operation was in compliance with TIER II but TIER III compliance was possible either with an after-treatment system or by operating in gas mode for LNG available gensets.

IMO & SO_X Emissions

A significant advantage of the alternative fuels considered is their really low sulfur content at an extend that are often described as sulphur-free fuels. Thus, no sulfur was supposed to be emitted from the fuels themselves rather from the pilot fuel injected to the engine which differ in amount on each occasion. On the other hand, VLSFO with a sulphur content of 0.5%, though compliant with the IMO regulations for worldwide routes outside of Emission Control Areas, they fail to comply with the ECAs requirements demanding a 0.1% sulphur content. Reaching for compliance with $SECA_S$ requirements for a conventionally fuelled vessel, it was assumed that MGO would be used for operation within the areas. MGO with a sulfur content of no more than 0.1% was accepted by the regulations. This shift however raised the fuel cost as MGO has a higher bunker price. Therefore, this explains further the approach with the MGO consumption within SECAs in 3.2.2 Fuel Consumption & Cost.

IMO & CII Regulation

Regarding CII from IMO, as mentioned earlier the regulation mandates that the considered ship should have an attained CII that is lower than the required CII rating corresponding to a mid-point C rating. Not reaching the required CII for 3 consecutive years with a D rating means a mandatory surrender of reasons for not complying and delivery of an emission reduction plan for the next year.

Since the CII refers to annual CO2 emissions, annual distance travelled and Capacity (DWT or GT) the fixed data for every fuel that were used for the CII calculation were the following:

- 292 days on sea with normal Main Engine and Genset operation
- 73 days at port only with genset operation

- Annual Distance Travelled [nm]: 94608
- Ship DWT Capacity [tons]: 80000

The corresponding CO2 annual emissions per fuel and vessel were presented in Table 41 and Figure 52: CO_2 Annual Emissions for CI.

Table 41: CO_2 Annual Emissions for CII

Fuel	CO_2 Annual Sea Emissions [tons]	CO_2 Annual Port Emissions [tons]
VLSFO/MGO	33360.915	1008.139
B24/MGO	27388.900	822.434
B30/MGO	25804.797	775.112
LNG	25188.639	733.578
Methanol	30625.878	817.326
LPG	29454.679	756.947
Ammonia	2885.955	46.342
Liquified Hydrogen	648.256	19.383

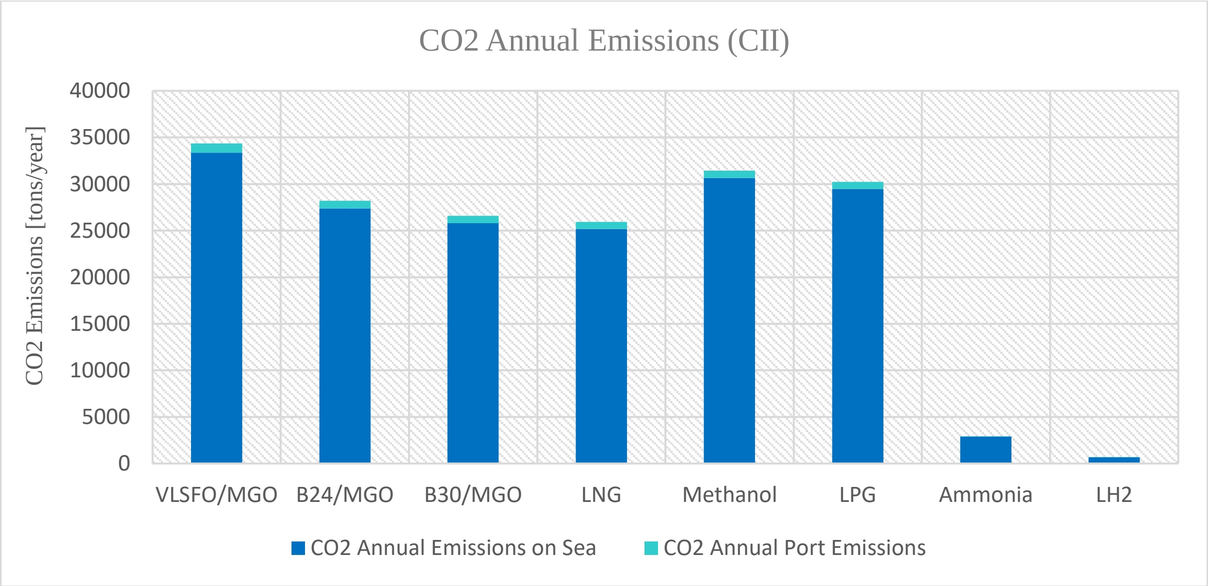

Figure 52: CO_2 Annual Emissions for CI

Table 42: Attained CII of each Vessel/Fuel

Fuel/ Vessel	Attained CII (Gensets at port)
VLSFO/MGO	4.541
B24/MGO	3.727
B30/MGO	3.512
LNG	3.425
Methanol	4.154
LPG	3.992
Ammonia	0.387
L. Hydrogen	0.088

For the CII rating of each vessel and their compliance it was necessary to calculate the required CII at the C-level mid-point as shown in Figure 53 with the incorporated reduction factors for each year after 2019.

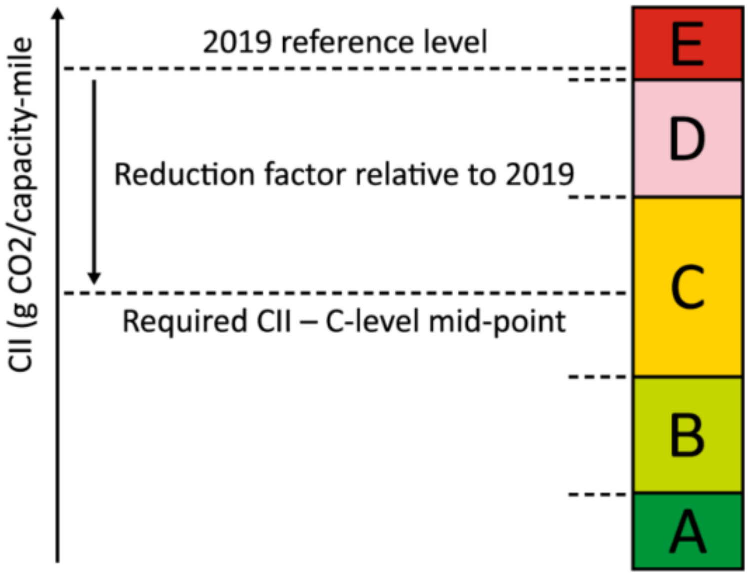

Figure 53: Required CII and Reference Level [77]

The CII reference level of 2019 was calculated by the Equation $\boldsymbol{CII_{REF}} = \boldsymbol{a} \times \boldsymbol{Capacity}^{-c} = \mathbf{4.232}$ (13 from IMO (Annex 10 MEPC.366):

$$\boldsymbol{CII_{REF}} = \boldsymbol{a} \times \boldsymbol{Capacity}^{-c} = \mathbf{4.232} \quad \textbf{(13)},$$

Where for bulk carriers: a=4745,

c=0.622

The required CII is subject to change through the years while it has already included a 7% reduction in 2024 compared to 2019 reference line and is decided to incorporate a reduction of 9% in 2025 and 11% in 2026. It was assumed that the next years will be quite on the same proportional reduction meaning that 2% reduction was added on each following year, however it is anticipated that the reduction factors will become stringent. Thus, the required CII was formed with yearly reduction factors as follows in Table 43 and Figure 54. The upper boundary of rating C and the rating D were also calculated from the CII Regulation Guidelines [78].

Table 43: Required CII and Rating Boundaries

Year	Reduction Factors from 2019 CII Ref	Required CII Rating C (Mid)	CII Rating C Upper boundary	CII Rating C Lower boundary	Inferior Boundary	Superior Boundary
2024	7%	3.935	4.172	3.699	4.644	3.385
2025	9%	3.851	4.082	3.620	4.544	3.312
2026	11%	3.766	3.992	3.540	4.444	3.239
2027	13%	3.682	3.902	3.461	4.344	3.166
2028	15%	3.597	3.813	3.381	4.244	3.093
2029	17%	3.512	3.723	3.302	4.145	3.021
2030	19%	3.428	3.633	3.222	4.045	2.948
2031	21%	3.343	3.544	3.142	3.945	2.875
2032	23%	3.258	3.454	3.063	3.845	2.802
2033	25%	3.174	3.364	2.983	3.745	2.729
2034	27%	3.089	3.274	2.904	3.645	2.657
2035	29%	3.005	3.185	2.824	3.545	2.584
2036	31%	2.920	3.095	2.745	3.445	2.511
2037	33%	2.835	3.005	2.665	3.346	2.438
2038	35%	2.751	2.916	2.586	3.246	2.366

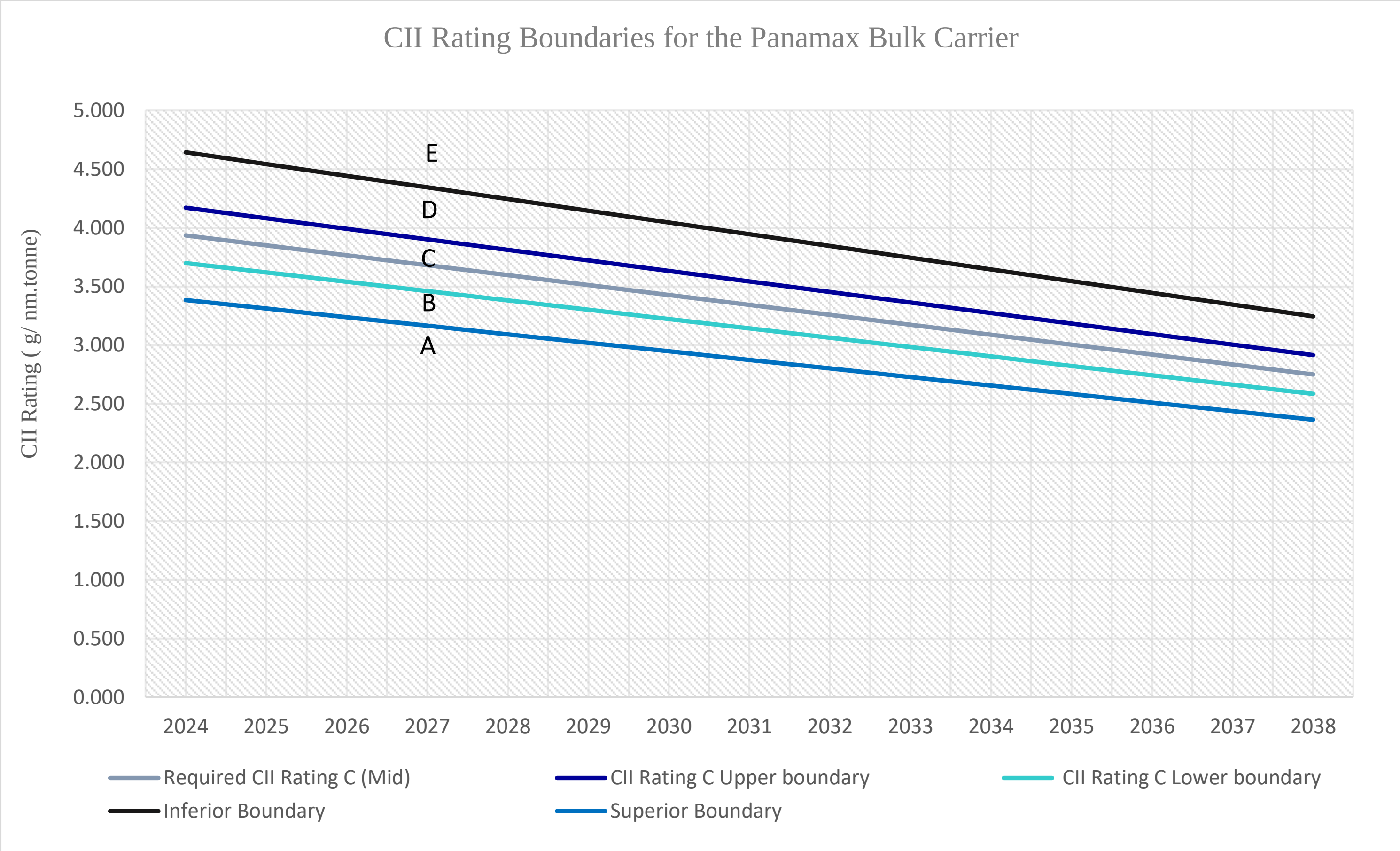

Figure 54: CII Rating Boundaries

As a result, the ratings of each vessel and fuel were concluded for the years considered as follows in Table 44.

