Impact of Fuel Switch to Methanol on the Design of an all Electric Cruise Ship

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***Abstract*— Current climate change policies require the reduction of both greenhouse gas and pollutant emissions of the marine sector. To achieve such a goal, the use of non-fossil fuels is one of the proposed solutions. Specifically, methanol has several advantages in respect to other fuels (both fossil and non-fossil), providing a feasible near-term solution for a more sustainable maritime transport. However, since methanol presents different characteristics in respect to actual fossil fuels, it is required to carefully evaluate the effect of its onboard integration on a ship to determine both the technical and economic feasibility of transitioning the onboard power production to such a fuel. The study presented in this paper analyzes the consequences deriving from equipping a modern all electric expedition cruise ship with methanol fuel, considering both technical and economic aspects.**

***Keywords*— decarbonization, maritime transport, cruise ship, methanol, redesign**

I. Introduction

Decarbonization is a critical goal in the maritime sector [1, 2]. Among all the solutions actually in study for achieving green ships, the use of alternative fuels is the most promising short-term one [3, 4, 5]. At present, the only synthetic fuel that begins to be used is methanol (MeOH) [6, 7]. Methanol is a liquid at room temperature and pressure, which has a rather low boiling point ($64.7°C$), is corrosive for metals, and it is toxic to humans. However, it is no more dangerous than other fuels of hydrocarbon derivation presently used in marine sector (like MGO). In fact, MeOH presents lower fire risks [8], having lower volatility, increased flammability requirements, lower steam density, less heat release (1/8 of MGO), and slower combustion (-75%). These properties translate into greater fire safety than the common petrol that fuels most land-based engines. However, MeOH is toxic for humans by ingestion, skin absorption, and vapors inhalation. Nevertheless, even after prolonged exposure, a fast and reliable treatment is available to ensure full recovery. The great advantage of MeOH lies in its non-toxicity towards the marine ecosystem [8], allowing to store it in direct contact with the hull plating, thus enabling the use of the vessel's double bottom as a tank [9]. Moreover, methanol is produced on large scale since 1923, being used in many application fields, having a global consumption over 100 Mt in 2021 (projection of 110 Mt at the end of 2022), with a very high offer (production capacity over 170 Mt in Dec. 2022) [8]. This ensures an existing infrastructure for production, distribution, and ship fueling (bunkering), and competitive prices with MGO [10]. Due to its properties [11], methanol can be used in existing Diesel engines with some modification and providing a small amount of MGO (pilot fuel) to ensure its ignition in the combustion chamber. In such application it provides an increase in CO_2 emissions (which can be offset by sourcing green produced MeOH), but a significant reduction in all the other pollutant emissions (it enables complying with TIER III emission limits with only the addition of an SCR) [12]. All these properties make methanol a great fuel for sustainable maritime transport on the short-term [13].

Expedition cruise ships are passenger ships that are aimed at peculiar consumers, which want a cruising experience that puts an emphasis of the experience ashore, on excursions and less-frequented ports. They are smaller than conventional cruise ships, in function of their destination (Antarctica, Arctic Circle, Fjords) and the related strict sailing regulations; they have a high comfort and silence levels, to the benefit of both the environment and passengers; they have a medium-high range; and their profitability is strongly influenced by limited variations in the number of passengers. For expedition cruise ships, environmental issues play a critical role because they sail in protected places and uncontaminated nature, they have customers that are extremely sensitive to sustainability issues, and they have strong media exposure. Thus, there is a strong driver towards adopting as soon as possible green solutions, at the technological state of the art, and compatible with the technical/economic aspects characterizing expedition ships [14, 15]. In this scenario, many shipowners are evaluating the opportunity of building "methanol ready" ships, which use MGO fuel oil but can be easily refitted to the MeOH fuel when the supply chain will be ready to support them. Their design focuses on 2 key aspects: fuel tanks prepared for the use of green methanol, and additional internal volumes for the future installation of all the methanol related subsystems. In this context, while nowadays being a standard for cruise ships for all its well-known advantages [16], electric ship architecture enables the required flexibility in fuel choice [17, 18].

