

Feasibility Analysis of a Methanol Fuelled Bulk Carrier

Giorgia Adami^{a,*}, Massimo Figari^a

^a Università di Genova, DITEN, Genoa, Italy

* giorgia.adami@edu.unige.it

Abstract

Emissions restrictions are growing worldwide due to climate change concern. In the maritime sector different fuels are under scrutiny to identify the best option toward a carbon free transport. Methanol, the simplest alcohol, is one of the most discussed alternative fuels. This work aims at investigating the use of this chemical as fuel on board from different perspectives in order to provide a complete picture. A 34000 DWT bulk carrier has been used as case study including both the hypothesis of a retrofit and a newbuilding. From the technical point of view the attention has been focussed on the ship general arrangement finding space for methanol tanks and fuel systems, in agreement with the existing ABS rules. A carbon footprint emission assessment has been performed, taking into account both IMO's and EU's regulations. To have a more complete overview, a preliminary economic evaluation is also performed with the estimation of OpEx and CapEx related to the methanol system on board. Results showed the technical feasibility with respect to the ship conversion and some criticality related to safety measures and the energy content of methanol. From the polluting impact point of view, the study highlights the importance of a Well to Wake (WtW) approach instead of considering only Tank to Wake (TtW) emissions. From this perspective, with a global decrease in GHG emissions of about 85% with respect to HFO, green methanol appears to be the only viable ecological solution. The use of bio methanol on board significantly affects OpEx, with an estimate increase of more than 250%, due to the high costs of methanol produced from renewable feedstocks and its small production worldwide.

Funding Statement: This work was carried out under research program BIPE 2021 of Genoa University supported by the Foundation Compagnia San Paolo.

Author Contributions: GA and MF equally contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

Keywords: Bulk Carrier, CapEx-OpEx Evaluation, Carbon Footprint, Methanol, Technical Feasibility

1. INTRODUCTION

Climate change and environmental protection are the most discussed issues for the future.

One of the major problems is Air Pollution, especially from Greenhouse Gases (GHG) emissions. The shipping sector, with a fleet almost entirely powered by fossil fuels, in 2018 was responsible of 2.89% of global anthropogenic emissions [1].

In light of these conditions, major ruling bodies are imposing increasingly restrictive regulations on the maritime sector; this leads to the need to find alternative solutions to fossil fuels.

This work aims to investigate one of the possible alternative fuels, the methanol, using a 34000 DWT bulk carrier well proven design as a case study including both the hypothesis of a retrofit and a newbuilding. The main focus is on developing a methodology that allows to verify the feasibility of the methanol solutions proposed. The methodology is based on three main pillars: technical, environmental and economic feasibility.

From the technical point of view, the attention has been focused on the ship general arrangement finding space for methanol tanks and fuel system following the ABS's "Requirements for Ethanol and Methanol fuelled Vessels".

The environmental impact of methanol used as marine fuel has been assessed following International Maritime Organization's (IMO) Annex VI and an approach based on European Union's (EU) FuelEU Maritime regulation. This allows to highlight differences and peculiarities of both the decarbonization strategies.

A preliminary economic evaluation has been carried out with the Operational Expenditure (OpEx) and Capital Expenditure (CapEx) calculation related to the fuel system on board in order to give a complete overview of this alternative solution.

The methanol solutions have been compared in every aspect to the original ship to highlight the differences with a fossil fuel propulsion.

1.1 State of the Art

Methanol, the simplest alcohol, is a chemical widely traded worldwide as a commodity; in recent years its characteristics have led to a growth of interest in its use as an alternative marine fuel [2].

Methanol is liquid under atmospheric conditions, which facilitates transport and storage; this advantage is limited by the low lower heating value (LHV 20 MJ/kg [3]) compared with traditional marine fuels. As a consequence, approximately twice as much fuel by weight must be bunkered to store the same energy on board [3]. In addition to being volatile, colourless, and extremely flammable, methanol is also toxic for humans and has a low flashpoint (12°C [3]). These peculiarities lead to the need for strict and dedicated regulations. In 2020, IMO published and adopted the “Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohols as Fuel” with a more prescriptive approach compared to the previous IGF code (2015). On that basis, some of the most important Classification Societies (DNV-GL, ABS, Lloyd’s Register, IRS) developed their own guidelines for methanol and ethanol fuelled vessels.

Methanol’s characteristics allow its use in traditional Compression Ignition engines with some modifications regarding injection and feeding system; moreover, a minimum amount of Diesel Oil (DO) should be used as pilot oil [4].

Major marine engine manufacturers (e.g., MAN, Wartsila) have expanded their portfolio with methanol dual fuel solutions; they also provide the possibility of retrofitting and adapting to methanol existing engines [5].

Analysing the context of the production, methanol can be produced efficiently from various sources including some fossil products but also from agricultural waste, biomass, urban garbage and other ecological feedstocks [3]. Methanol is classified according to the type of raw material used for its production in: Grey Methanol when Natural Gas is the feedstock, Brown Methanol if produced from Coal, Blue Methanol when produced from both fossil and bio-feedstocks, Green Methanol that is obtained exclusively from green sources, this category includes also e-methanol from carbon capture. This distinction is really important for the emissions evaluation; in fact, the environmental impact is different between the various paths of production.