Table 44: CII Rating of each Vessel through the Years

Year	VLSFO CII Rating	B24 CII Rating	B30 CII Rating	LNG CII Rating	Methanol CII Rating	LPG CII Rating	Ammonia CII Rating	LH2 CII Rating
2024	D	C	B	B	C	C	A	A
2025	D	C	B	B	D	C	A	A
2026	E	C	B	B	D	C	A	A
2027	E	C	C	B	D	D	A	A
2028	E	C	C	C	D	D	A	A
2029	E	D	C	C	E	D	A	A
2030	E	D	C	C	E	D	A	A
2031	E	D	C	C	E	E	A	A
2032	E	D	D	C	E	E	A	A

2033	E	D	D	D	E	E	A	A
2034	E	E	D	D	E	E	A	A
2035	E	E	D	D	E	E	A	A
2036	E	E	E	D	E	E	A	A
2037	E	E	E	E	E	E	A	A
2038	E	E	E	E	E	E	A	A

As it was shown, operating on the conventional VLSFO can barely hold a D rating for three consecutive years which is the maximum permitted period before delivering plans for emission reduction. Similar was the case for methanol which however refers to the currently available grey methanol but will come down roughly to 10% of the above emissions when green methanol will be largely available and ready for bunkering. LPG has the next worse CO2 emissions profile and was only compliant for 6 consecutive years. Biofuels and LNG were compliant for most of the part of their lifecycle while ammonia and LH2 retained an astonishing A rating throughout all of the years as it was expected. It is important to be noted that the TCO was affected indirectly by the means that after three consecutive years of being entitled with a rating D it would be necessary to change the operation of the conventional fuel to biofuels as long as these are compliant with a minimum C rating for the year in question leading ultimately to higher fuel costs as explained in 3.2.2 Fuel Consumption & Cost. As far as the alternative fuels are concerned, a way to remain compliant after a D rating would be to implement energy efficient technologies such as air lubrication and low friction hull coatings, maintaining a low drag by keeping the hull fouling free or by reducing the vessel’s speed. However, the most sustainable method would be to be ready for other alternative fuels incorporation.

3.2.6 Manning Costs

One of the greatest operational expenditures for the shipping companies refers to manning costs which can account for up to 50 % of the vessel’s opex. These costs are formed primarily (80%) by the wages of the officers including salaries, standby and holiday payments and secondarily travel costs, food supplies, specific training costs, medical supplies and provisions. This parameter was expected to differ from vessel to vessel according to the specific training needed in order to deal with every different fuel but most importantly based on the dangers every fuel is linked with, which would dramatically affect the salaries on board as working on vessels carrying highly hazardous fuels must be more appealing for the officers with crew wages. This is the case with highly explosive fuels as data suggests and is expected to be even more intense for toxic fuels such as ammonia.

For the manning costs presented in Table 45 and Figure 55, conventional, LNG and LPG were gathered from maritime data and reports (Drewry) [11]. The costs referred to a panamax size dry bulk carrier as mentioned earlier and were proportionally increased depending on the fuel. More specifically, manning costs for methanol was increased by 10% compared to the conventional, LNG were increased 85%, LPG by 20%, ammonia by 230% and liquified hydrogen by 280%.

Table 45: Manning Cost per Vessel

Fuel	Manning Costs [$/day]
VLSFO	2650
B24	2650
B30	2650
Methanol	2915
LNG	4903
LPG	3180
Ammonia	6095
LH2	7420

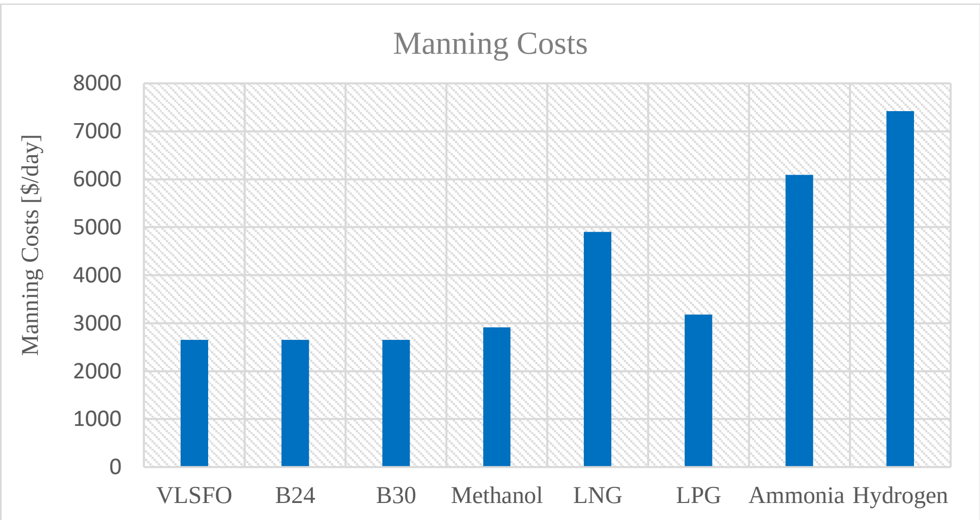

Figure 55: Manning Costs per Vessel/Fuel

As it was shown, wages regarding biofuels were not expected to differ compared to the conventional fuel. Additionally, from the well-established fuels LNG manning costs are certainly on the higher side due to being flammable and explosive, cryogenic temperatures raising safety concerns regarding burns and frostbites as well as rapid vaporization and extreme pressure increase risks leading in higher salaries. However, ammonia and liquified hydrogen have potentially much higher hazards since the former is really toxic and a large part of the shipping sector is doubtful about the fuels adaptation and the working willingness from the crew side while the latter is even more flammable, explosive, has much lower cryogenic temperatures and potential pressure buildup since it is the most volatile fuel of all can be catastrophic. Thus, expectations regarding manning costs for ammonia and hydrogen were much higher.

3.2.7 Port Dues

As mentioned in section 1.3.2 Opex port tariffs were subject to change depending on the fuel used for propulsion and being carried on each vessel. It has been discussed that alternatively fueled ships are possible to receive a priority for port service reducing the needed cost for the vessel's stay which however will be mostly based on relative regulations. More importantly though, ports have already incorporated rules regarding privileges and concessions over alternative fuel use. In this part, a generalization was made, and port taxes were provided from the Maritime & Port Authority of Singapore (MPA) since data were easier to be calculated and fluctuations between port taxes were not expected to vary greatly. Given that, port dues tariffs are in general determined by factors like the vessel's size in Gross Tonnage, the length of the stay and the purpose of the call. This raised the need of defining the GT of the panamax bulk carrier of the analysis which was found from statistics of different panamax bulkers of 80000 DWT tons[79]. The typical and average value was equal with GT 43507. Additionally, the charges reduction for the alternative fuels varied from port to port but the approach of MPA was used which order:

- 25% concession for using LNG and low carbon fuels and max. 4 days at port
- 30% concession for zero carbon fuels use in the port and max 4 days stay

For the biofuels case, no concession was considered since MGO was used at ECAs and some ports were located in such areas.

The charges were different for cargo operations and for fuel bunkering as well, therefore it was assumed that 4 days were needed for loading and discharging of the dry bulk cargo in each port and 2 days were needed for every bunker call. The port fees were formed from the following Equations [80]:

$$\boldsymbol{Port\,Tariff}_{\boldsymbol{Cargo\,Operations}} = \frac{\mathbf{43507}}{\mathbf{100}} \times \mathbf{9.50}\ [\$]\ ,\ \ \mathbf{4}\ \boldsymbol{days\ stay}\ \ (\mathbf{14})$$

$$\boldsymbol{Port\,Tariff}_{\boldsymbol{Bunkering}} = \frac{\mathbf{43507}}{\mathbf{100}} \times \mathbf{6.00}\ [\$]\ ,\ \ \mathbf{2}\ \boldsymbol{days\ stay}\ \ (\mathbf{15})$$

The port dues for each port call were presented below in Table 46 and Figure 56:

Table 46: Port Tariffs for each Call per Vessel and Fuel

Ship / Main Fuel	Port Dues Tariffs for Cargo Operations (4 days at port) [$]	Port Dues Tariffs for Bunkering Operations (2 days at port) [$]
Conventional (VLSFO, Biofuels)	4133	2610
Methanol	3100	1958
LNG	3100	1958
LPG	3100	1958
Ammonia	2893	1827
L.Hydrogen	2893	1827

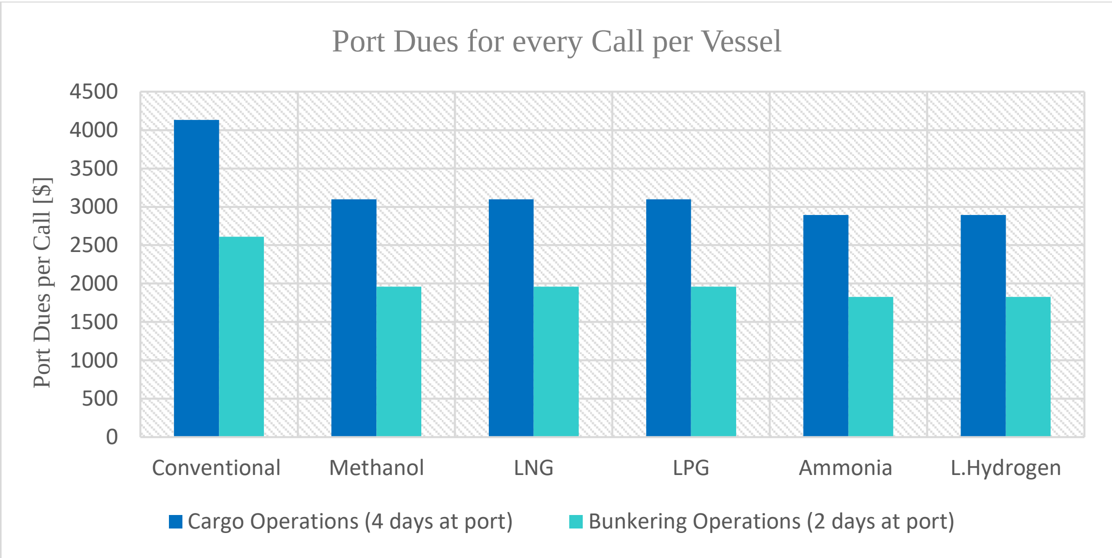

Figure 56: Port Dues per Call and Vessel

The case of hazardous fuels was interesting however since it has already been discussed for ammonia fueled ships that their acceptance is a susceptible matter, and some ports may prohibit entering the nearby province of the port. In such situations the bunkering or cargo loading/discharging could happen at some ports by vessel-to-vessel procedures which would increase the cost and the duration of the call. Something like this however was not possible to be determined and exceeded the limits of this thesis.

3.2.8 Off-hire periods

As previously explained in 1.3.2 Opex, off-hire periods describe the situation where the shipowner company is not receiving any hire payments from the charterer side due to the ship being unavailable for service for a short period of time. The particular circumstances and specifications under which the out of service periods are considered as off hire periods are defined on the terms of each charter party and may vary significantly depending on the contract signed. The profitability of the ship is directly affected from charters and hire payments, therefore off-hire periods are crucial for the total cost of ownership.

The off-hire periods could be an outcome of different reasons such as scheduled maintenance, unscheduled repairs from failures and accidents, port delays relative with administration and the different nature of the fuel as well as bunker issues and delays. An example of the latter could be the case of ammonia which may lead to more days needed near a bunkering station due to safety reasons. Thus, except for the revenue losses which are the major impact on the TCO there are also operational costs that are meanwhile affecting the shipowner and add to the total operational expenditures.

However, in the framework of this master thesis it would be extremely complicated to specify the different characteristics of this parameter as it is entirely defined on the different charter party agreement and consequently there were no such calculations taken into consideration regarding the off-hire periods.

3.2.9 Insurance Costs

Insurance costs is another section that is expected to vary according mainly to the machinery and the fuel driving the engine and the generators. Hazardous fuels meaning explosive, highly flammable and toxic fuels are associated with greater dangers for the ship and so with higher insurance costs the biggest part of which are covered by Hull & Machinery and Protection & Indemnity insurance. For the conventional fuel as well as LNG and LPG engines, reports from Drewry [11] were again valuable and helpful for estimations and some insight on how the insurance costs are affected by the fuel. Hull & Machinery were provided as one aggregated cost thus given that hull insurance remained fixed for all vessels, the part for Machinery was assumed to cover 30% of the Hull & Machinery costs. For the rest fuels qualitative estimations resulted through discussions contacted with specialists from shipping companies based on how the maritime sector is currently being formed. Machinery Insurance of methanol fuelled vessels was assumed to be 20% increased from the conventionally fuelled, ammonia fuelled vessels 50% increased from the LNG vessels and LH2 had double the cost of LNG.