The study here presented analyzes the consequences deriving from the design choice of fueling a modern expedition cruise ship with methanol. Focus is given to the evaluation of the additional volumes required to meet the same range requirements for an expedition ship initially designed for operation with MGO, and to the simulation of the potential loss of payload (i.e., passengers) and consequent loss of profitability of the ship. On the bases of the results, alternative ship design development criteria are evaluated, to recover the ship's profitability as close as possible to the initial one.

II. Ship Characteristics

The ship used as case study has the following characteristics:

- Gross Tonnage (GT) → 2770 GT
- Length Over All (LOA) → 160 m
- Length Between Perpendiculars (LBP) → 155 m
- Breadth (B) → 26.50 m
- Accommodation beds (Lb) → 530
- Crew → 214
- Service speed (Vs) → 13 kn
- Range → 7600 *nm*
- Sea Margin (*SM*) → 15%

Accommodation beds number is an indicator of the number of passengers (*pax*) that can possibly be sailing onboard, and it is roughly equal to double the cabins. However, the market segmentation in the cruise sector relies on other two parameters. The first is the ratio between gross tonnage (i.e., ship size) and the number of passengers: *GT/pax*. The second is the ratio between the number of crew members and the number of passengers: *crew/pax*. Clearly, a high GT/pax means more space for each passenger, while a high crew/pax means better services for the passengers. Having a high value in both is an indicator ship's luxury level. Thus, to obtain a first indication about the suitability of the case study ship for its scope, it is worth noting that this ship presents both GT and pax values that are above the average, therefore configuring itself as a non-exclusive product.

The required range plays a key role for the shipowner, enabling seasonal transfers without intermediate supplies (from the summer polar destinations to the winter Antarctic ones). Moreover, it allows to manage fuel availability in locations where the supply is unfavorable due to high prices. Therefore, having a high range is critical. At the same time, the regulatory constraints in places with a high environmental sensitivity, such as Antarctica and the Norwegian Fjords, must be taken into consideration. A modern summer cruise in the Norwegian Fjords will first require crossing the North Sea, which is an emission control area since Jan 1, 2021. The latter is characterized by limitations both on emissions of sulfur oxides (% $S\ m/m$ <0.10%) and on nitrogen oxide emissions (TIER III). In addition, Norwegian national legislation requires onboard countermeasures to eliminate visible smoke.

In this context, the use of methanol in combination with the Dual Fuel internal combustion engine technology, guarantees:

- SOx emissions reduction ≈ 100%
- CO_2 emission reduction = 8% (Tank to Wake)
- GHG emission reduction ≈ 100% if green methanol is used (Well to Wake).

III. Design Constraints

To analyze the consequences deriving from equipping a modern all electric expedition cruise ship with methanol fuel, it is required at first to determine the relevant design constraints. Specifically, a first design based on conventional fuel (MGO) is performed, to evaluate the size of the fuel tanks required for meeting the range specified by the owner (hypothesizing two bow and two stern fuels tanks).

A. Power calculation

Using the electric load balance of similar ships, it is possible to determine the hotel (and auxiliaries) load:

Photel = 3000 kW

Applying mathematical models to the ship's main data, it results the power at the propeller axis (delivered power):

PD = 3228 kW

Then, the sea margin (SM) allows obtaining the power to obtain the service speed in real operation:

PD_{SM} = 3712 kW

The ship is based on a Diesel-electric propulsion architecture, thus endowed with an Integrated Power System (IPS - Fig. 1). A set of four Diesel Generators (DGs) provide power to the onboard loads and to the propulsion, ensuring a suitable amount of power with three running DGs, while keeping the fourth one as a redundant unit (to face faults and maintenance out of services in one of the others). To meet the required Vs goal, the dual-fuel Wärtsilä $6L32DF$ DGs (3360 kW each) have been selected. These machines are optimized for the TIER III emission regulation, when used in combination with an SCR.

To obtain the brake power (*Pb*) at the DGs' prime movers, the identification of the efficiency chain of the Diesel-Electric propulsion is needed. The Table I data is thus applied, obtaining:

$Pb_{prop} = \frac{PD_{SM}}{\eta_{me}\eta_{fc}\eta_{trasf}\eta_{alt}} = 4121\ kW$ propulsion

$Pb_{hotel} = \frac{P_{hotel}}{\eta_{alt}} = 3086\ kW$ hotel/auxiliaries

$Pb = Pb_{prop} + Pb_{hotel} = 7208\ kW$ total

As planned, the Pb can be met with three running DGs, being their total maximum continuous rating (MCR) equal to 10,080 kW, thus resulting in a 71.5 % load factor.