Presently two different metrics have been in use to define the GHG emissions: the ones produced on board from combustion process are the so-called Tank to Wake (TtW) or end-life emissions, and the Well to Tank (WtT) emissions are those related to raw material extraction, fuel production, transport

and storage onshore. The WtW emissions include the entire chain.

The methanol produced from different raw materials has the same chemical properties, thus TtW emissions are the same because they are based on the methanol molecule: for each gram of fossil-based methanol 44/32 gram of CO₂ are emitted.[6]

Considering other on-board pollutant emissions, the use of methanol, a sulphur free chemical, eliminates 99% of Sulphur Oxides (SO_x) emissions compared to fossil fuels; this allows to comply with SECA areas restriction [6]. With regards to Nitrogen Oxides (NO_x) emissions are still present but reduced by approximately 60% [6] compared with traditional fuels and there are easy solutions that allows to respect Tier III regulation. Particulate matters emissions are reduced by about 95% compared to HFO [3]. From a technical point of view the low NO_x and SO_x emissions avoid having to install Scrubbers or other exhaust gas treatment devices with a saving in economic terms and space on board.

With the focus on Carbon Footprint or GHG emissions, the emissions to consider having a complete overview are the WtW and from this point of view differences arise between the different path of methanol production.

The fossil-based methanol produces, over the entire chain, carbon dioxide (CO₂) emissions comparable to fossil Diesel Oil (DO). Full lifecycle emissions for natural gas-based methanol, are 103 - 110 gCO₂/MJ LHV or 2.05 - 2.20 kg CO₂eq/kg while the carbon footprint of methanol produced from coal is nearly 300 gCO₂eq/MJ, which is about 3 times higher than the previous one [6].

Considering methanol obtained by green sources, TtW emissions are considered climate neutral resulting in a significant reduction in overall carbon emissions of about 60-80% [6]. The Methanol Institute suggest that the TtW emissions of this type of methanol count as zero because they were previously absorbed from the atmosphere [6]. Some production paths even allow to negativize CO₂ emissions [6].

In light of these considerations, the only option that effectively reduce GHG emissions, is the use of methanol from green feedstocks.

Green methanol is a small reality compared to the total global production; only 0.2 Mt/year of renewable methanol are produced worldwide [7] by a handful of commercial producers. This fact leads to incredibly high costs as well as not having, nowadays, enough to meet the possible demand of the maritime sector.

Looking at the State of the Art with regards to existing vessels and new orders, from 2015, with the Stena Germanica conversion to methanol, the

global interest in the use of methanol as marine fuel has grown exponentially. Some important Companies e.g., Methanex Waterfront Shipping, CMA-CGM and A.P. Moller-Maersk, have started to enlarge their fleet with methanol powered ships.

A.P Moller-Maersk has 19 methanol dual fuel ships on order and the first feeder vessel of 2100 teu will arrive in autumn 2023 [8]. The strategy of this colossal deserves attention; in fact, they engage in strategic partnership across the globe to scale green methanol production by 2025 [9]. This highlight that collaboration and investments in innovative projects are the most important ways to reach a net zero fuel value chain.

Additionally, the academic and research interest on this fuel solution and on the importance of techno-economic-environmental analysis is high and the following papers have been useful for this work. Denitz et al. [10] studied environmental and economic performance of methanol, ethanol, liquefied natural gas, and hydrogen as marine fuels. Horvath et al. [11] analysed the most cost-effective combination of synthetic fuels and fuel cells or internal combustion engines to replace fossil oil as the main propulsion fuel in the shipping industry in 2030 and 2040. Ammar [12] studied the application of methanol dual-fuel engine for a cellular container ship from environmental and economic points of view.

The rest of the paper is structured as follows: Section 2 contains the description of the methodology, Section 3 is related to the Case Study, in Section 4 the results have been analysed and the Section 5 is dedicated to the conclusions.

2. MATERIAL AND METHODS

This section aims to describe the proposed methodology used to identify a feasibility metric for methanol fuelled bulk carriers.

2.1 Pillar 1: Technical requirements for the safe use of methanol as fuel on board

The technical requirements used in this work for evaluating the installation of methanol fuel tanks and supply system are dictated by ABS's guideline for methanol and ethanol fuelled vessels [13] that incorporates IMO's MSC.1/Circ.1621. The most significant points have been highlighted below.

Methanol can be stored on board in integral, independent and portable tanks; each of these options are considered in the Rules.

Fire and explosion safety is one the most important aspects to consider for a low flashpoint fuel; for this reason, integral methanol tanks are surrounded by protective cofferdams. The

cofferdam is not mandatory on those surfaces bounded by shell plating below the waterline, other methanol tanks or fuel preparation spaces ("Sect 5, 3.2 ABS's guideline"). The distance between the tank and the cofferdam should be at least 600 mm with A-60 insulation.

Methanol has also a corrosive nature, for this reason stainless steel is the proposed material for fuel storage tanks; however, for large structural tanks or in case of a retrofit, silicate coatings on structural steel can be used.

Storage tanks need to be ventilated and inerted at any time during normal operation; a nitrogen inert system is required on board.

