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ALTERNATIVE PROPULSION SYSTEMS AND LOW/ZERO CARBON FUELS FOR DIFFERENT MARINE VESSELS

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Abstract. In 2022, shipping was responsible for around 706 million tonnes of carbon dioxide emissions, up 5% from 2020 and back to 2017-2018 levels. To accelerate the energy transition and reduce emissions in this sector, the International Maritime Organization (IMO) has set ambitious goals requiring all stakeholders' radical actions. Several solutions have been proposed such as cruise speed reduction, on-board installation of a Carbon Capture and Storage system, use of low/zero carbon fuels in conventional internal combustion engines, and introduction or replacement of the main and auxiliary engines with novel technologies. Thanks to their high energy conversion efficiency, and reduced environmental impact, the interest in fuel cell-based systems for shipping propulsion has been rising in the last few years. In this work, the replacement of fossil fuel-based marine engines with fuel cell technology is analysed from technical and environmental points of view. A preliminary technical assessment, aiming at defining different powertrain configurations, is performed by starting from the characterization of the selected ships, in terms of installed power, navigation routes, and load profiles. The feasibility of the proposed solutions is evaluated by considering the fuel consumption and the emissions avoided with respect to the conventional solutions.

1. Introduction

In 2022, the maritime sector has been responsible for about 706 million tons of carbon dioxide ($MtCO_2$) emitted, again achieving the 2017-2018 levels [1]. The most recent data from the International Maritime Organization (IMO) shows that, if governments fail to intervene, CO_2 emissions from this sector could grow between 50% and 250% by 2050 [2]. In 2023, IMO adopted the "IMO Strategy on Reduction of GHG Emissions from Ships", envisaging a reduction in the carbon intensity of international shipping by at least 40% by 2030. Moreover, the interest in decarbonizing is also due to the extension of the EU's Emissions Trading System (EU ETS) to the shipping sector. Since January 2024 the shipping companies must purchase and surrender (use) EU ETS emission allowances for each tonne of CO_2 emitted (or CO_2 equivalent) from all large ships (of 5,000 gross tonnage and above) entering EU ports, regardless of the flag they fly [3]. The critical issues related to the decarbonisation of the maritime sector, due to the specificity of the international transport system, the different stakeholders and the wide variety of ship types and

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sizes, imply that several strategies and actions need to be adopted. The introduction of green hydrogen and hydrogen carriers such as ammonia and methanol (i.e. low or zero-carbon fuels and biofuels) [4] and low-emissions propulsion technologies (i.e. fuel cells) is a valid option for long-term carbon dioxide emissions reduction. Ammonia and methanol can be produced from renewable electrolytic hydrogen. Ammonia is a chemical compound of hydrogen and nitrogen without carbon content but not entirely emission-free [5]. It can be stored in liquid form, making it significantly easier to store than hydrogen, it is not flammable in air but presents high toxicity. Methanol on one side is not toxic and easier to store in a liquid state than hydrogen, but even if it is used as a fuel in fuel cells it is not carbon neutral. It is interesting to note that hydrogen as well as methanol and ammonia can be used to power both internal combustion engines (ICEs) and fuel cells (FCs) providing a sustainable and efficient alternative to current fossil fuels. However, the using of these fuels in the fuel cells is more attractive for the reduced environmental impact so the interest in fuel cell-based systems for shipping propulsion has been rising in the last few years [6]. Nowadays, Proton Exchange Membranes Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) are considered the most suitable technologies in the maritime sector. For years, many international projects have been evaluating the best FC-based system design and integration onboard ships. The fuel cells operate modularly like batteries, allowing for easy integration into maritime applications. FC technology has found application in many research projects including the most recent TecBIA, HI-SEA, ShippingLab, FLAGSHIPS, and Maranda. TecBIA, a national Italian research project, designed a PEMFC system based on 2 × 71 kW modules fuelled by hydrogen stored in 48 Metal Hydride tanks onboard the ship. The HI-SEA project, funded by Fincantieri and the University of Genoa, aimed to realize a PEMFC system, powered by compressed H_2, stored at 200 bar to cover 240 kW. In the ShippingLab project, based in Denmark, an LT-PEMFC system hybrid with batteries has been realized for a dredger in Hvide Sande Port. The compressed hydrogen, useful to fuel cells, has been produced via a water electrolysis process powered by 3 MW wind turbines. The FLAGSHIPS project developed a 2 × 200 kW PEMFC system with 350 kg hydrogen stored at a 300 bar onboard the first ship operated on the Seine River in Paris, France. Finally, the goal of the Maranda project has been to develop and test a marine power plant based on PEMFC (2 × 82.5 kW modules) fuelled by hydrogen at 350 bars in a hybrid system for a ship.
In conclusion, it is evident that PEMFC is the most used technology compared to SOFC due to its higher maturity. Nevertheless, many studies are focused on the use of SOFC technology thanks to its fuel flexibility (directly or in indirect mode) [7].
In this context, the objective of this study is to perform a preliminary technical analysis, carried out by applying a properly developed code, to assess the performances and emissions of fuel cell-based systems, fed with hydrogen and hydrogen carriers, installed on board medium and large size ships to replace conventional fossil fuel-based marine engines.