B. Fuel consumption calculation

By considering the three DGs operating in Diesel mode (MGO fuel, Lower Heating Value - LHV = 42.7 MJ/kg) at 71.5 % load factor, and applying a 5% tolerance to the factory provided SFOC (Specific Fuel Oil Consumption), it results:

$SFOC_{MGO}$ = 196.6 g/kWh @ 71.5% MCR

Therefore, it results an MGO fuel consumption per hour and per day respectively of:

$$Comb_{hourMGO} = \frac{SFOC_{MGO}}{1000} Pb_{disp} \frac{71.5}{100} = 1417 \text{ kg/h}$$

$$Comb_{dayMGO} = \frac{Comb_{hourMGO}}{1000} 24 = 34 \text{ t/day}$$

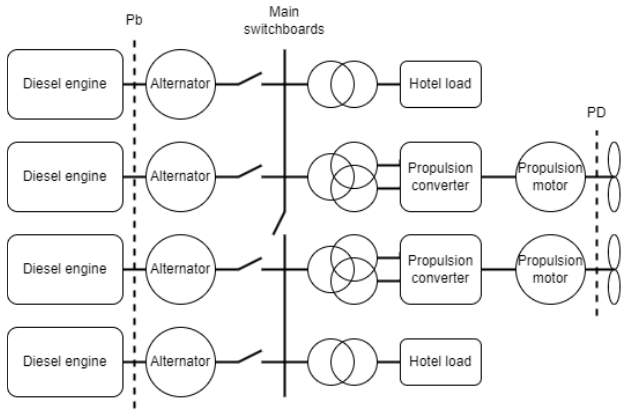

Fig. 1. Ship's Integrated Power System

TABLE I. EFFICIENCY OF THE DIESEL-ELECTRIC PROPULSION CHAIN

Component		Value
Electric propulsion motor	ηme	0.965
Propulsion frequency converter	ηfc	0.970
Propulsion transformer	$\eta trasf$	0.990
Alternator	ηalt	0.972

TABLE II. ADDITIONAL FUEL SYSTEM PARAMETERS

Parameter		Value
Volumetric density of MGO	ρ_{MGO}	0.86 t/m³
Volumetric density of MeOH	ρ_{MeOH}	0.79 t/m³
Fill factor	ff	0.98
Non pumpable fuel	Imp	0.03

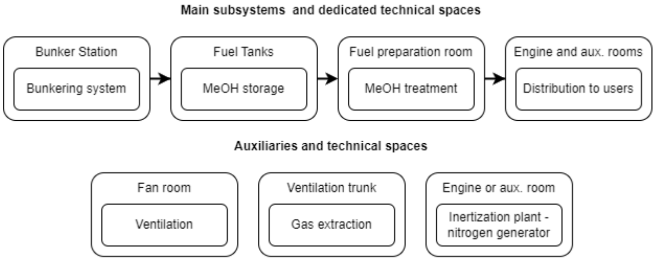

Fig. 2. Onboard MeOH plant

The latter allows calculating the nautical miles per ton of MGO fuel required by the DGs operating in Diesel mode:

$$MGO_{nm/t} = Vs \frac{1}{Comb_{hourMGO}} 1000 = 9.1 \text{ nm/t}$$

With the same process, it is possible to evaluate the resulting fuel consumption when the DGs operate in MeOH mode. Specifically, the motor burns methanol (LHV = 19.9 MJ/kg) as main fuel, while using a small amount of MGO as pilot fuel (required to ignite the methanol in the combustion chamber). The data is as follows:

$SFOC_{MeOH}$= 381.3 g/kWh @ 71.5% MCR

$SFOC_{MGO(pf)}$= 21.9 g/kWh (≈ 6% $SFOC_{MeOH}$)