The ABS's guide dedicates section 8 to bunkering. The key aspects for the positioning of the bunker station are ventilation and safety; in particular is important to analyse the risk of fuel exposure in case of spillage during ordinary operations.

Methanol as fuel needs a system of valve trains, pumps, filters and heat exchangers to supply the engine at specific conditions. Pumps submerged in methanol tanks should be arranged with double barriers preventing from being directly exposed to the fuel. The space for the fuel supply system must be separate from the engine room although an entrance is permitted via airlock.

In non-hazardous enclosed areas stainless steel double-walled pipes are necessary for fire safety reasons.

The location of the vent mast requires a minimum safety distance to deck, air intake, opening to accommodation, service spaces, and ignition sources.

It is present practice with dual fuel engines to have on board an amount of diesel oil as safety measure. This is required to ensure a safe return to port with fuel oil propulsion in case of failure of the methanol system. This requirement makes even more difficult to find volumes for methanol on board, especially in the case of a retrofit.

This work provides an amount of DO to ensure 7 days of navigation in oil-only mode.

2.2 Pillar 2: Environmental KPI

IMO in 2018 adopted the Initial Strategy on reducing GHG emissions from ships with the ambition to impose a regulatory framework that effectively reduces the global fleet's environmental impact. [14]

With this purpose various technical and operational indexes and tools have been set including Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII) that will be evaluated in this paper.

The EEDI is used to calculate a vessel's energy efficiency with a complex formula taking the ship emissions, capacity and speed into account. [14] The equation can be summarised with:

$$EEDI \left[\frac{gCO_2}{t Nm} \right] = \frac{\sum P \times C_f \times SFC}{Capacity \times Speed} \quad (1)$$

where P is the Power, Cf is a conversion factor, and SFC is Specific Fuel Consumption. For bulk carriers the capacity means Deadweight [15].

Equation (1) allows to evaluate the Attained EEDI (EEDI_a) that has to be compared with the so called Required EEDI (EEDI_r) [16].

$$EEDI_a \leq EEDI_r \quad (2)$$

$$EEDI_r = \left(1 - \frac{x}{100} \right) \cdot Ref. Line Value \quad (3)$$

where x is the reduction factor that varies with time [16]. The reference line value must be evaluated with the following equation:

$$Ref. Line Value = a \cdot b^{-c} \quad (4)$$

The parameters a, b, c are provided by IMO's regulation [16] depending on ship types and size.

The CII is a rating scheme (A-E) developed by the IMO to measure the annual performance in terms of CO₂ per DWT and distance covered [17]. Even in this case the CII of the ship, the Attained CII (CII_a), has to be compared with the Required Annual one (CII_{ar}) [18].

$$CII_a = \frac{M}{W} \quad (5)$$

Where M is the Mass of CO₂ emissions in grams and W represents the transport work Tons x Nautical Miles [t Nm].

$$M = FC_j \times C_{f_j} \quad (6)$$

FC_j is the total mass in grams of consumed fuel oil of type j in the calendar year while C_{fj} represents the fuel oil mass to CO₂ mass conversion factor for fuel oil type [18].

Transport work W can be evaluated as follows [17]:

$$W = C \times D_t \quad (7)$$

C represents the ship capacity and is different for ship types (for bulk carrier=DWT); D_t is the total distance traveled [Nm].

The Required Annual CII (CII_{ar}) equation is the following [19]:

$$CII_{ar} = \left(1 - \frac{Z}{100} \right) CII_{ref} \quad (8)$$

Z is an annual reduction factor

$$CII_{ref} = a Capacity^{-c} \quad (9)$$

The parameters are tabled in IMO's requirement [20].

The requirement also provides the boundaries for determining a ship's annual operational carbon intensity performance from the year 2023 to 2030.

The boundaries are determined by the required annual operational CII in conjunction with the so called "dd vectors"; by comparing the attained annual operational CII of a specific ship with the four boundaries, a rating from A to E is assigned. [21]

In this work an estimate of the EEDI and CII is presented for both the original ship and the methanol propelled vessel.

In 2021, European Commission adopted the "Fit for 55" package that is a series of legislative proposal with the objective of reducing GHG emissions. [22]

The maritime sector is included in this path of decarbonization with the FuelEU Maritime proposal. In March 2023, the European Council and Parliament agreed that FuelEU will come into force from January 2025 [22].

This regulation includes a technical annex with the methodology for establishing the GHG Intensity Limit on the energy used on board by a ship.

The peculiarity of this index is that it considers the emissions over the entire chain, the so called Well to Wake emissions [23].

$$GHG Intensity Index \left[\frac{g CO_{2eq}}{MJ} \right] = WtT + TtW \quad (10)$$

From 2025, the average GHG intensity of the energy used on-board during the reference period shall be calculated and not exceed the target value otherwise a penalty has to be paid. Such target value will be reduced over the years.

EU's regulation focusses the attention also to the energy needed by the ship moored at the quayside; only onshore power supply or zero emissions technologies are allowed.

In this work an estimate of WtW emissions is calculated for both the original ship case and the methanol propelled vessel (instead of the GHG

Intensity Index). The calculation is based on data from literature and equations from regulations with the hypothesis to ignore the contribution of marine gas oil for electric generation. The small amount of DO used as pilot oil has been neglected, too.