2. Method and Materials

The methodology proposed in this study consists of four steps (see Figure 1):

- Step 1: The vessels are selected, and the operating data are collected and evaluated;
- Step 2: The characterization of the fuel cell-based system configurations is defined according to the power demand on board the ship;
- Step 3: A numerical algorithm is developed and applied to the conventional and proposed powertrain configurations;
- Step 4: The performance assessment is carried out in terms of fuel consumption, efficiency, and emissions.

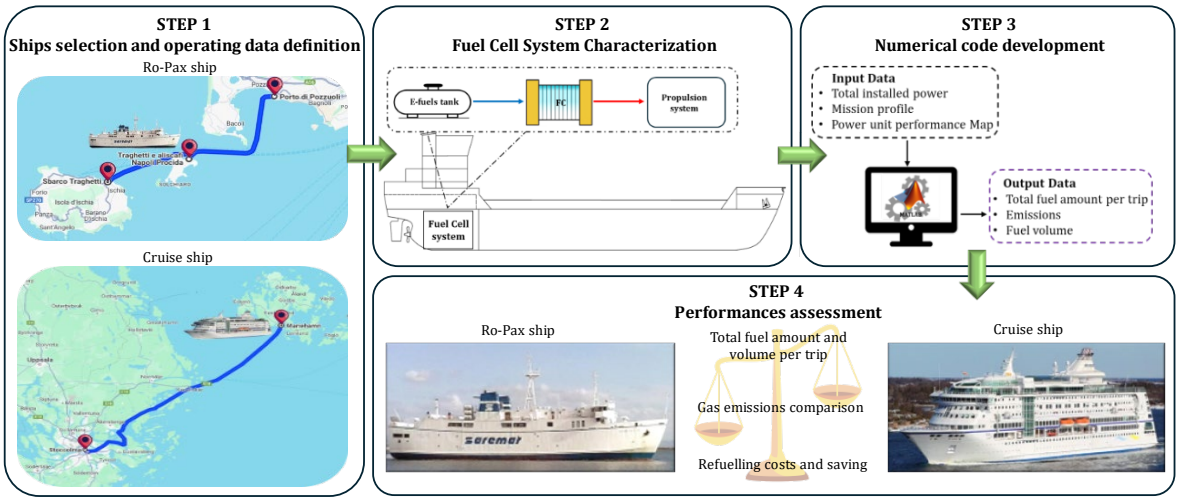


Figure 1. Detailed flow chart of the methodological approach

In particular, in Step 1, starting from a statistical literature review, vessels are selected in the category of passenger ships, specifically ferries and cruise ships. In Figure 2, a database of 115 Ro-pax ferries and 128 cruise ships, in terms of gross tonnage (GT) and installed power, is illustrated. The Ro-pax (built between 1960 and 2023) have a gross tonnage up to 50,000 GT and installed powers from 1.2 MW to 67 MW; the cruise ships (built between 1972 and 2024) have a gross tonnage and an installed power ranging from 12,000 to 250,000, and from 11 MW to 120 MW, respectively. It can be noted that for Ro-pax ships with GT lower than 20,000, the installed power increases quite linearly with the size of the ship and reaches a max value of 20 MW. Above these limits, the installed power has great variations, that could depend on the designed service speed and operational profile. Similarly, for cruise ships the installed power varies almost linearly with the ship size.
The ships, selected for the feasibility analysis, are highlighted in Figure 2 and in Table 1 their main characteristics are summarized.