Therefore, it results a methanol fuel consumption per hour and per day respectively of:

$$Comb_{hourMeOH} = \frac{SFOC_{MeOH}}{1000} Pb_{disp} \frac{71.5}{100} = 2748 \text{ kg/h}$$

$$Comb_{dayMeOH} = \frac{Comb_{hourMeOH}}{1000} 24 = 66 \text{ t/day}$$

and an additional MGO consumption for the pilot of:

$$Comb_{hourMGO(pf)} = \frac{SFOC_{MGO(pf)}}{1000} Pb_{disp} \frac{71.5}{100} = 158 \text{ kg/h}$$

$$Comb_{dayMGO(pf)} = \frac{Comb_{hourMGO(pf)}}{1000} 24 = 3{,}8\text{t/day}$$

resulting in the following nautical miles per ton of methanol fuel required by the DGs operating in MeOH mode:

$$MeOH_{nm/t} = Vs \frac{1}{Comb_{hourMeOH}} 1000 = 4{,}7 \text{ nm/t}$$

Additional parameters need to be introduced, concerning the fuel storage in their respective tanks. These are depicted in Table II. In particular, the fill factor is a constraint established by the IGF Code, which imposes a maximum tank filling threshold at the maximum temperature of the liquid fuel or, equivalently, at the maximum gas pressure, with the aim of reducing the risk of tank explosion.

C. Integration of a MeOH system onboard a ship

The onboard methanol fuel plant diagram is depicted in Fig. 2. As can be easily seen, dual-fuel engines are not the only element to be installed onboard to obtain a MeOH fueled ship. Several auxiliary subsystems are also necessary, such as a pressure control system inside each fuel tank, a system of relief valves, an inerting system (with its nitrogen generator) and ventilation, and fuel lines to the prime movers. However, the most impacting element to be integrated onboard are the methanol fuel tanks. Their sizing follows the amount of MeOH to be embarked, which is related to the required ship range (in methanol operation). Considering the volumetric energy density of MGO (36.30 GJ/m^3), which is about 2.3 times higher than the volumetric energy density of methanol (15.74 GJ/m^3), and neglecting non pumpable fuel, volume occupied by components inside the tanks, and reduction of the maximum tank filling according to the maximum gas pressure), it results:

$$V_{MeOH} = 2.3 \text{ x} \cdot V_{MGO}$$

where V_{MeOH} and V_{MGO} are the methanol and the MGO required fuel volumes to obtain the same range.

The fuel tank type also follows the methanol peculiar characteristics. The MeOH is a non-cryogenic fuel, thus it can be stored in common fuel tanks. However, MeOH tanks require the installation of a cofferdam, due to its low flash point value (less than 60 °C @ 20°C ambient temperature). A system for detecting liquid and gas leaks must be placed inside the cofferdams, which will activate the inerting system in case of leak. In addition, the DNV register establishes both the minimum distance of the pipes from the ship's side (800 mm), and the minimum size of the openings obtained on the cofferdams for possible inspections (600 mm x 800 mm). This leads to a reduction in the storable fuel in the same volume in respect to MGO, or equivalently higher onboard occupied volume. However, rules allow the cofferdam removal if one of the follow conditions is met:

- Tank walls in contact with plating below the lowest waterline
- Adjacent tanks (for walls in common)
- Tank walls delimiting Fuel Preparation Rooms.

Thus, the onboard arrangement of the fuel tanks require:

- Fuel tanks located in a single ship area
- Limiting the tank subdivisions to Safe Return to Port needs only
- Adding fuel tanks in the vessel's double bottom.

All the above leads to a further increase in the required volume of onboard MeOH fuel tanks in respect to MGO.

IV. EVALUATION OF SHIP RANGE AND FUEL/TANKS VOLUME WITH MGO AND MEOH

In the following it is analyzed the arrangement of the stern tanks only. Due to the ship layout design choices, the results will be considered valid also for the bow tanks, obtaining the general arrangement of all the fuel tanks of the ship.