For both HFO and methanol propulsion the WtT emissions data have been selected from literature while the TtW emissions, for the fossil fuelled case, have been calculated in accordance with (11) from Annex I [21] of EU COM (2021) 562 [24].

$$CO_{2eq,TtW,j} = (Cf_{CO_2} \times GWP_{CO_2} + Cf_{CH_4} \times GWP_{CH_4} + Cf_{N_2O} \times GWP_{N_2O}) / LCV \quad (11)$$

According to [6], the TtW emissions from bio methanol (for example from solid biomass), have been considered climate neutral, and therefore not accounted for. The following table summarises the emissions data available in literature for Green Methanol.

Table 1. Green Methanol Emissions [6]

Green Methanol Emissions		
Well to Tank	13.5	gCO ₂ /MJ
Tank to Wake	0	gCO ₂ /MJ
Well to Wake	13.5	gCO ₂ /MJ

2.3 Pillar 3: Economic KPI

In this work CapEx and OpEx have been estimated to provide a preliminary economic assessment.

The attention has been focussed on the costs related to the Fuel and Engine Systems, in order to better highlight the variations in comparison to traditionally fuelled vessels.

CapEx are initial and fixed costs that are not dependant on the intensity of the operation of the vessel. The data required for their evaluation are the costs of the Engine and the Storage that include the Supply System.

An EMSA's Report [25] suggests the costs in terms of EUR/kW for engine and storage in case of newbuilding (reported in Table 2).

Engine cost can be considered almost equal in case of retrofit and newbuilding while the Storage and Supply system costs in case of retrofit should be more expensive. EMSA suggests, on the base of best engineering judgement, an increment of about 13-17% to newbuild CapEx [25].

The sum of costs in EUR/kW has been multiplied by the main engine power [kW]. Moreover, following a further in-depth analysis on available data, an amount of EUR 500000 has been

added to the Methanol CapEx to improve the accuracy of the calculations.

OpEx are variable costs that depend on ship lifetime and its operativity. The OpEx considered for this work are only related to the Fuel and the Engine systems; they have been divided in: Bunkering costs, Maintenance and Repair (M&R) costs.

Table 2. Engine and Storage Costs

Ship Category	Fuel Type	Engine Cost (EUR/kW)	Storage Cost (EUR/kW)
Large Vessels	Fuel Oil	200	60
Deep Sea Vessels	Bio-Methanol	280	100

Additionally, the Diesel Oil amount considered for the OpEx evaluation is only the one related to the use as Pilot Oil in methanol dual fuel engine.

The original vessel used as case study in this project is HFO fuelled, contract data specifications shows that specifically the fuel is IFO 380 so this type of fossil fuel has been considered. The mean value of Global Average Bunker Price (GABP) for the last three years (2019-22) has been used; and this value is of 414.75 USD/mt [26] or 403 EUR/mt (based on change 1EUR=1.03USD-17 Nov.22).

For M&R costs of a 2T fuel oil engine, the literature suggests costs of about 1.2-7.3 €/MWh/year [25]; a value of 1.5 has been chosen after analyzing some reports. Also considering tanks, fuel preparation, and supply system a final cost of 2.5 €/MWh/year has been used for M&R costs calculations for the original ship.

The EMSA's report on biofuels [25] provides a cost table of green methanol from different feedstocks for 2020 and a forecast for 2030 and 2050 that is summarised in Table 3; the first price scenario has been selected for the work.

Table 3. Green Methanol Costs [24]

Ship Category	2020 [€/MWh]	2030 [€/MWh]	2050 [€/MWh]
Green Methanol "bio-e methanol"	131	103	82
Green Methanol CCU	161.5	120	84.5
Green Methanol DAC	190	147.5	100.5

For DO costs the same procedure as IFO380 has been used; this allows to find a cost of 673 €/mt [26]. Through the specific consumptions and the hypotheses made on the hours of ship operativity and lifetime of the ship (Table 5), it has been

possible to estimate the tons of fuels necessary during the whole life of the ship.

A market survey has shown the M&R costs that amount to approximately 30 EUR/kW/year divided in 20 EUR/kW/year attributable to main engine and the remaining to Storage and Supply.

After defining the specific consumption of the main engine in the two cases of propulsion, with simple operations of sums and multiplications, the OpEx costs have been evaluated.

3. CASE STUDY

The original ship's fuel oil tanks are located aft inside Engine Room (Fig. 1) and in this area is positioned also the separator room.