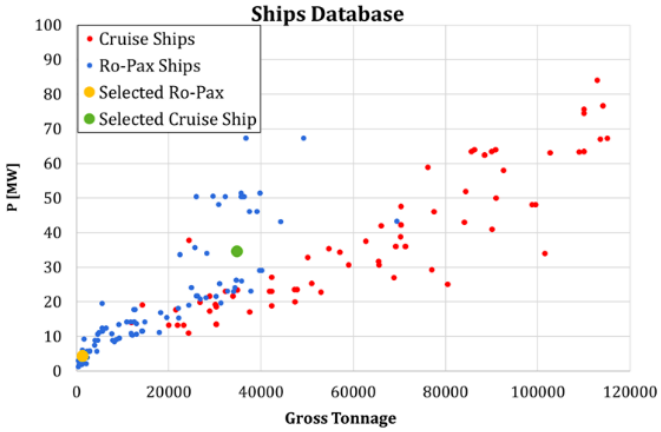
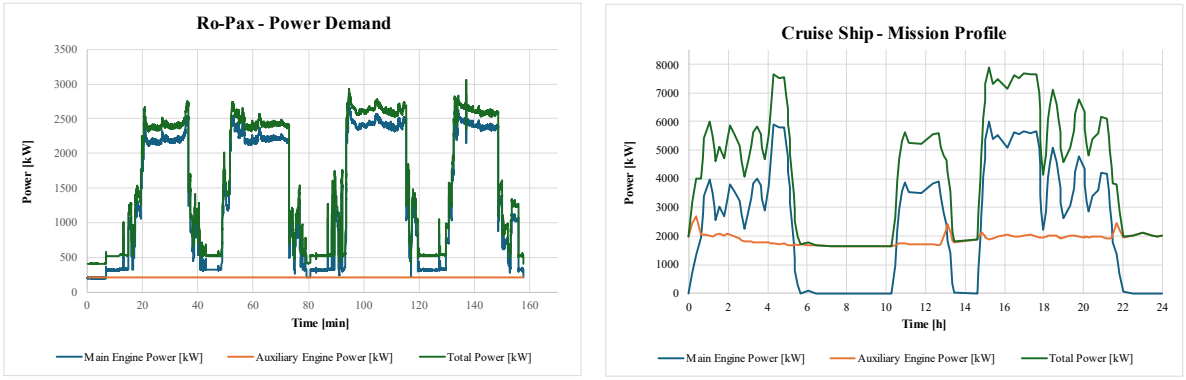


Figure 2. Statistical Literature Review and Ship Selection

Table 1. Main characteristics of selected ships

Ship type	Ro-Pax Ship	Cruise Ship
GT	1,398	34,924
Total installed Power	4.24 MW	34.44 MW
Main Engine	2 x Caterpillar (1.853 MW each)	4 × Wärtsilä 6L46 (5.85 MW each)
Auxiliary Engine	2 x Scania (0.269 MW each)	4 x Wärtsilä 6L32 (2.760 MW each)

The Ro-pax ship connects the islands of the Gulf of Naples to the mainland, considering a round-trip Ischia-Pozzuoli with a stop in Procida. Its mission profile is presented in Figure 3 (a) [8]. Each round trip takes about 2h and 40 minutes. The ship is 70 m long and has 2 main engines (1.853 MW Caterpillar at 1000 rpm), with a total power of 3.7 MW. The average power demand during the trip is about 2 MW. According to the IMO guidelines in MEPC 78/17/Add.1 (2022) and the assumptions in ref. [9], the installed power of the auxiliary engines is 0.538 MW (2 Scania gensets of 0.269 MW each). Based on the mission profile and the assumptions related to the auxiliary power demand, the ship is thought to operate with 2 main engines and 1 auxiliary engine at a constant load factor of 75%.
The cruise ship operates in the Baltic Sea between Stockholm (Sweden) and Mariehamn (the Aland islands). The typical daily mission profile is illustrated in Figure 3 (b) [10]. This ship is characterized by a length of 177 m, 4 main engines of 5.85 MW each, and 4 auxiliary engines of 2.76 MW each. The total energy demand is satisfied by the main engine for the propulsion, and by the auxiliary engine for the on-board energy requirements. By analysing the mission profile, it can be observed that the ship uses only 2 of the installed Wärtsilä 6L46 engines and 2 of the auxiliary Wärtsilä 6L32 engines.