A. MGO configuration

Considering the 7600 nm of range, equally subdivided in the bow and stern tanks (3800 nm each), it is possible to calculate the required volume of the latter. Having calculated the fuel consumption in t/day in the previous section, it is necessary to evaluate the maximum expedition length in days ensured by the tanks (half of the maximum range):

$$EL = \frac{Range}{2} \frac{1}{Vs} \frac{1}{24} = 12{,}2 \text{ days}$$

The MGO fuel to be stored in the stern tanks is thus:

$$MGO_{EL} = EL \cdot Comb_{dayMGO} = 415 \text{ t}$$

The fuel volume and the fuel tanks capacity are therefore respectively equal to:

$$V_{MGO} = \frac{MGO_{EL}}{\rho_{MGO}} = 483 \text{ m}^3$$

$$V_{tanksMGO} = V_{MGO}\left(1 + \frac{Imp}{100}\right) + V_{MGO}\left(1 - \frac{ff}{100}\right) = 508 \text{ m}^3$$

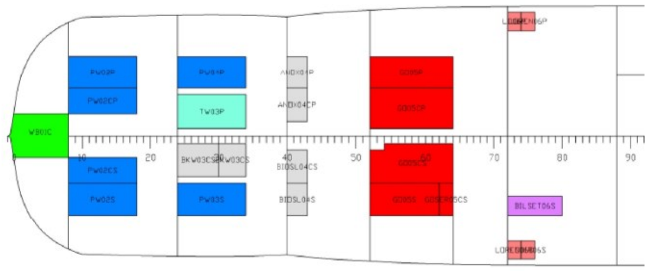

Fig. 3. Fuel capacity plan: MGO configuration (tanks in red)

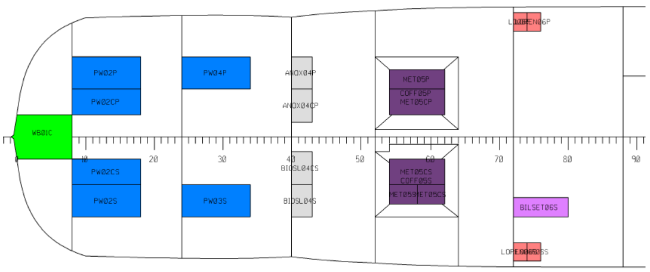

Fig. 4. Fuel capacity plan: stern tanks (in purple) with internal cofferdam

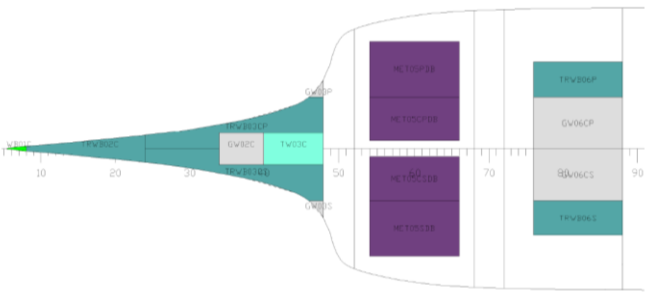

Fig. 5. Fuel capacity plan: double bottom MeOH tanks (in purple)

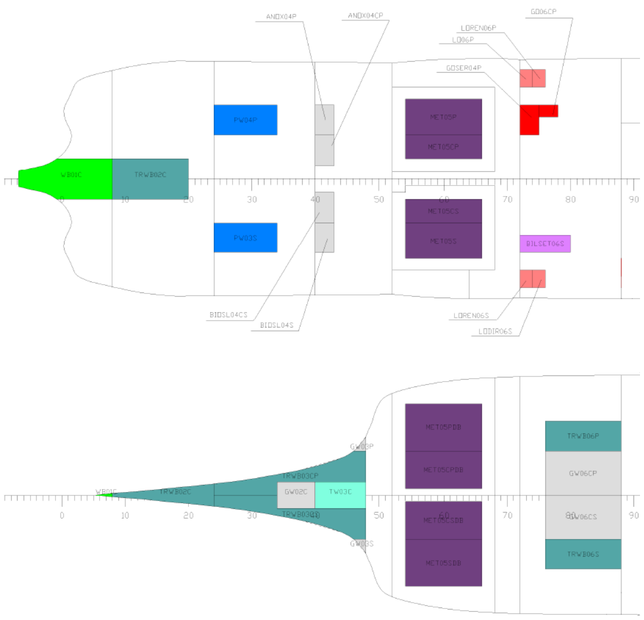

Fig. 6. Fuel capacity plan: stern tanks with external cofferdam and double bottom tanks (in purple)

The total amount of fuel in the stern storage area is subdivided into two tanks, one starboard and one port, each having the following volume:

$$V_{singletankMGO} = \frac{V_{tanksMGO}}{2} = 254 \text{ m}^3$$

To ensure structural continuity and with reference to the frames' longitudinal interval (0.7 m), each tank is 8.4 m long, 7.7 m wide, and 4 m high. The resulting onboard arrangement of the tanks is shown in Fig. 3.