Table 4. Original Ship Data

Item	Value
Length Overall, max	180.00 m
Breadth moulded at design, max	30.00 m
Depth moulded to upper deck at side	14.70 m
Scantling Draught	9.75 m
DWT Scantling Draught	34000 t
Total Cargo Volume	45500 m ³
Heavy Fuel Oil tanks total volume	1700 m ³
Diesel tanks total volume	200 m ³
Service Speed at Scantling Draught	14 knots
Engine Output at CSR (80% MCR)	6100 kW
CMCR Main Engine	7600 kW
Daily Consumption of HFO at CSR	26.4 t
Auxiliary Engines Daily Consumption	2 t
Endurance	18500 Nm
SFOC Main Engine	170g/kWh

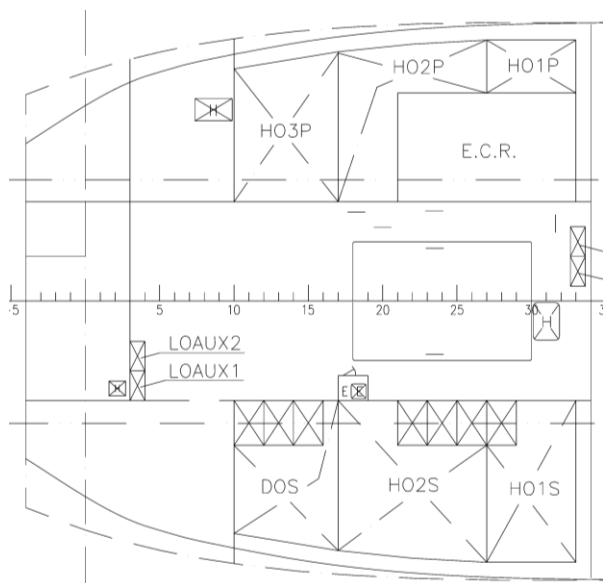


Figure 1: Original Ship's Fuel Tanks Layout

For the various calculation that will follow for both original ship and methanol solutions the operativity data used are listed in Table 5.

Table 5. Operational Data

Operational Data		
Ship Lifetime	20	years
Operating Time	6000	h/year
Distance Travelled in one year	60000	Nm

The data and formulas presented in chapter 2 have been used to evaluate costs and environmental parameters for the original fossil fuelled vessel. The results, which are presented in Table 6, have been used as comparison parameters with the methanol solutions.

The vessel under analysis has been designed before IMO's regulations for emissions control; this lead to have results in term of EEDI and CII that do not comply with actual standards. This problem has been solved by comparing the new solutions in percentage terms with the HFO solution.

Table 6. Original Ship Index and Parameters

Emission Indexes for Original Ship		
EEDI	6.70	gCO ₂ /tNm
CII	10.86	gCO ₂ /tNm
WtT Emission HFO	13.5 [14]	gCO ₂ eq/MJ
TtW Emission HFO	78	gCO ₂ eq/MJ
WtW Emissions HFO	91.5	gCO ₂ eq/MJ
Economical Parameters for Original Ship		
CapEx	1976000	EUR
OpEx	64524000	EUR

3.1 Methanol Solutions

In this work both cases of retrofit and newbuilding have been proposed; the following considerations must be applied to both solutions.

It has been hypothesized that the changes made on fuel system for the methanol use are not such as to modify the power request for the propulsion; thus, the main engine power of 7600 kW has been maintained. With methanol propulsion a Specific Gas Consumption (SGC, that represents methanol consumption) of 350 g/kWh and a Specific Pilot Oil Consumption (SPOC) of about 8.35 g/kWh have been considered. The data just defined are based on information about MAN B&W ME-LGIM, CEAS Engine Data Reports [4].

Moreover, in this study the attention has been focused on the main propulsion; for this reason, the Auxiliary Engines are considered diesel fuelled also in the new solutions.

As regards the Methanol Supply System, the footprint has been estimated based on the size of

one of the currently commercially available [27]; the selected volume is of about 65 m³.

It is nowadays a customary practice to store on-board an amount of diesel oil for safety purpose; for this reason, a volume of 210 m³ is dedicated to ensuring 7 days endurance in fuel oil-only mode.

For the Retrofit case, the simplest solution has been selected: the methanol tanks have been positioned in the spaces originally dedicated to HFO tanks, trying to use all available volumes and limiting the changes. All the safety measures mentioned before (section 2.1) have been considered for the installation.

This solution provides to accommodate the Methanol Supply System in a volume previously used as a tank, providing a direct access from the open deck.

The proposed layout, represented in Fig. 2, admits storing 1120 m³ of Methanol divided in four tanks. Moreover, 280 m³ diesel oil are provided for pilot oil and safety purposes. The yellow dashed spaces in the retrofit tank layout figure represent safety cofferdams.

The lower LHV of methanol compared to fossil fuels, combined with the reduction of volumes dedicated to primary fuel due to safety and operational needs, lead to an inevitable reduction in ship's endurance.

The techno-economic-environmental results of the proposed retrofit solution are summarized in Section 4, Table 7(a,b,c).