The general idea was that the higher the risk of system's failure for a fuel the higher the insurance cost; however, the lack of knowledge on new technologies and fuels that have not been really tested on sea raises the costs from insurance companies due to the uncertainty of the outcome of the future voyages. This aspect though is expected to decrease in the next years as fuels become more popular and prominent in the sector opening the way for the less explored fuels like hydrogen and ammonia by gaining the trust from insurers. In summary, insurance costs for a panamax dry bulk carrier powered by the fuels discussed were formed as presented in Table 47 and Figure 57.

Table 47: Daily Insurance Costs per Fuel/Vessel

Fuel	Fixed Costs [USD/day]	Machinery [USD/day]	Insurance Costs [USD/day]
VLSFO	378	36	414
B24	378	36	414
B30	378	36	414
LNG	378	389	767
Methanol	378	44	421
LPG	378	138	516
Ammonia	378	584	961
Hydrogen	378	778	1156

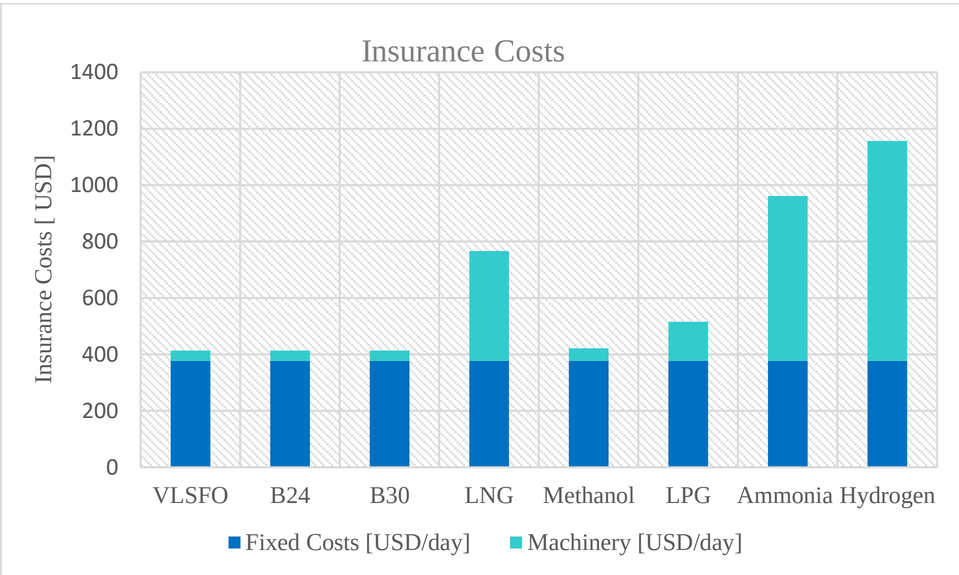

Figure 57: Insurance Costs per Vessel

4. Life Cycle Costs & Scenarios

In this section the capital and operational expenditures that were calculated in chapter 3. Methodology & Calculations were incorporated to reach to a yearly and subsequently a Total Cost of Ownership referring to the whole life cycle of the vessel. The life cycle was selected to have a 15-year-span as explained in CII calculations.

As mentioned, for 20% of the year the vessel was at port covering its needs only with gensets being in operation. For the rest 80% of the days the ship was travelling on sea with 20% of that time being withing SOx and NOx ECAs, an assumption which formed the fuel consumption of the main engines and gensets. The above corresponded in 292 days of voyage on sea annually with Main Engine and Genset operation and 73 days at port. With the approximate average vessel's speed of 13.5 kn the annual distance travelled was 94608 nm. Additionally, with the considered range of 10000 nm the vessel would need approximately 10 bunker port calls with an equivalent time of 20 days at port for bunkering procedures and the rest days for cargo operations. Given that the port time for cargo handling was 4 days per call, an approximate value of 13 port calls for cargo loading/ unloading per year resulted.

Given the above, three different voyage scenarios that affected the OPEX were made corresponding to the three possible outcomes of environmental taxes mainly regarding the EU ETS system. These referred to voyages within the European Economic Area (EEA), voyages entering or exiting the EEA and voyages outside of the EEA covering though ECAs like the North American East and Western seas or potentially Japan and Australia in the near future. The Total Cost of Ownership was calculated as follows in this chapter. Initially, the total CAPEX of each vessel was calculated as it remained fixed regardless of the Operational Scenarios. Following, the total Opex was presented with EU ETS Allowances being divided in three different scenarios. In the final analysis, the TCO was shown aggregated for the three different voyage scenarios.

4.1. Life Cycle Capex of each Fuel/ Panamax Bulker

At this point it should be highlighted that the cost of the hull construction and shipyard work as well as outfitting costs were not taken into account in the analysis as they were expected to remain fixed and are not to be changed from the conventional fuel. The main interest was focused on the costs that were prone to change according to the fuel used for propulsion. Aggregating all the capital costs of each fuel and vessel it was possible to present them as shown in Table 48 and Figure 58.

Table 48: Total Capex of each Fuel/ Bulker

Fuel	Engine [M$]	Supply & Safety Systems [M$]	Gensets [M$]	Boilers [M$]	Fuel Tanks Capex [M$]	Total Capex [M$]
Conventional (VLSFO, Biofuels)	2.640	0.25	0.175	0.228	0.892	4.184
LNG	4.620	4.76	0.231	0.301	5.875	15.790
Methanol	3.300	0.69	0.221	0.287	2.587	7.087
LPG	3.520	1.13	0.231	0.300	2.162	7.346
Ammonia	6.600	2.19	0.242	0.314	3.333	12.677
L.Hydrogen	9.240	5.67	0.273	0.355	10.968	26.501

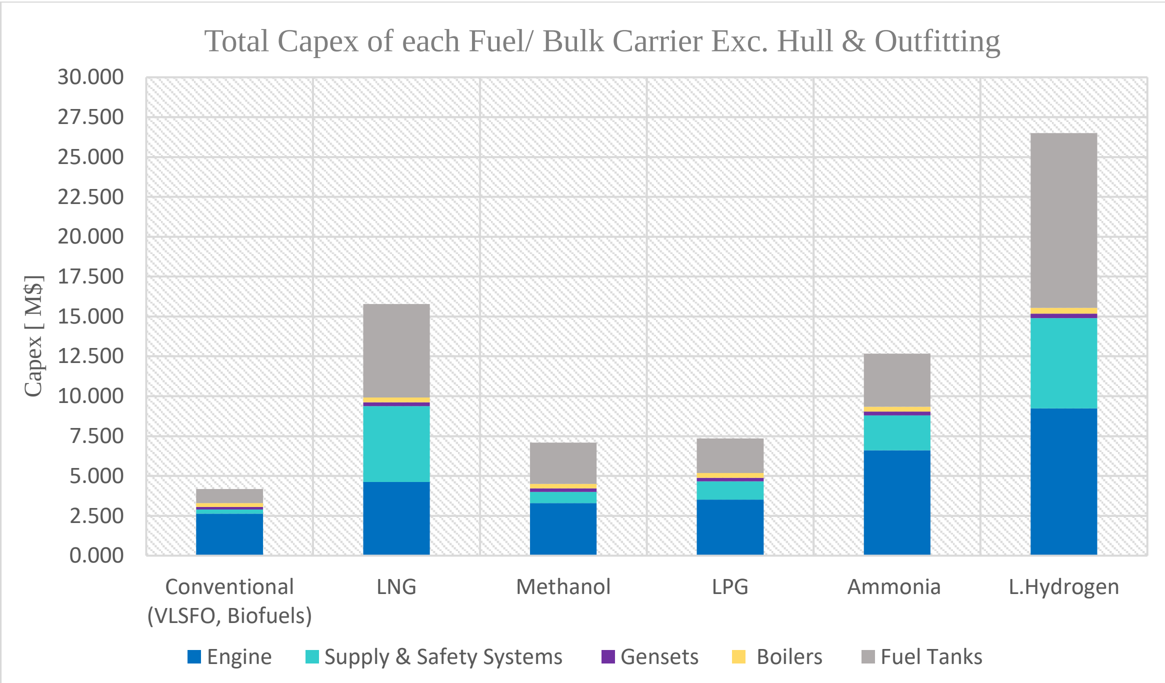

Figure 58: Total Capex for each Fuel/Bulker

4.2. Life Cycle Opex of each Fuel/ Panamax Bulker

All the operational expenditures were annualized and thereafter turned into lifecycle costs and eventually presented aggregated at the end of each of the three scenarios.

4.2.1. Lifecycle Total Fuel Costs

The total fuel costs were calculated with operation of the main engine for 292 days annually and for 15 years and operation of the gensets for 365 days (assumed that they were needed when at port) and for 15 years. The results were the following:

Table 49: Total Lifecycle Fuel Costs for each Panamax Bulker

Fuel/ Ship	Engine's Main Fuel [M$]	Engine's MGO [M$]	Engine's Pilot Fuel [M$]	Genset Main Fuel [M$]	Genset's MGO [M$]	Genset Pilot Fuel [M$]	Total Fuel [M$]
VLSFO	74.049	24.617	0.000	10.701	3.373	0.000	112.740
B24	90.106	24.617	0.000	12.892	3.373	0.000	130.989
B30	89.259	24.617	0.000	12.773	3.373	0.000	130.022
LNG	67.416	0.000	1.919	11.116	0.000	0.387	80.838
Methanol	93.015	0.000	6.406	14.318	0.000	0.705	114.444
LPG	42.914	0.000	6.406	6.468	0.000	0.370	56.158
Ammonia	154.551	0.000	9.083	25.295	0.000	0.968	189.896
L.Hydrogen	61.503	0.000	1.919	10.549	0.000	0.405	74.376

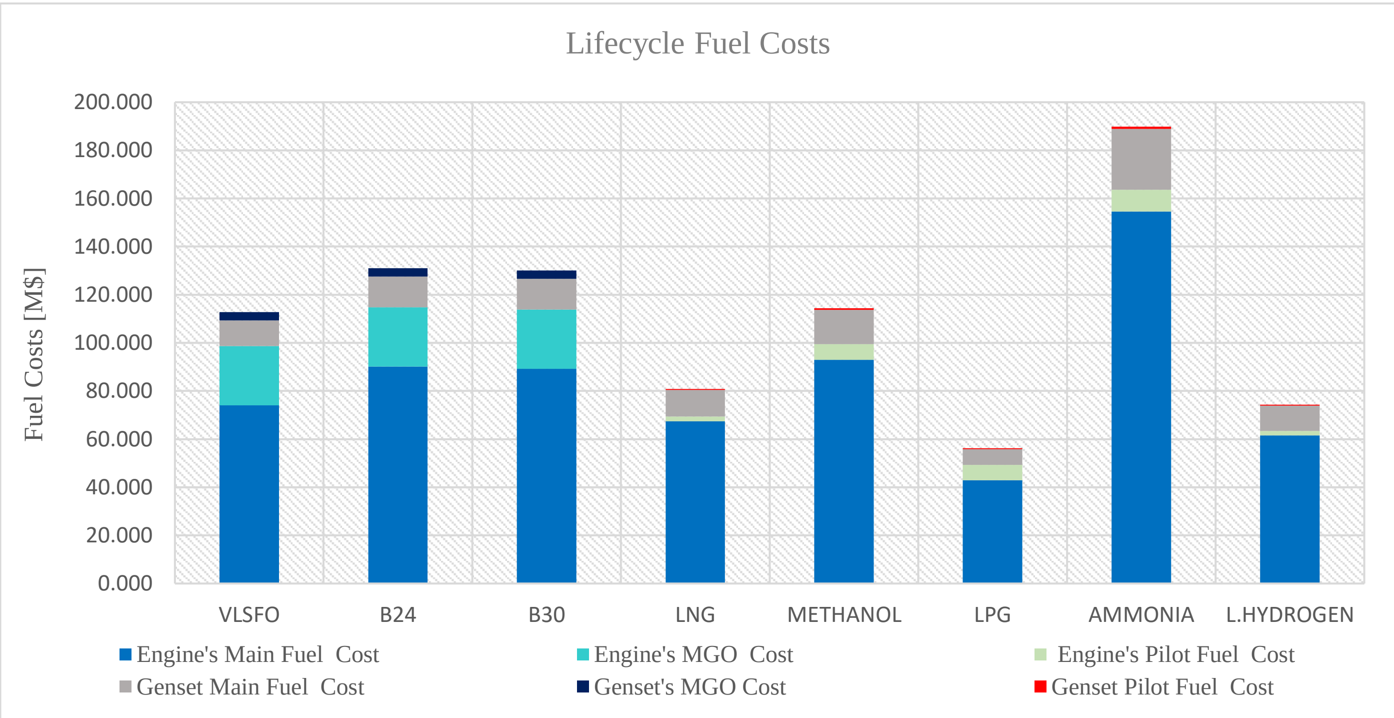

Figure 59: Total Lifecycle Fuel Costs

4.2.2. Lifecycle EU ETS Total Allowances Cost

Voyages Within the European Economic Area (EEA)

The CO2 equivalent tons emitted were calculated from the emissions from the operation of both the main engine and the gensets for 292 days and operation of the gensets alone for the rest 73 days during which the vessel remained at port either for bunkering or for cargo loading and unloading. The corresponding allowances for intra EEA voyages were shown in Table 50 and Figure 60.