B. MeOH configuration, MGO sized fuel tanks plus additional tanks in the double bottom

The range guaranteed by the stern tanks in this configuration is calculated in the following hypotheses:

- Tanks external volume is the MGO calculated one
- Presence of cofferdams inside the methanol tanks, reducing their available fuel capacity
- Additional fuel tanks in the ship's double bottom.

Considering the previously described cofferdam requirements, and the need of ensuring structural continuity of the ship, the thicknesses of the cavities in the 3 main dimensions are 1.4 m in length, 1.4 m in width, and 0.7 m in height. The cofferdam needs to be placed on all the tank surfaces, but the bottom one, which is in contact with the double bottom (Fig. 4). By applying these reductions to the tank size above identified, it results that only 35% of the MGO tank capacity is available for MeOH storage. In the double bottom two additional fuel tanks can be installed (Fig. 5), presenting a volume and a fuel capacity respectively equal to:

$$V_{dbtanks} = 244 \text{ m3}$$

$$V_{MeOH(db)} = \frac{V_{dbtanks}}{1.05} = 232 \text{ m3}$$

Therefore, the onboard methanol fuel volume is equal to:

$$V_{MeOH(2)} = \frac{V_{MGO} \cdot 35}{100} + V_{MeOH(db)} = 401 \text{ m}^3$$

that leads to a range of:

$$Range_{MeOH(2)} = V_{MeOH(2)} \cdot \rho_{MeOH} \cdot MeOH_{nm/t} = 1489 \text{ nm}$$

The resulting range is lower than the 3800 nm initially established, due to both the greater SFOC of methanol and the fuel capacity loss caused by the refitting procedure. For this reason, "refitting" methanol tanks on existing ships, whose fuel tank volume has been sized solely and exclusively for MGO operation, will lead to a substantial reduction in range values. This reduction may only be partially compensated using the tanks created in the double bottom of the vessel.

C. MeOH, increased volume fuel tanks plus additional tanks in the double bottom

To increase the range in methanol operation, a bigger tank volume is needed. A first solution is to increase the fuel volume while limiting the impact on the onboard spaces, by:

- Setting the tanks fuel capacity equal to the MGO one
- Increasing the volume of the stern tanks only by the cofferdams size (i.e., cofferdam applied externally)
- Installing additional fuel tanks in the double bottom.

With these assumptions (Fig. 6), 54% of the total tanks volume is occupied by cofferdams, leaving 46% of the volume available for bunkering. In this configuration, the onboard methanol capacity and the resulting range will be:

$$V_{MeOH(3)} = V_{MGO} + V_{MeOH(db)} = 715 \text{ m3}$$

$$Range_{MeOH(3)} = V_{MeOH(3)} \cdot \rho_{MeOH} \cdot MeOH_{\text{nm/t}} = 2654 \text{ nm}$$

Such a configuration is still unable to guarantee the required range, thus making it necessary to further increase the methanol fuel capacity, with a consequent increase in the stern tanks volume and an impact on the ships' general plan.

D. MeOH, required fuel tanks capacity and fuel volume to guarantee the required range

To determine the amount of methanol to meet the required range, the same calculation used for the MGO tanks sizing is applied. Thus, the MeOH to be stored onboard is:

$$V_{MeOH} = \frac{Range}{2 \cdot \rho_{MeOH} \cdot MeOH_{nm/t}} = 1024 \text{ m}^3$$

Being the double bottom tanks already occupying all the available space, this means enlarging the stern tanks up to:

$$V_{sterntanksMeOH} = V_{MeOH} - V_{MeOH(db)} = 792 \text{ m}^3$$

Applying the cofferdam thicknesses on the tanks along the 3 main directions, it results that 48% of the volume will be occupied by cofferdams, and 52% of the volume will be available for bunkering. The total volume of the stern tanks and of the single tanks (13.3 m length, 11.9 m width, and 5.1 m height each) is thus:

$$V_{tanksMeOH} = \frac{V_{MeOH}}{1-0.48} 1.05 = 1600 \text{ m}^3$$

$$V_{singletankMeOH} = \frac{V_{tanksMeOH}}{2} = 800 \text{ m}^3$$

It is also necessary to store onboard MGO for the engine pilot, in a dedicated tank. The nautical miles per ton of MGO (used as pilot fuel) in MeOH operation are:

$$MGO_{mn/t(pf)} = Vs \frac{1}{Comb_{hourMGO(pf)}} 1000 = 82 \text{ nm/t}$$

which leads to following required MGO fuel capacity:

$$V_{MGO(pf)} = \frac{Range}{2 \cdot \rho_{MGO} \cdot MGO_{mn/t(pf)}} = 57 \text{ m}^3$$