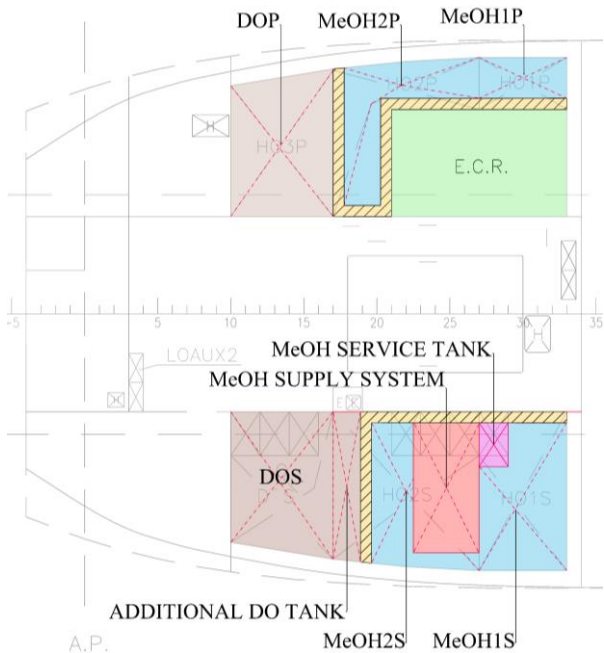


Figure 2: Methanol Retrofit Tanks Layout

In case of newbuilding no changes in the main dimensions of the vessels have been considered. The proposed solution is based on the hypothesis of a rearrangement of the original fuel tank area merged with finding spaces for methanol from the cargo hold n° 5 that is the closest to the engine room.

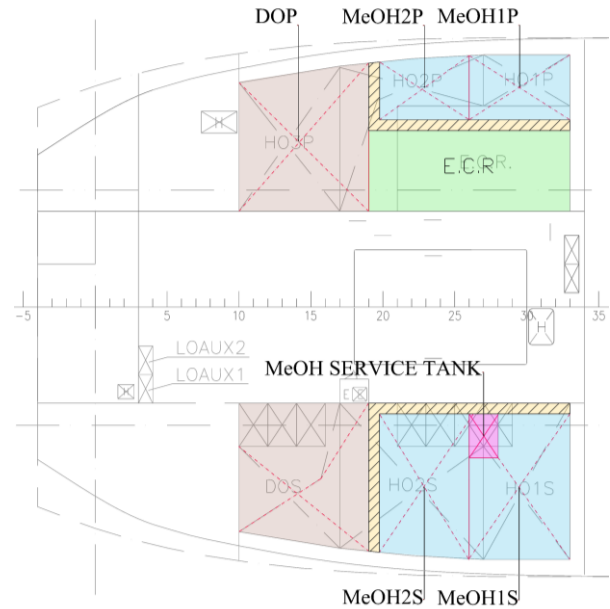


Figure 3: Newbuilding Tank Layout Engine Room

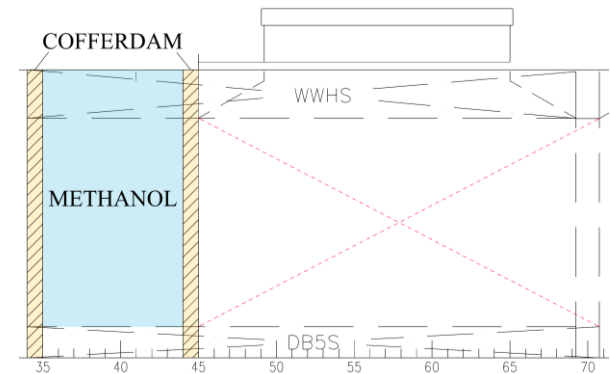


Figure 4: Newbuilding Tank Layout Cargo Area

In figs 3 and 4 the yellow dashed areas represent the cofferdams installed for safety purposes.

The Methanol Supply System has been located inside the engine room where the HFO separator room was originally positioned. This is possible ensuring the access to this area via airlock.

The newbuilding case layout allows to obtain 3557 m³ of methanol storage volume and an additional Diesel volume of about 430 m³. This methanol solution ensures a ship's range similar to the original HFO powered vessel.

The main drawback of this option is the cargo volume reduction of about 8%. Reasoning on equal freeboard with the original vessel, the cargo reduction would be more problematic in the case of light cargo while it might not be impacting in the case of heavy cargo.

4. RESULTS

This chapter has the purpose to summarise the results obtained in this work.

Tables 7 (a,b,c) shows the comparison between the original HFO fuelled ship and the new solutions powered by methanol. It is worth mentioning that both solutions have been designed avoiding variations on ships main dimensions and that the costs are related only to the engine and fuel storage & supply system.

Table 7a. Methanol Solutions Comparison Pillar 1

Pillar 1: Technical Feasibility		
HFO Volume "Original Ship"	1700	m3
Methanol Volume "Retrofit"	-34%	
Methanol Volume "Newbuilding"	+109%	
Endurance "Original Ship"	18500	Nm
Endurance Methanol "Retrofit"	-69%	
Endurance Methanol "Newbuilding"	0%	
Cargo Volume "Original Ship"	45500	m3
Cargo Volume Methanol "Retrofit"	0%	
Cargo Volume Methanol "Newbuilding"	-8%	

Table 7b. Methanol Solutions Comparison Pillar 2

Pillar 2: Environmental Feasibility		
EEDI "Original Ship"	6.70	gCO2/tNm
EEDI "Methanol"	-9%	
CII "Original Ship"	10.86	gCO2/tNm
CII "Methanol"	-4%	
WtW Emissions "Original Ship"	91.5	gCO2eq/MJ
Well to Wake Emissions "Green Methanol Ship"	-85%	

Table 7c. Methanol Solutions Comparison Pillar 3

Pillar 3: Economic Feasibility		
CapEx* "Original Ship"	1976000	EUR
CapEx Methanol "Retrofit"	+94%	
CapEx Methanol "Newbuilding"	+71%	
OpEx "Original Ship"	64524000	EUR
OpEx "Green Methanol 2020"	+269%	
OpEx "Green Methanol 2030"	+193%	
OpEx "Green Methanol 2050"	+173%	

* CapEx only related to Propulsion Equipment

The retrofit results show that, with the purpose of limiting the structural changes and following the rule safety requirements, the storage volume dedicated to methanol is limited. Consequently, taking into account the low LHV of the alternative fuel, the energy stored on board and the ship's endurance are considerably reduced compared to the original vessel. This disadvantage could be mitigated by a frequent bunkering given that 88 of the world's largest 100 ports can supply methanol [24].