Table 50: Lifecycle EU ETS Allowances Cost / Voyages Within EEA

Fuel	CO2 Eq. [t]	Lifecycle ETS Allowances Total Cost [M$]
VLSFO	515535.814	51.554
B24	423170.003	42.317
B30	398698.621	39.870
LNG	425838.274	42.584
Methanol	471648.062	47.165
LPG	453174.394	45.317
Ammonia	58482.413	5.848
L.Hydrogen	10014.584	1.001

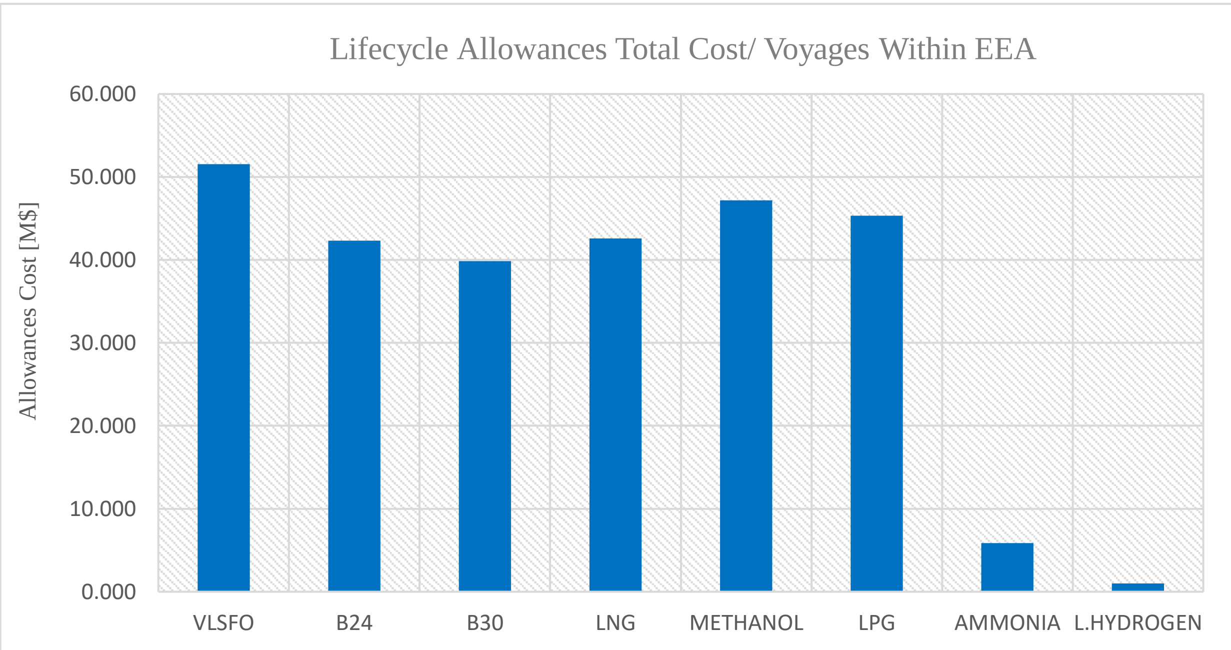

Figure 60: Lifecycle Allowances Total Cost / Within EEA

As expected, ammonia and LH2 lifecycle allowances cost was kept really low due to their great emission profile. It was interesting that methanol's CO2 emissions were extremely high and just below VLSFO's which is justified from the fact that the considered methanol here was grey as data are currently provided only for the available and ready for use fuels. It is expected however that green methanol will reduce the emissions to the level of ammonia but it is suggested that its cost will probably exceed all the current bunker fuels price.

Voyages Entering or Exiting the EEA

This affected only the cost of the allowances as only 50% of the emitted CO2eq were covered in EU ETS allowances. The EU ETS costs was depicted within Table 51 and Figure 61

Table 51: Total Allowances Cost for Voyages Entering/Exiting EEA

Fuel	CO2 Eq. [t]	Lifecycle Allowance Total Cost [M$]
VLSFO	515535.814	25.777
B24	423170.003	21.159
B30	398698.621	19.935
LNG	425838.274	21.292
Methanol	471648.062	23.582
LPG	453174.394	22.659
Ammonia	58482.413	2.924
LH2	10014.584	0.501

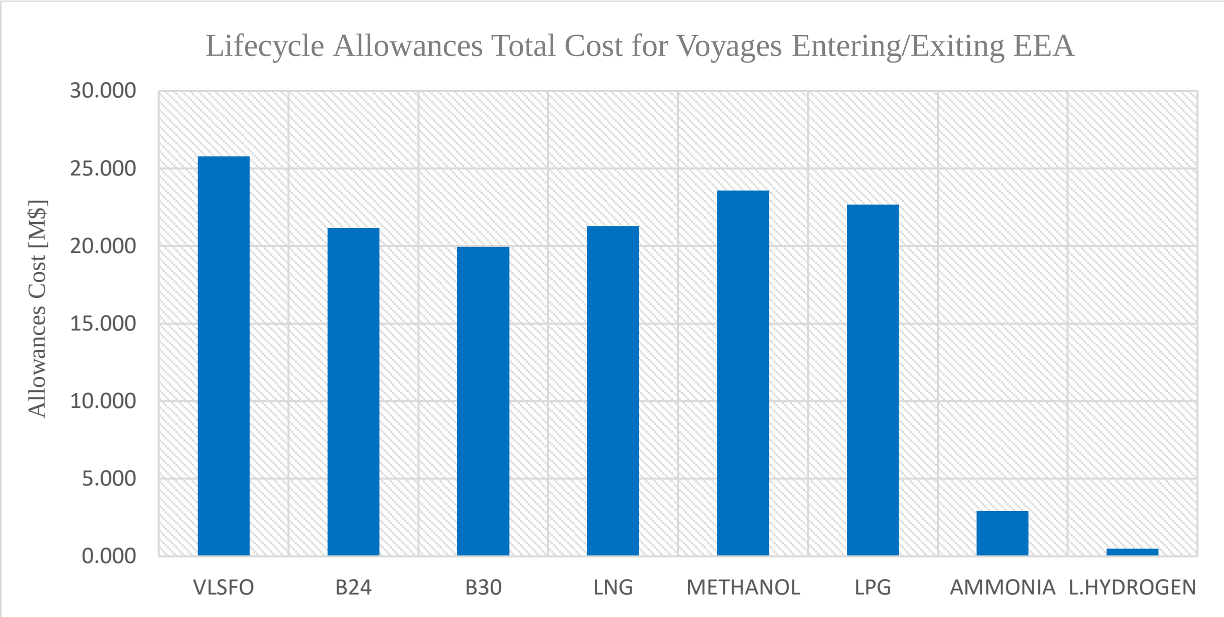

Figure 61: Lifecycle Allowances Cost for Voyages Entering/Exiting EEA

Voyages Outside of EEA Covering ECAs

The current condition for trips out of the EEA does not cover any allowances or straightforward emission taxes. Despite that, IMO is already putting pressure on the alternative fuel adaptation and similar taxes incorporation is likely to be seen in the near future.

4.2.3. Lifecycle Lubricating Oils Total Cost

In this part, a plain annualization and application for the 15 years lifespan was made for each vessel as the daily costs were provided by Drewry Operational Reports and were considered equal for the whole year. The specific data that were discussed in 3.2.3 Lubrication were utilized. The total lubricating oils costs were presented in Table 52 and Figure 62.

Table 52: Lifecycle Lubricating Oils Cost

Ship/Fuel	Lifecycle Lubricating Oils Costs [M$]
VLSFO	2.190
B24	2.190
B30	2.190
LNG	2.792
Methanol	3.285
LPG	2.792
Ammonia	3.614
Hydrogen	2.792

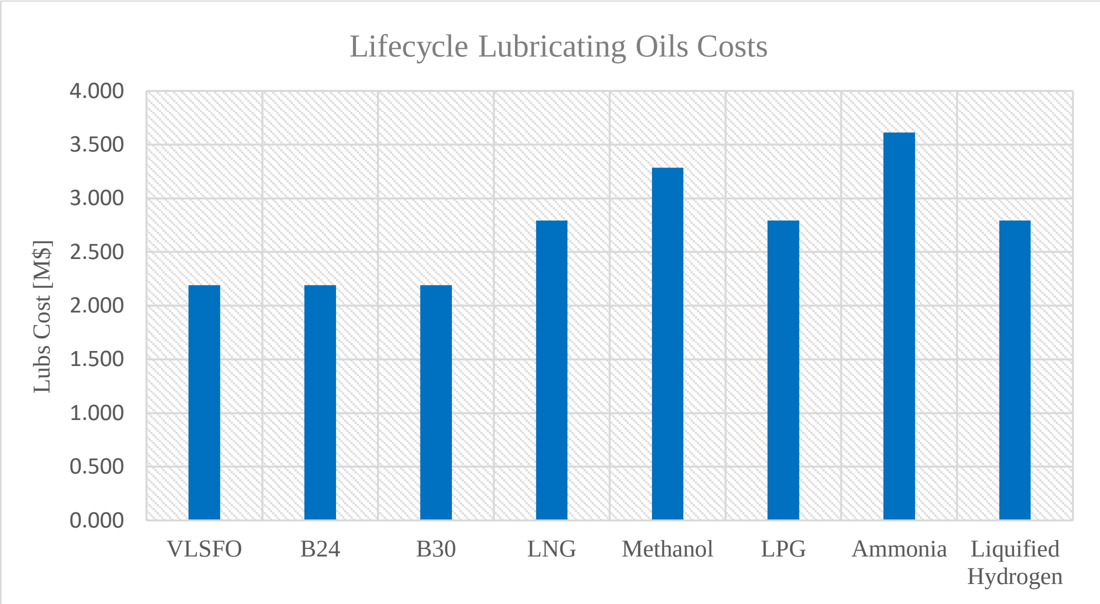

Figure 62: Lifecycle Lubricating Oils Total Cost

4.2.4. Lifecycle Repair & Maintenance (R&M) and Drydocking Costs

Lifecycle R&M Costs

Repair & Maintenance costs as explained 3.2.5 Maintenance & Repair (M&R) and Drydocking were provided as statistics for the conventional and LNG fuelled ships from maritime reports. while for methanol, LPG, Ammonia and LH2 some proportional maintenance cost increase was considered which was separated in different sections. The total costs were calculated for the 15 years span and presented in Table 53 and Figure 63:

Table 53: Lifecycle R & M Costs of each Fuel/ Panamax Bulker

Ship / Main Fuel	Fixed Maintenance & Repair Costs [M$]	Main Engine [M$]	Boilers [M$]	GenSets [M$]	ER Auxiliaries [M$]	Lifecycle R&M Cost [M$]
Conventional (VLSFO, Biofuels)	0.583	0.234	0.025	0.222	0.086	1.150
Methanol	0.583	0.281	0.030	0.266	0.104	1.263
LNG	0.583	0.348	0.056	0.348	0.333	1.669
LPG	0.583	0.293	0.031	0.278	0.108	1.292
Ammonia	0.583	0.422	0.044	0.400	0.155	1.603
L.Hydrogen	0.583	0.697	0.112	0.697	0.667	2.755