V. MeOH ONBOARD INTEGRATION EFFECTS

A. Gross tonnage increase

Using MeOH requires bigger fuel tanks to attain the same range in respect to MGO, with a direct impact on the onboard available volume. Additional volumes are also required for accommodating methanol loading and handling facilities, fan rooms, ventilation ducts and case vent ducts, fuel preparation room, and nitrogen room. In the absence of suitable design countermeasures, the total volume occupied by the methanol tank system plus auxiliaries (V) corresponds to a GT value that can be evaluated using the following formula:

$$GT = (0.2 + 0.02 \cdot \log_{10} V) \cdot V$$

The first impact is given by the increased volume of the stern tanks, which can be evaluated as:

$$\Delta V_{tanks} = V_{sterntanksMeOH} - V_{tanksMGO} = 1092 \text{ m}^3$$

with a related 285 GT increase (GT_{tanks}).

The methanol bunkering requires 2 dedicated bunker stations located on the same bridge of the MGO bunker station. The estimated volume of these is 261.4 m^3 (considering 74.9 m^2 occupied surface), which relates to an increase of 65 GT (GT_{bs}). Next to the fuel tank compartment, the methanol plant requires a nitrogen room and a fuel preparation room. The former housed the inerting system and the nitrogen generator, while the latter houses the fuel preparation subsystems. To limit the length of the nitrogen pipes and to avoid installing a dedicated ventilation system, it is preferable to locate the nitrogen room inside the engine room. The fuel preparation room requires 30 m2 of surface, while the nitrogen room requires 20 m2, leading to a total 262.5 m3 of occupied onboard volume. This is related to a 65 GT total increase (GT_{nr+fpr}). Further space onboard is reserved for the ventilation ducts and the crate vent ducts, which must cross all the 11 decks of the expedition ship, starting from deck 2. These will require 413.1 m^3, i.e., an equivalent 104 GT increase (GT_{vd+cvd}). Additional subsystems (like pressure relief valves room and methanol fan room, located in the high decks), require further 364.3 m^3, with an increase in 95 GT (GT_{prv+mf}). Moreover, a vent mast must be installed on the highest ship deck, at least 15 m from other air vents, openings, or ignition sources. In conclusion, also considering the need of doubling all the above depicted volumes and GT to consider the specular subsystems installed in the ship's bow section, the integration of methanol as fuel for the case study ship requires:

$$GT_{MeOH} = 2 \cdot \left(GT_{tanks} + GT_{bs} + GT_{nr+fpr} + GT_{cv+to} + GT_{prv+mf}\right) = 1136 \text{ GT}$$

Thus, the ship will increase its gross tonnage from the starting 27700 up to 28836 GT (4.1 % increase).

B. Economic impact of different design solutions for installing MeOH tanks and related subsystems

The onboard available volumes reduction due to the MeOH integration affects the economics of the ship's operation, depending on the specific solution adopted.

1) Passenger number reduction, at same ship GT

The first design hypothesis envisages keeping the gross tonnage of the expedition ship constant (at 27700 GT). At the end of a complex procedure of space redefinition, the result will be a reduction of the payload, therefore of the number of passengers. From the case study data, it results a 52.3 GT/pax index, which can be used to do a preliminary evaluation of the passengers' number reduction caused by the MeOH subsystems integration. It is relevant to notice that such value is an overestimation of the reduction in the passenger number, which can be exactly determined only with a detailed redesign of the ship's general plan. The resulting reduction in passengers' number is:

$$GT_{MeOH} \,/\, 52.3\ GT/pax \cong 22 \text{ pax } (-\ 4.2\ \%).$$

The passengers' number reduction has an impact on the economic performance of the ship, which can be coarsely estimated by considering the consolidated financial statement 2019 of Hurtigruten Group AS (expedition) [19]. Specifically, PCN (Passenger Cruise Night) is the number of beds occupied for each day of cruise. It is assumed an exchange rate between euro and Norwegian crown equal to 0.097 eur/nok (value at 20 Sept. 2022). Moreover, the number of passengers must be evaluated using the annual occupancy rate, equal to 77%:

$$Pax_{effMGO} = 0.77 \cdot 530 = 408 \text{ pax with MGO}$$

$$Pax_{effMeOH} = 0.77 \cdot 508 = 391 \text{ pax with MeOH}$$

Therefore, the actual gross receipts from tickets will suffer a drop of 4.2% following the switch to methanol, as shown in Table III. The same reduction value will also affect variable costs, which are closely related to the number of passengers onboard the ship, such as commission costs, flights, hotels and food, drinks, excursions. The result is a net revenue reduction of 4.2% (Table III). However, the 4.2% reduction in ship revenues will cause a much greater decrease in the ship's economic result and margin. Indeed, assuming the substantial invariability of the other cruise costs (e.g., depreciation, fuel, ports, wages and salaries, insurance, etc.), the reduction of 22 passengers leads to the Table IV results. Hence, the economic result is the parameter that will be most affected by the drop in passengers, with an 8.1 % decrease, which has a significant effect on the profitability of the vessel.

TABLE III. Gross and net ticket revenue variation with MeOH

	Total from statement euro	Potential per day euro	Potential per day (MeOH) euro	Variation %
Gross ticket revenue	129,831,202	239,108	229,182	- 4.2
Commissions, flights, hotels	33,766,961	62,188	59,607	
Food, beverages, excursions	7,364,700	13,563	13,000	
Net ticket revenue	88,699,541	163,356	156,575	

TABLE IV. Margin variation with MeOH

	Total from statement euro	Potential per day euro	Potential per day (MeOH) euro	Variation %
Net cruise costs	43,398,867	79,927	79,927	
Margin	45,300,674	83,429	76,649	- 8.1

2) Deckhouse installation

As an alternative design choice, the opportunity of increasing the ship's size can be evaluated. This is achievable by creating a deckhouse capable of recovering the "lost payload". Typically, such a design choice leads to the construction of a deckhouse with size (volume and weight) close to the additional GT caused by the methanol integration. Obviously, this can be done assuming, as a first approximation, that the ship has sufficient margin of stability and does not require a recalibration of the hydrostatic and hydrodynamic characteristics after adding the deckhouse volume and weight. Assuming, from the average market values, a parametric cost of expedition ships near to 12,000 $€/GT$, it can be assumed that the addition of the deckhouse leads to an increase in ship cost of the order of:

$$\Delta Cost_{deckhouse} = 12{,}000 \cdot GT_{MeOH} = 13{,}600{,}000\ €$$

Comparing this cost with the annual margin reduction values due the reduction of passengers obtained in the previous section (i.e., 6780 euro per day), it is possible to evaluate the payback period (PBP) of this solution:

$$PBP = \Delta Cost_{deckhouse}/(6780 \cdot 365) = 5.5 \text{ years}$$

It follows that the increase in the volume of the ship, such as to compensate for the additional tonnage requirement caused using an alternative fuel, is an economically viable choice if allowed by the dimensional stability constraints of the specific ship design.

VI. Conclusion

In this paper the use of methanol for energy production in an all-electric expedition cruise ship has been investigated, as a feasible near-term solution for a more sustainable maritime transport. The paper evaluated the effect of the onboard integration of a methanol-based power plant, considering both technical and economic aspects. Being the methanol requiring an increased fuel volume in respect to conventional fuel (MGO), additional volume must be found in the ship, to allow the same operational range. However, this means reducing the ship's payload (i.e., the number of passengers) or increasing its gross tonnage to compensate. The former leads to a direct revenue loss for the owner, which can be considered as a "cost" for ensuring a sustainable operation of the ship. Conversely, the latter (an increase in the volume of the ship such as to compensate for the additional tonnage requirement due to the methanol integration) is an economically viable choice, presenting a particularly short payback time (estimated 5.5 years). Still, compatibility with the stability constraints of the specific ship design must be checked.

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