Considering the newbuilding solution, it is evident from table 7a that the modifications allow to store the same energy on board and consequently to reach the same endurance of the fossil powered ship. This is possible with a cargo reduction of about 8%. The loss of cargo volume may not be too impactful when carrying heavy loads, but more accurate considerations need to be made in this regard.

Paying attention to GHG emissions and carbon footprint both IMO's and EU's strategy for decarbonisation have been considered.

What emerged in this work is that, focussing on TtW emissions with the IMO's approach, EEDI and CII have a limited improvement (in the order of -5%/-10%) with respect to the HFO fuelled ship; this fact is also confirmed in the literature. This consideration, together with the yearly increasing restrictive limits for IMO's indexes, lead to consider methanol as a viable alternative marine fuel mainly for the short term.

However, following the EU's strategical path to decarbonisation thus considering WtW emissions methanol could be also considered as a long-term solution.

With a complete overview of the emissions over the entire fuel chain differences arise between the different type of methanol production, which is not evident from the IMO perspective.

Considering grey/brown methanol, total emissions could be equivalent or slightly higher compared to fossil fuels based on the different raw materials.

In light of the evidence, green methanol is the only real option to effectively reduce GHG emissions in fact allows their reduction of 85% compared to HFO; and this is valid and unchanged even for a long-term analysis.

Proceeding with the analysis of the economic sphere, methanol fuelled vessels, like every new solution or idea, need an intensive design phase with an accurate risk analysis and shipyards must cope with new demands and special features. This inevitably leads to an increase in CapEx in both retrofit and newbuilding cases but in the first the proportional increase is greater. This could

probably be overcome or reduced after a series of newbuilding or retrofits and with the help of pilot projects and academic studies.

In the OpEx evaluation fuel costs represent the greater part and the high price of green methanol nowadays is a barrier to its expansion as alternative marine fuel. As mentioned above and as read in various papers, forecasts for the future price of bio-methanol are optimistic: in 2050 could be halved [24].

5. CONCLUSIONS

In this chapter a summary of what emerged during the drafting of this project is presented.

This work has been focussed on finding a methodology that allows to evaluate the technical, economic and environmental feasibility of the use of methanol as fuel for bulk carrier vessels.

From the technical point of view, there are several options to store methanol on board but here two of the simplest and less invasive solutions have been presented.

The results show that it is not too difficult to convert a bulk carrier to methanol in both retrofit and newbuilding cases. The major difficulty is to find enough space for methanol tanks, due to the low energy content of this chemical and some additional safety requirements such as cofferdams. The liquid condition of methanol at ambient pressure and temperature allows an easy bunkering and the storage in conventional fuel tanks.

The current common practice to store a large amount of DO to ensure a safe return to port, in case of methanol system failure, is a barrier for methanol fuelled vessels especially in case of retrofit. More projects and experience with different ships applications would lead to safer and more reliable systems for methanol and, as result, lower diesel storage.

The environmental results highlight the importance of the strategic path to decarbonisation and the difference between a Tank to Wake and a Well to Wake approach. This aspect is really important because if emissions continued to be regulated only on a TtW basis the effectiveness of the methanol will be only on the short-term period.

Considering the results on a WtW basis, green/bio methanol from renewable feedstocks appears to be the only true feasible option to reduce the carbon footprint.

The methodology used in this work shows an overall feasibility for the use of methanol for small size bulk carrier with a major criticality related to operating costs. Additionally, the methodology account for the price reduction of bio methanol as suggested by literature; this will be possible only if

demand from ship operators will rise at the same pace of the green methanol production [28].

REFERENCES

- [1] IMO, "Fourth Greenhouse Gases Gas Study 2020", 2021. [Online]. Available: <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf>
- [2] ABS, "Sustainability whitepaper: Methanol as Marine Fuel", 2021. [Online]. Available: <https://safety4sea.com/wp-content/uploads/2021/02/Sustainability-Methanol-as-Marine-Fuel.pdf>
- [3] J. Ellis, K. Tanneberger, "Study on the use of ethyl and methyl alcohol as alternative fuel in shipping". Report prepared for the European Maritime Safety Agency, Rep. no. 20151204.5, 2017. Accessed 2023. [Online]. Available: <https://emsa.europa.eu/air-pollution/alternative-fuels/items.html?cid=329&id=2726>
- [4] MAN, CEAS Engine data report for MAN B&W ME-LGIM. [Online] Available: <https://www.man-es.com/marine/products/planning-tools-and-downloads/ceas-engine-calculations>
- [5] Longspur Research. "All at Sea: Methanol in Shipping", 2022. [Online]. Available: <https://www.methanol.org/wp-content/uploads/2022/01/Methanol-and-Shipping-Longspur-Research-25-Jan-2022.pdf>
- [6] Methanol Institute, "Carbon footprint of methanol", 2022. [Online]. Available: https://www.methanol.org/wp-content/uploads/2022/01/CARBON-FOOTPRINT-OF-METHANOL-PAPER_1-31-22.pdf
- [7] IRENA and Methanol Institute, "Innovation Outlook: renewable methanol", International Renewable Energy Agency, 2021, Abu Dhabi. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf?rev=ca7ec52e824041e8b20407ab2e6c7341
- [8] A.P. Moller-Maersk Press Release, 05 Oct. 2022. [Online]. Available: <https://www.maersk.com/news/articles/2022/10/05/maersk-continues-green-transformation>
- [9] A.P. Moller-Maersk. Press Release, 10 Mar. 2022. [Online]. Available: <https://www.maersk.com/news/articles/2022/03/10/maersk-engages-in->