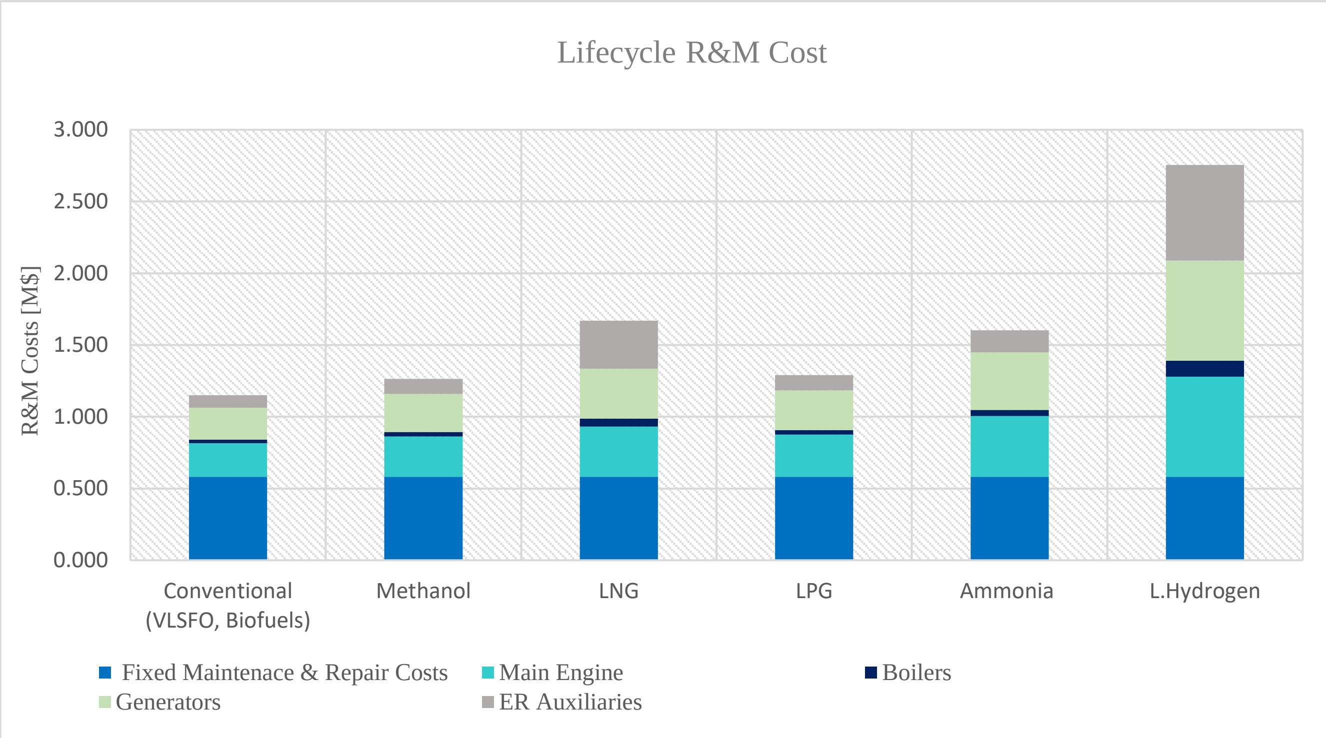

Figure 63: Lifecycle R&M Costs of each Vessel

Lifecycle Drydocking Costs

The interest here was on the number of intermediate and full surveys the bulker was necessary to have through the 15 years of its lifetime. More specifically, it was anticipated that intermediate surveys would occur every 2.5 years and full surveys every 5 years. Given that, with a lifetime of 15 years the vessel would need to have three intermediate surveys and 2 full surveys when 5 and 10 years old as on the fifteenth year the vessel would become unavailable for operation and probably be led to scrapping. Therefore, the total drydocking costs were calculated and shown in Table 54 and Figure 64: Lifecycle Drydocking Costs.

Table 54: Lifecycle Drydocking Surveys Total Costs per Fuel/Vessel

Ship / Main Fuel	Fixed Costs [M$]	Machinery [M$]	Valves & Piping [M$]	Drydocking Total Costs [M$]
Conventional (VLSFO, Biofuels)	2.466	0.695	0.313	3.473
Methanol	2.466	0.764	0.344	3.573
LNG	2.466	0.907	0.408	3.780
LPG	2.466	0.910	0.410	3.786
Ammonia	2.466	1.250	0.563	4.278
L.Hydrogen	2.466	1.813	0.816	5.095

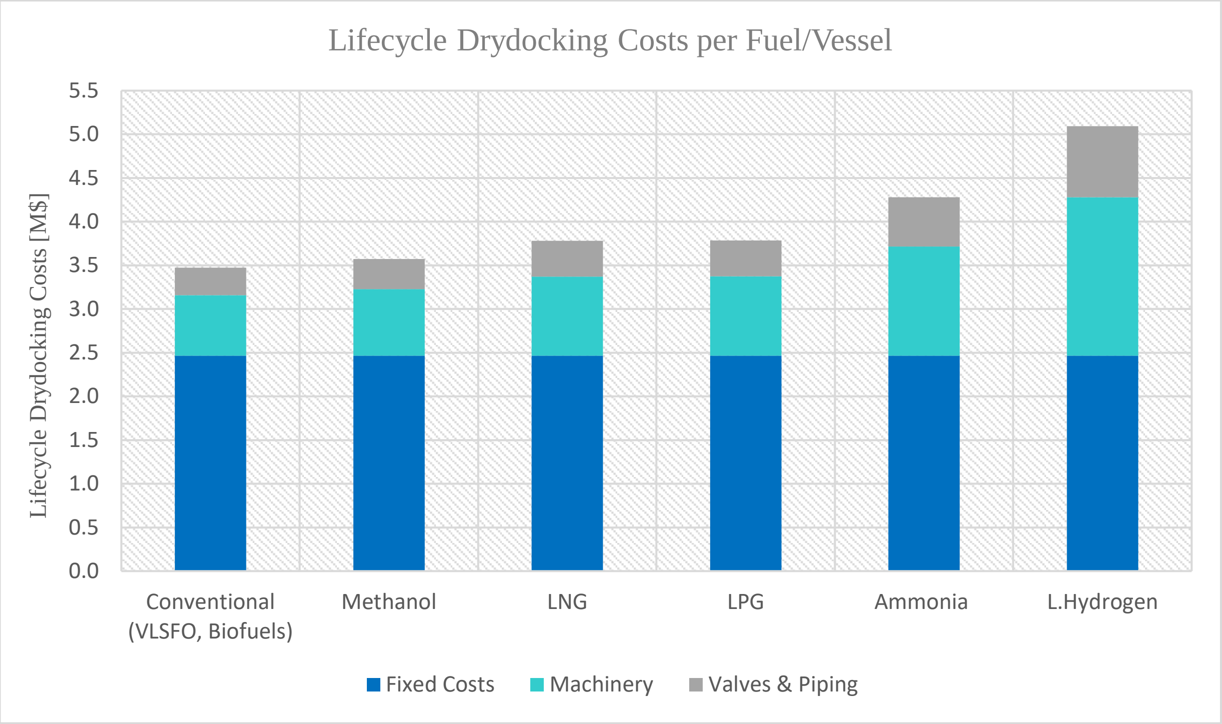

Figure 64: Lifecycle Drydocking Costs

4.2.5. Lifecycle Manning Costs

The lifecycle costs for manning per vessel were assessed just by using the daily costs for a 15 years lifespan and the results were gathered in Table 55 and Figure 65 that follow.

Table 55: Lifecycle Manning Costs per Fuel/Vessel [M$]

Fuel/Vessel	Lifecycle Manning Costs [M$]
VLSFO	14.509
B24	14.509
B30	14.509
Methanol	15.960
LNG	26.841
LPG	17.411
Ammonia	33.370
LH2	40.625

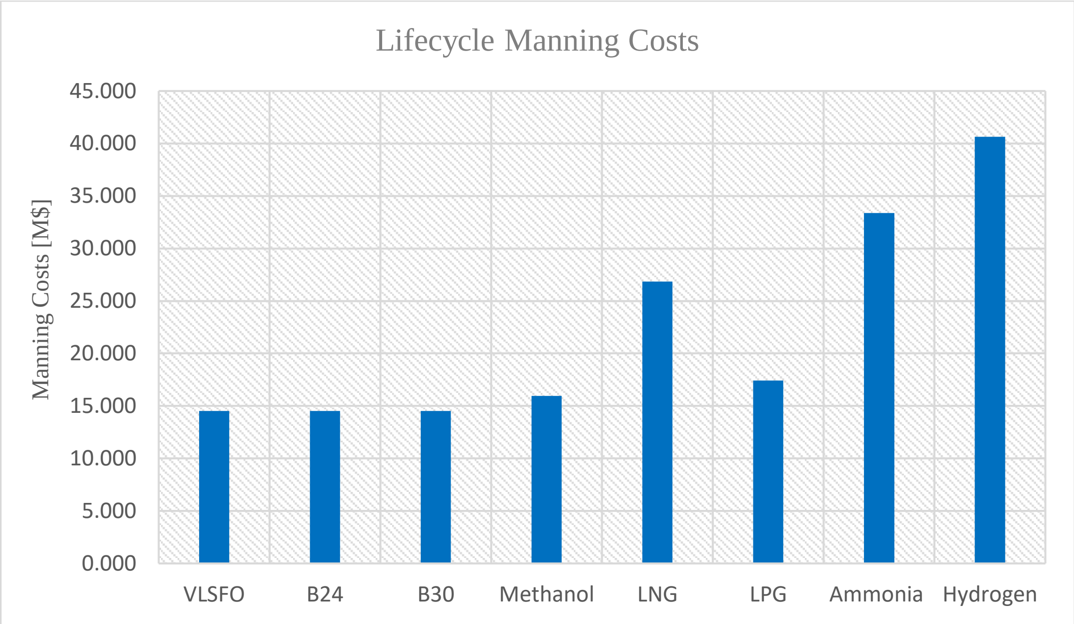

Figure 65: Lifecycle Manning Total Costs

4.2.6. Lifecycle Port Dues Tariffs

Port dues as mentioned were formed with the MPA data for port calls for bunkering or cargo handling procedures. Given the yearly port calls needed as further explained in 4. Life Cycle Costs & Scenarios the lifecycle port tariffs were possible to be estimated. The results were given in Table 56 and Figure 66 below:

Table 56: Lifecycle Port Dues

Main Fuel	Port Dues-Yearly Cargo Calls (13) [$]	Port Dues-Yearly Bunkering Calls (10) [$]	Lifecycle Port Dues-Cargo Operations [$]	Lifecycle Port Dues- Bunkering [$]	Lifecycle Total Port Dues [$]
Conventional (VLSFO, Biofuels)	53731	26104	805967	391563	1197530
Methanol	40298	19578	604475	293672	898148
LNG	40298	19578	604475	293672	898148
LPG	40298	19578	604475	293672	898148
Ammonia	37612	18273	564177	274094	838271
L.Hydrogen	37612	18273	564177	274094	838271

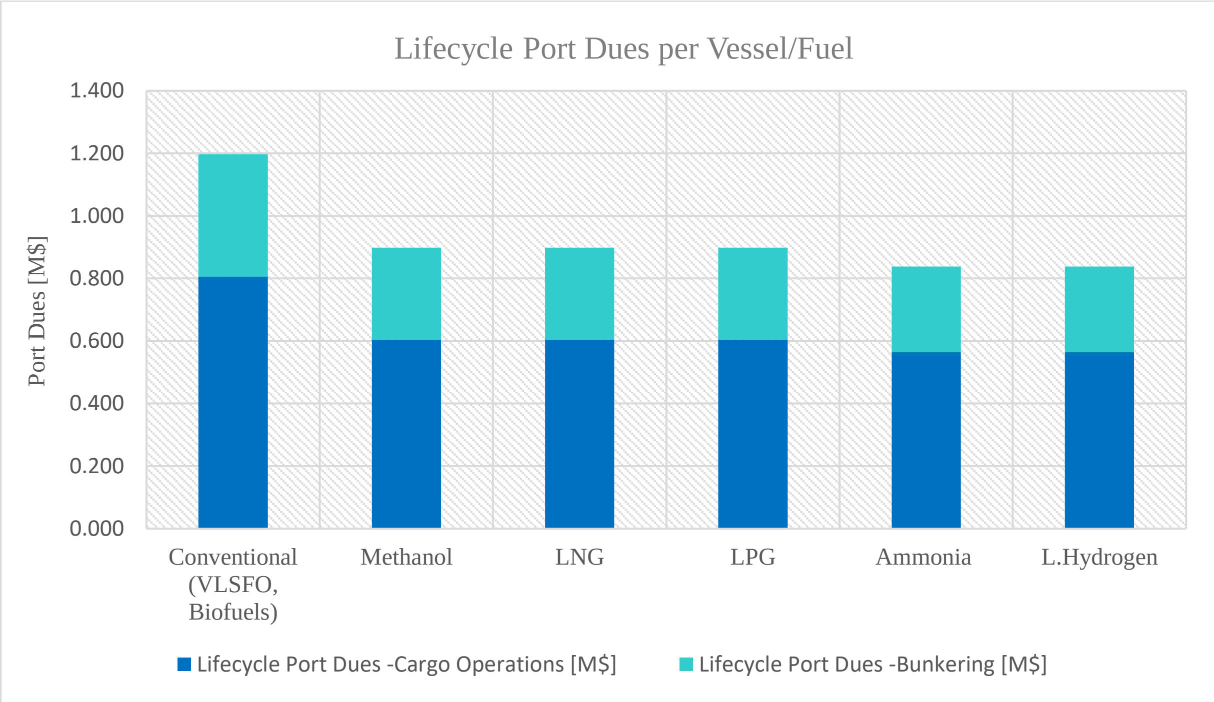

Figure 66: Lifecycle Port Dues per Vessel & Fuel

As it was anticipated, conventional fuels were again inferior in terms of operational costs and it is suggested that ports are likely to further increase this advantage in favor of the use of alternative fuels with some ports having already integrated additional penalties in charges for operation on fuels that do not comply with IMO's environmental regulations. Hence, this cost difference is, as it seems, only getting bigger.

4.2.7. Lifecycle Insurance Costs

The lifecycle insurance costs were presented aggregated in Table 57 and Figure 64: Lifecycle Drydocking Costs with the calculations of the daily costs that were made.

Table 57: Lifecycle Insurance Costs per Fuel/ Panamax Bulker

Fuel	Fixed Costs [M$]	Machinery [M$]	Lifecycle Insurance Total Costs [M$]
VLSFO	2.068	0.199	2.267
B24	2.068	0.199	2.267
B30	2.068	0.199	2.267
LNG	2.068	2.130	4.198
Methanol	2.068	0.239	2.307
LPG	2.068	0.757	2.825

Ammonia	2.068	3.196	5.264
Hydrogen	2.068	4.261	6.329

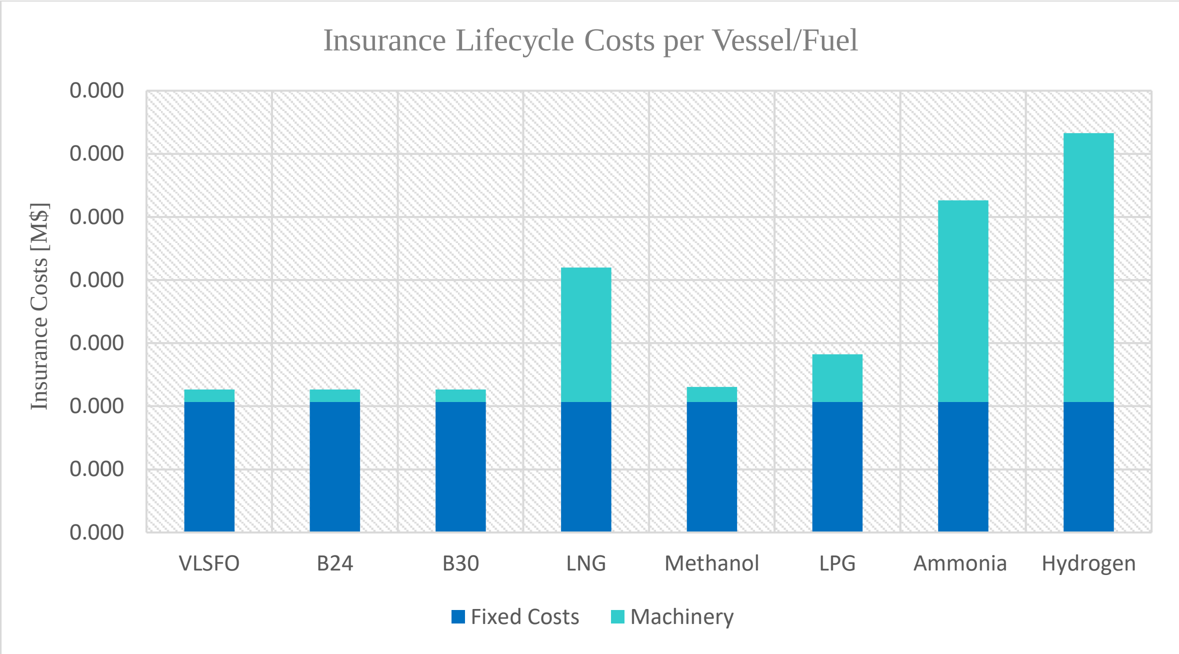

Figure 67: Insurance Lifecycle Costs per Fuel/Vessel

The extreme insurance costs of Ammonia and Liquified Hydrogen is a result of the uncertainty on their operation, lack of experience and most importantly their high risk as they are considered very dangerous due to toxicity and explosiveness. As mentioned though, these values are expected to reach normal levels as soon as the use of the fuels become more frequent and further technical knowledge will provide certainty and confirmation on their trustworthiness.

4.2.8. Lifecycle Aggregated Opex

Voyages Within the European Economic Area (EEA)

The total lifecycle operational expenditures were gathered altogether in Table 58 and Figure 68.

Table 58: Aggregated Opex for Intra EEA Voyages per Vessel

Fuel/Vessel	Fuel Cost [M$]	EU ETS Allowances Cost [M$]	Lubricating Oils Cost [M$]	R&M and Drydocking [M$]	Manning Cost [M$]	Port Dues [M$]	Insurance Cost [M$]
VLSFO	112.740	51.554	2.190	3.473	14.509	1.1975	2.267
B24	130.989	42.317	2.190	3.473	14.509	1.1975	2.267
B30	130.022	39.870	2.190	3.473	14.509	1.1975	2.267
LNG	80.838	42.584	2.792	3.573	15.960	0.8981	4.198
Methanol	114.444	47.165	3.285	3.780	26.841	0.8981	2.307
LPG	56.158	45.317	2.792	3.786	17.411	0.8981	2.825
Ammonia	189.896	5.848	3.614	4.278	33.370	0.8383	5.264
LH2	74.376	1.001	2.792	5.095	40.625	0.8383	6.329

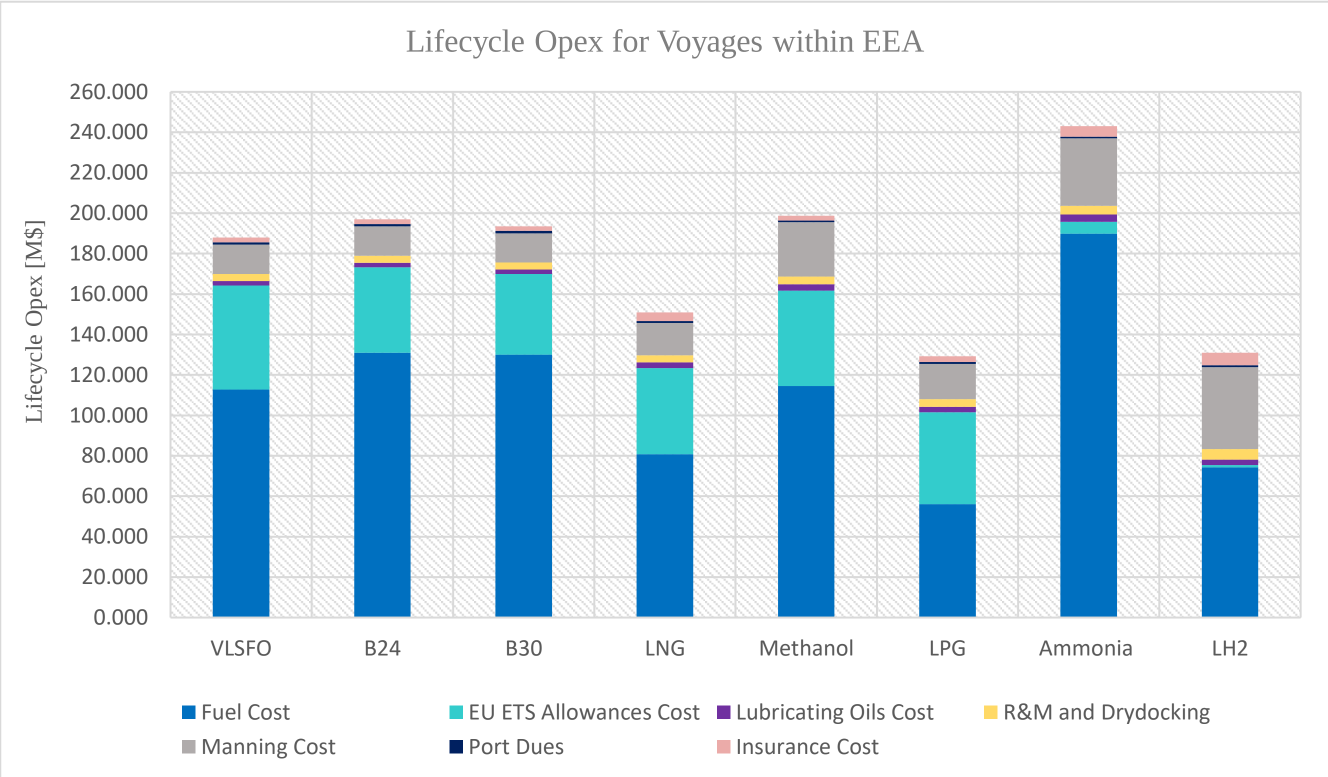

Figure 68: Lifecycle Opex for Voyages within EEA

Voyages Entering or Exiting the EEA

The equivalent total lifecycle operational expenditures for voyages entering or exiting the EEA were shown in Table 59 and Figure 69.

Table 59: Lifecycle Opex for Voyages Entering/Exiting EEA

Fuel/Vessel	Fuel Cost [M$]	EU ETS Allowances Cost [M$]	Lubricating Oils Cost [M$]	R&M and Drydocking [M$]	Manning Cost [M$]	Port Dues [M$]	Insurance Cost [M$]
VLSFO	112.740	25.777	2.190	3.473	14.509	1.1975	2.267
B24	130.989	21.159	2.190	3.473	14.509	1.1975	2.267
B30	130.022	19.935	2.190	3.473	14.509	1.1975	2.267
LNG	80.838	21.292	2.792	3.573	15.960	0.8981	4.198
Methanol	114.444	23.582	3.285	3.780	26.841	0.8981	2.307
LPG	56.158	22.659	2.792	3.786	17.411	0.8981	2.825
Ammonia	189.896	2.924	3.614	4.278	33.370	0.8383	5.264
LH2	74.376	0.501	2.792	5.095	40.625	0.8383	6.329

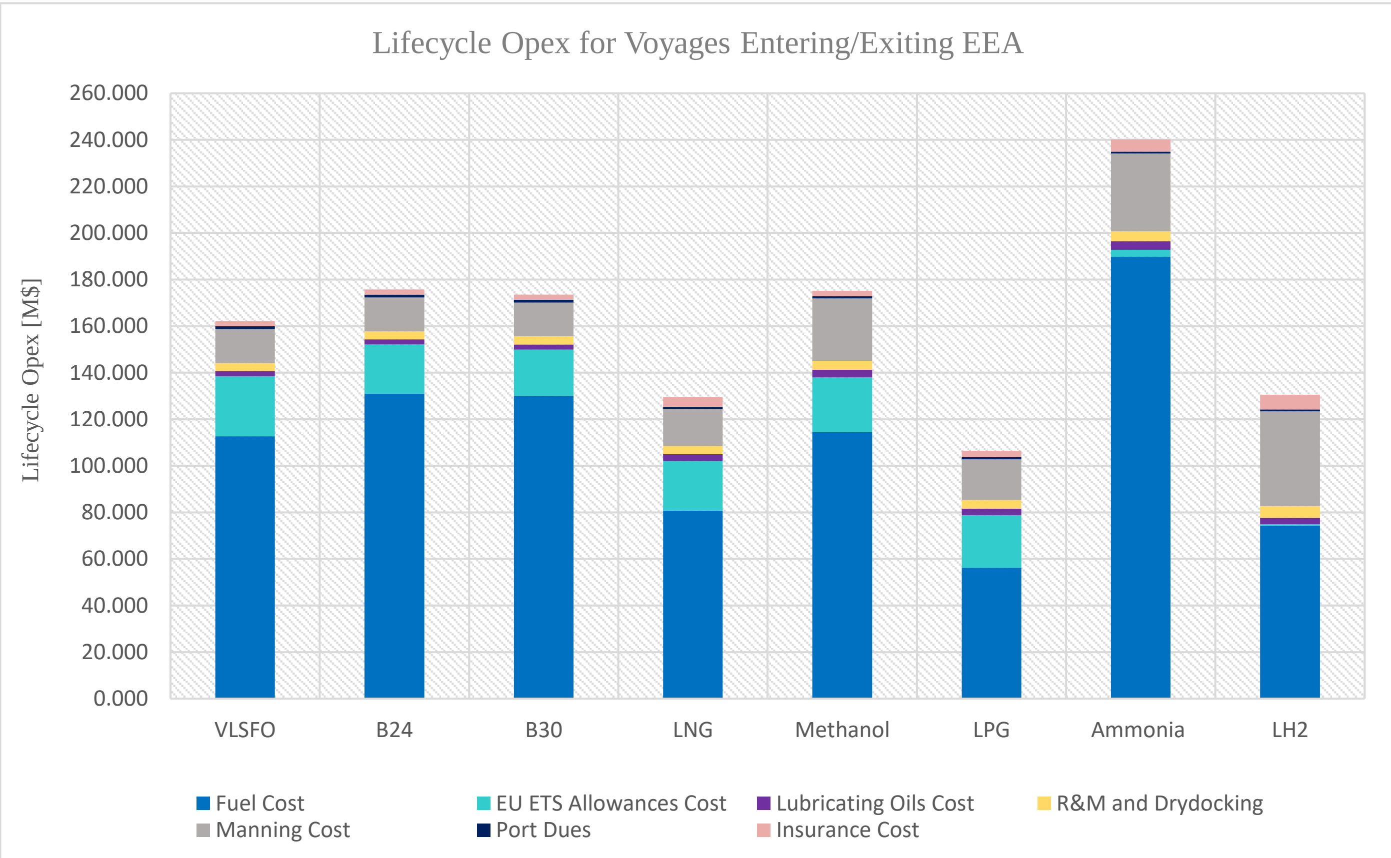

Figure 69: Lifecycle Opex for Voyages Entering/Exiting EEA

Voyages Outside of the EEA

The total operational costs for voyages outside of the EEA but with 20% of the on sea voyage being within ECAs as it was assumed for all the scenarios were presented in Table 60 and Figure 70.