- [strategic-partnerships-to-scale-green-methanol-production](#)
- [10] C. Deniz, B. Zincir. “Environmental and economical assessment of alternative marine fuels”. In: *Journal of Cleaner Production*, 113 (2016) pp. 438-449
- [11] S. Horvath, M. Fasihi, C. Breyer. “Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040”. In: *Energy Conversion and Management* 164 (2018) pag. 230-241
- [12] N. R. Ammar. “An environmental and economic analysis of methanol fuel for a cellular container ship”. In: *Transportation Research Part D*, 69 (2019) pp. 66-76
- [13] *Requirements for Methanol and Ethanol Fueled Vessels*, American Bureau of Shipping, 2022. [Online]. Available: <https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/328-requirements-for-methanol-and-ethanol-fueled-vessels/328-methanol-and-ethanol-fueled-vessels-reqts-july22.pdf>
- [14] *Initial IMO Strategy on Reduction of GHG Emissions from Ship*, Resoultion MEPC.304(72), IMO, Apr. 2018. [Online]. Available: [https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304\(72\).pdf](https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf)
- [15] MAN energy solutions, “Energy Efficiency Design Index”. [Online]. Available: https://man-es.com/docs/default-source/document-sync/eedi-eng.pdf?sfvrsn=23fbab95_3
- [16] *2021 Revised MARPOL Annex VI*, Resolution MEPC75/15/Add.1 Annex I, IMO, 2021. [Online]. Available: <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.328%2876%29.pdf>
- [17] DNV-GL, “IMO GHG Strategy” <https://www.dnv.com/maritime/hub/decarbonize-shipping/key-drivers/regulations/imo-regulations/ghg-vision.html#:~:text=The%20IMO's%20Initial%20GHG%20Strategy,by%202050%2C%20compared%20to%202008.>
- [18] *2021 Guidelines on Operational Carbon Intensity Indicators and Calculation Methods*, Resolution MEPC.336(76) Annex 10, IMO, 2021. [Online]. Available: [https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.336\(76\).pdf](https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.336(76).pdf)
- [19] *2021 Guidelines on the Operational Carbon Intensity Factors Relative to Reference Lines*, Resolution MEPC.338(76) Annex 12, IMO, 2021. [Online]. Available: [https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.338\(76\).pdf](https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.338(76).pdf)
- [20] *Guidelines on the Reference Lines for use with Operational Carbon Intensity Indicators*, Resolution MEPC.353(78) Annex 15, IMO, 2022 [Online]. Available: [https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.353\(78\).pdf](https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.353(78).pdf)
- [21] *Guidelines on the Operational Carbon Intensity Rating of Ships*, Resolution MEPC.354(78) Annex 16, IMO, 2022. [Online]. Available: [https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.354\(78\).pdf](https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.354(78).pdf)
- [22] ABS Regulatory News No. 08/2023, “EU FIT FOR 55: Maritime FuelEU Regulation”. [Online]. Available: <https://ww2.eagle.org/content/dam/eagle/regulatory-news/2023/ABS%20Regulatory%20News%20-%20Fit%20for%2055%20-%20FuelEU.pdf>
- [23] *Annexes to the Proposal for a Regulation of the European and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC*, COM (2021)52 final, European Commission, Brussels, 2021. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:078fb779-e577-11eb-ala5-01aa75ed71a1.0001.02/DOC_2&format=PDF
- [24] *Directive EU 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*, Directive (EU) 2018/2001, European Parliament and the Council of EU, 2018.
- [25] European Maritime Safety Agency, Update on Potential of Biofuels in Shipping”, Rep.no. 4837444, Lisbon, 2022.
- [26] Ship & Bunker Website. [Online]. Available: <https://shipandbunker.com/prices#IFO380>
- [27] Alpha Laval, *Alpha Laval Fuel Conditioning Module (FCM) Methanol*. [Online]. Available: <https://www.alfalaval.com/products/process-solutions/fuel-conditioning-solutions/fuel-conditioning-modules/fcm-methanol/>
- [28] S. Warden, “Alternative Marine Fuels Series Wrapped Up”, 2018. [Online]. Available: <https://www.czapp.com/analyst-insights/alternative-marine-fuels-series-wrapped-up/>