Table 60: Lifecycle Opex for Voyages Outside of the EEA

Fuel	Fuel Cost [M$]	EU ETS Allowances Cost [M$]	Lubricating Oils Cost [M$]	R&M and Drydocking [M$]	Manning Cost [M$]	Port Dues [M$]	Insurance Cost [M$]
VLSFO	112.740	0.000	2.190	3.473	14.509	1.1975	2.267
B24	130.989	0.000	2.190	3.473	14.509	1.1975	2.267
B30	130.022	0.000	2.190	3.473	14.509	1.1975	2.267
LNG	80.838	0.000	2.792	3.573	15.960	0.8981	4.198
Methanol	114.444	0.000	3.285	3.780	26.841	0.8981	2.307
LPG	56.158	0.000	2.792	3.786	17.411	0.8981	2.825
Ammonia	189.896	0.000	3.614	4.278	33.370	0.8383	5.264
LH2	74.376	0.000	2.792	5.095	40.625	0.8383	6.329

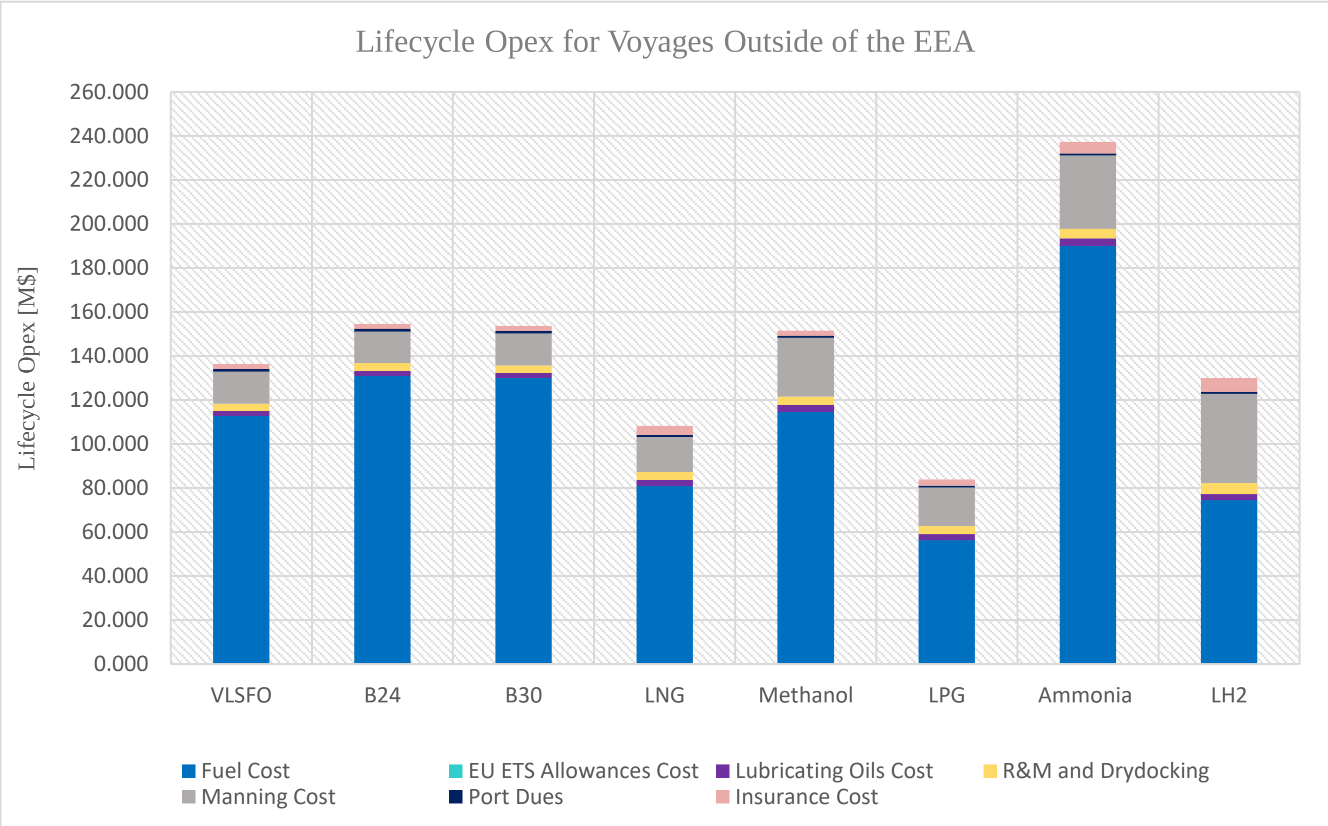

Figure 70: Lifecycle Opex for Voyages Outside of the EEA

As it is clearly shown, the main part of the cost of the operational expenditures was consisted of the fuel cost throughout the lifecycle of the ship. This is based on two aspects: the bunker price and the fuel consumption which is needed. Although fuel consumption is not expected to vary significantly, the bunker prices are constantly changing even during the writing of this thesis. This feature hence is partly indicative and could not remain fixed for the lifecycle of the vessel particularly when new fuels are involved as their bunker price is expected to decrease as they become more available.

4.3. Life Cycle TCO of each Fuel/ Panamax Bulker

In this section the total cost of ownership for the panamax bulk carrier when using different fuels were conclusively presented. General and standards costs like hull construction and shipyard work cost for the vessel were not included. The factors presented were the ones that were considered as variables from vessel to vessel based on the fuel being used for propulsion. The TCO (capex and opex in chart) of each fuel was presented aggregated for comparison purposes below.

4.3.1. Life Cycle TCO / Voyages Within the EEA

The total cost of ownership for voyages within the European Economic Area is presented in Figure 71 below for comparison purposes.

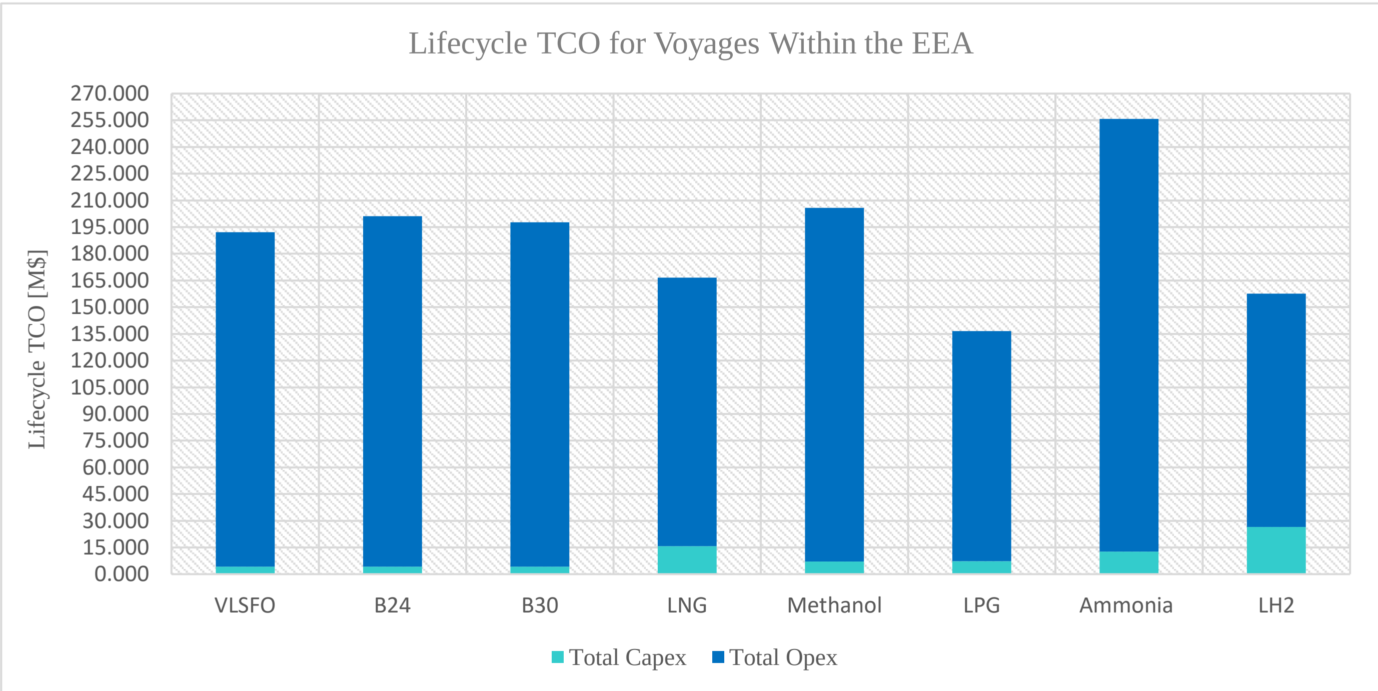

Figure 71: Lifecycle TCO for Voyages Within the EEA

4.3.2. Life Cycle TCO / Voyages Entering/Exiting the EEA

The corresponding TCO for voyages from or entering the EEA was presented as follows in Figure 72 with the reduced EU ETS Allowances costs incorporated.

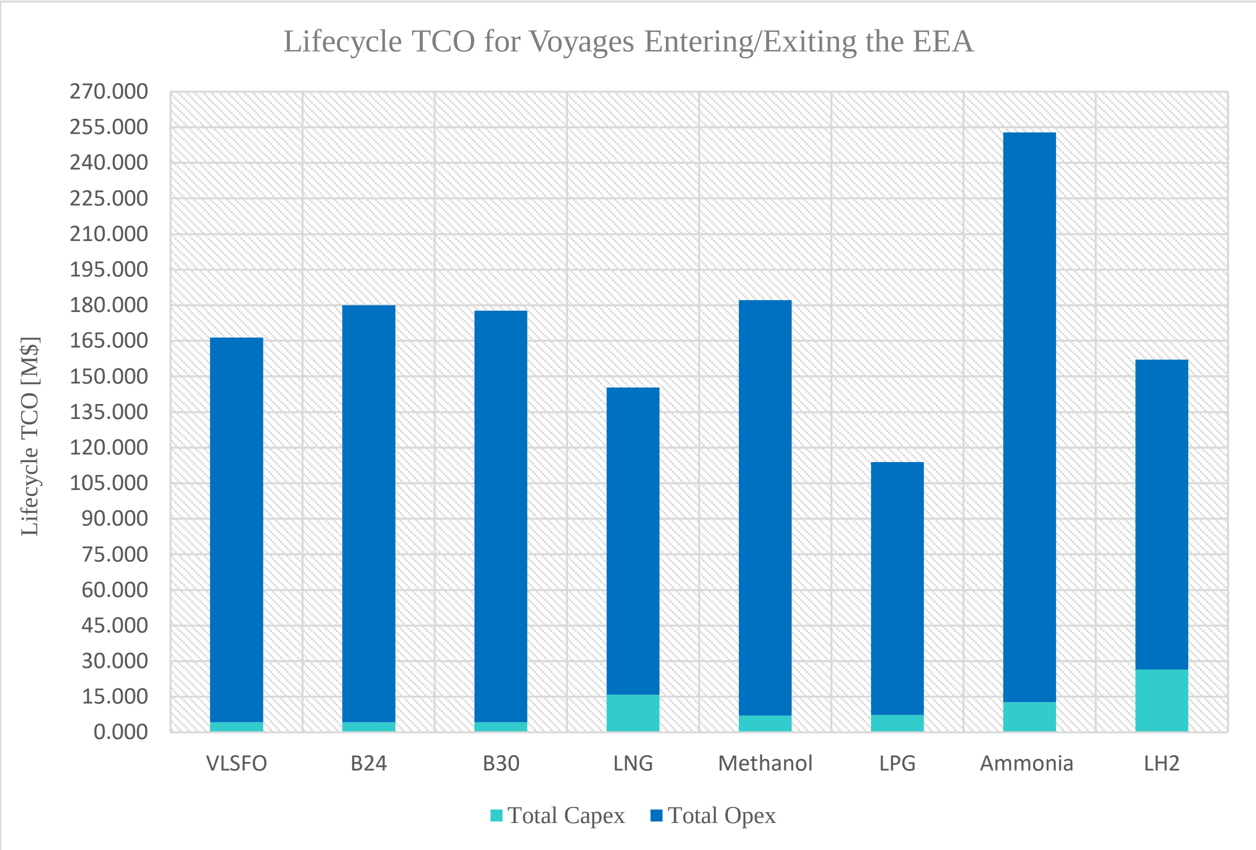

Figure 72: Lifecycle TCO for Voyages Entering/Exiting the EEA

It should be noted that even though LPG has the lowest total cost of ownership with the current bunker price assumed to be equal for the following 15 years, the aspect that is not straightforward cost related but is extremely decisive on the sustainability of the vessel/fuel is the CII rating of the vessel. As analyzed, LPG was compliant for only 6 years with three years of D rating included when LNG kept a compliant rating for 12 years out of 15. VLSFO was IMO compliant for barely two years meaning that it was not an accepted solution for future voyages and a swift to biofuels was needed as B30 was CII compliant for 11 years. For the following years higher biofuel blends as B50 should be used to remain accepted for sea routes. On the other hand, the extreme TCO of ammonia which was mainly due to its very high fuel consumption as well as a relatively high bunker price was partly counterbalanced with a flawless A CII rating for the whole lifecycle of the ship as it is considered as a zero carbon fuel. This was also the case for LH2 however the extreme size of the fuel tanks needed which were 5 times the size of the conventional for the same energy output raises cargo reduction problems and vessel's range questions. A solution for hydrogen since it has the best emissions profile would be to reduce the range of the ship in order for the voyage to be efficient.

4.3.2. Life Cycle TCO / Voyages Outside of the EEA

In the final part of the total costs and results section the TCO of each fuel/vessel for voyages carried out on waters outside of the EEA was presented in Figure 73:

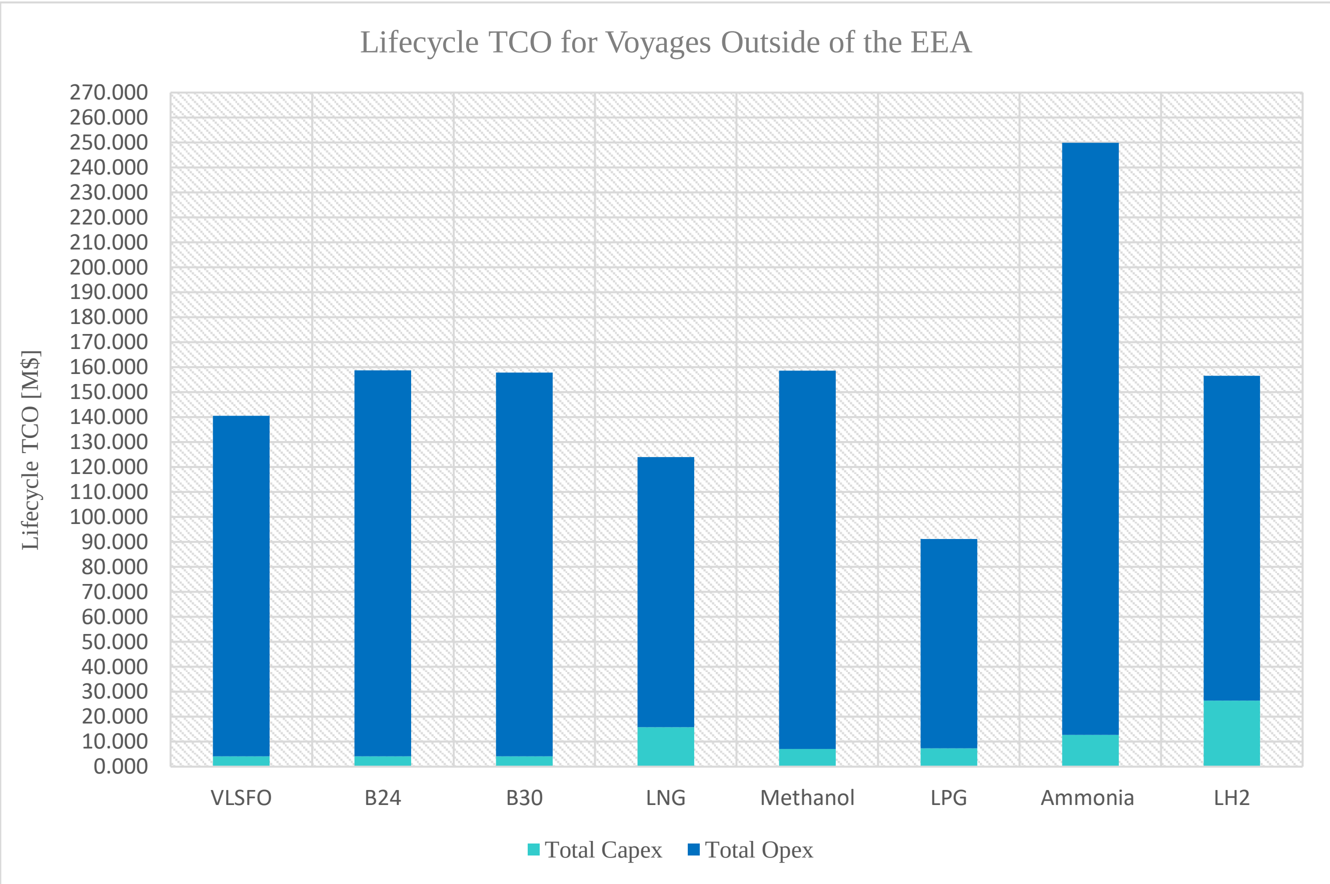

Figure 73: Lifecycle TCO for Voyages Outside of the EEA

The approach here did not include any of the Allowances from EU ETS for the greenhouse gases emitted from the vessels as this is a regulation mandated by the European Union. CII however is still affecting every vessel thus conventional or high cargo content fuels could not remain compliant and speaking of a low total cost of ownership while not possible to sail has no use. So, it is clear that a lower TCO does not straightly equals a better solution, but the fuel should be also compared with the CII rating of the vessel as extensively discussed in 3.2.4 Emissions & Environmental Taxes.

5. Conclusion & Discussion

Reaching the final chapter and having calculated the capex and opex for the panamax bulk carrier operating on all the different fuels discussed, it was possible to compare the results. At this point the complexity that a realistic calculation of the TCO includes was important to be highlighted since a lot of parameters that were assumed in this thesis were not possible to remain fixed for the lifespan of the vessel. Such parameters were the price of bunker fuels, which will vary and be higher when green methanol, ammonia, and hydrogen are well introduced to the market; the insurance costs, which will decrease in the future for currently less explored fuels and as ammonia and liquified hydrogen become more popular and safer. Additionally, the environmental taxes which will be stricter and allowances cost is likely to see a rise as it is already suggested that the permitted allowances will be reducing gradually meaning that not all the emissions will be possible to be paid in allowances. Moreover, the reduction factors for the CII regulation have been proposed to be higher in the following years without any specific guidance though, meaning that the rating that resulted for every vessel may be even worse after the first three years. The TCO comparison was not direct about the cost, but the CII ratings should also be considered in order to check the sustainability of the fuel. It should be noted that additional environmental taxes will be added through the Fuel EU system which is planned to incorporate well-to-wake emissions. This will further open the gap between conventional and high carbon fuels and environmentally friendly ones.

As far as the fuels and the results were concerned, it was remarkable that LPG had the lowest TCO in all three scenarios which was a result of the low total fuel cost due to the high LHV and low bunker price. Despite that, it can’t be considered as a feasible long-term solution as the the CII rating of the vessel was barely compliant for the six upcoming years with three consecutive years of a D rating. More to that, the LPG availability remains in low levels as terminals only exist as storage facilities and still need to integrate bunkering infrastructure in order to support ship voyages a procedure that is controversial on whether it is beneficial given the emissions profile of LPG.

Moreover, the case of methanol was interesting as it came with higher emissions than biofuels and a higher TCO than the conventional propulsion. The former was also linked with the second worse CII rating after VLSFO. This surprising finding was justified by the fact of using grey methanol for the calculation of this study since the bunker prices were only available for this type and by the very low lower heating value of methanol which resulted in 2.46 higher consumption per mass of fuel to achieve the same energy output compared to the conventional. Nevertheless, methanol’s bunkering infrastructure only referred to grey methanol with 18 active bunkering facilities and 11 under development hence this was the type taken into account. It is suggested however, that green methanol will have a 90% lower CII rating profile but at the same time will come with a much higher bunker price possibly even higher than hydrogen as the energy needed for production is very high. Hence, green methanol could be an efficient alternative and has recently gained a lot of interest with lots of environmental benefits but with a higher TCO mainly due to fuel costs.

On the other hand, LNG propulsion resulted in the second lowest TCO after LPG for voyages entering/exiting EEA or voyages outside of the EEA with a much better CII rating throughout the lifespan of the ship being compliant for 12 out of 15 years making one of the most promising short-term solutions. Despite that, it is obvious that it can’t be viable in the long-term since environmental benefits are expected to reduce with stricter regulations coming up and the target being at net zero GHG emissions around 2050.

Given the environmental deficiency of VLSFO and moving towards a transitional period, biofuels were a good alternative as they can be used as drop in fuels and their TCO was calculated very close particularly for intra EEA voyages. The CII compliance of the B24 and B30 vessels was viable for 8 and 11 years respectively through the lifespan of the ship. For the remaining years lacking compliance, higher biofuel blends shall be used but again only for a short-term period.

The highest TCO throughout the 15 years was assessed by far for the ammonia fuelled vessel with the main factor being the fuel cost of the operational expenditures. Even though the capex was at mid-level, lower than LNG, ammonia’s opex were in the very high end affected by the lowest lower heating value of all the fuels discussed and subsequently the very high fuel consumption from the main engine and gensets. The extreme total cost for the lifespan of the vessel in combination with the safety issues that arise from the toxicity of ammonia makes the profitability and the trustworthiness of ammonia powered vessels rather low and further improvements need to be done so as to be a beneficial and sustainable solution for maritime decarbonization targets. More to that, bunkering infrastructure needs to be developed at least on the existing ammonia storage facilities for loading and discharging. The environmental benefits despite that should not be ignored.

Liquified Hydrogen on the contrary, had appealing long term specifications with a surprising low total cost of ownership given the new technologies and the lack of technical knowledge on the vessel’s performance. With the main drawback being the large volume of tanks needed onboard and most importantly the current total lack of bunkering infrastructure, the results though promising have yet to overcome some barriers in order to be incorporated in maritime and be capable of contacting profitable voyages. Nevertheless, the Total Cost of Ownership results of LH2 were very promising and could lead to a sustainable maritime future if further steps are taken.

Conclusively, it should be highlighted that the methodology followed in this analysis tried to take into consideration as many parameters as possible to be evaluated in the framework of a master thesis for the assessment of the total cost of ownership for a Panamax Bulk Carrier. The capital and operational costs that were projected in a 15-year lifespan of the vessel aiming for more realistic and usable results could hopefully offer valuable data to the maritime sector about the fuel that may lead the way in the upcoming future. It was noted however that maritime companied, though willing to invest on alternative fuels, they are still hesitant due to lack of experience and long-term sustainable solutions and incomplete infrastructure and availability of the carbon free fuels. It is believed that biofuels will take over the already existing conventionally fuelled ships and LNG powered vessel will see an increase in the short term.

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