(a) (b)

Figure 3. (a) Ro-Pax Mission Profile and (b) Cruise Ship Mission Profile

Thus, according to the sizes of the conventional engines installed on the selected ships, in Step 2, the fuel cell-based system configurations, depicted in Figure 4, are defined. The fuel cell units that can be installed are based on PEMFC and SOFC technologies; in particular, it is assumed that the PEMFC-based power system is fed with pure hydrogen (stored on board as compressed gas), and the SOFC-based power system is fed with methanol or ammonia. In this last case, the fuel is directly sent to the SOFC unit, avoiding an external fuel processing reactor, thanks to its high operating temperature (in the range of 700°C - 900°C) and the Nichel-based catalyst used in the anode.

For the PEMFC-based power system, the anode and cathode off-gases are recovered for heating the fuel and air entering the fuel cell unit; for the SOFC-base power system, the anode and cathode off-gases are sent to the catalytic burner whose exhausts are used for pre-heating the feeding streams (fuel and air). Furthermore, focusing on the fuel cell output voltages, they usually do not meet the voltage requirements on-board. Therefore, the energy management system is equipped with an inverter, to convert the voltage as necessary. The power generated is split between the propulsive and load demands through the switchboard; moreover, it can also be observed that in some particular cases (rapid load factor variations in SOFC configuration) the necessity for a battery storage system is helpful for the energy management strategy [11].

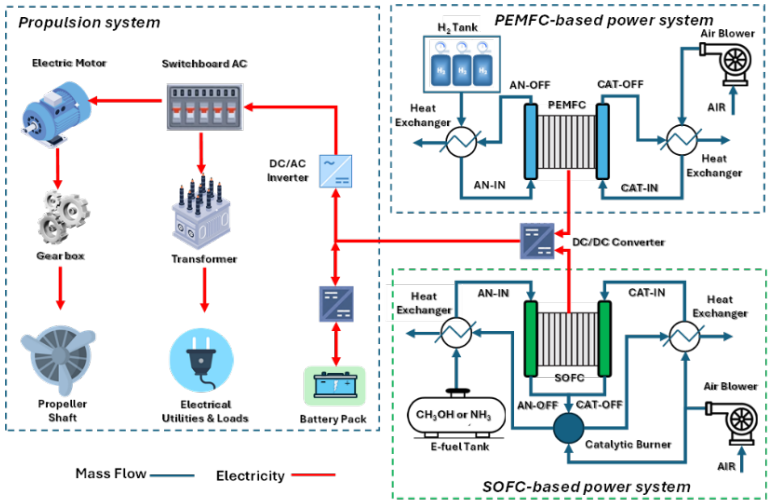


Figure 4. Fuel cell-based propulsion system.

The PEMFC power module consists of two 50 kW stacks by Proton Motor. Details on this module are illustrated in ref. [12]. With referring to the SOFC-based propulsion systems, the methanol-SOFC and ammonia-SOFC units, operated at 800°C and 1 bar, are sized by considering the polarization curves (cell voltage vs current density), derived from experimental data available in ref. [13] and ref. [14], respectively. The SOFC-based system (for both methanol and ammonia) consists of a 100 kW module. Table 2 summarises the main data of the selected fuel cell modules.

Table 2. Operating conditions and performances of the fuel cell modules

	Unit	H_2-PEMFC	Methanol-SOFC	Ammonia-SOFC
Module rated power	kW	100	100	100
Module efficiency at rated power	%	48	39	48

The selected fuel cell modules can operate between 20% and 100% of the rated power. Figure 5 shows the fuel cell module efficiency (referred to the low heating value of fuels), for the Hydrogen-PEMFC, Methanol-SOFC, and Ammonia-SOFC in their operating ranges. The net efficiency, taking into account the available data of the PEMFC module [15] and of the SOFC ones, is calculated as follows:

$$\eta_{net} = \frac{V \cdot I_{module} - P_{aux}}{\dot{m}_f \cdot LHV_f} \quad (1)$$

where V (V) and I_{module} (A) are the values of the voltage and current of the fuel cell module in its operating range, P_{aux} (W) is the power absorbed by the auxiliaries, $\dot{m}_f$ (kg/s) is the fuel mass flow rate and LHV_f is its lower heating value (J/kg).

It is worth noticing that for the Hydrogen-PEMFC module, the maximum efficiency (49%) is achieved at 75% of the rated power; the maximum net efficiencies are equal to 42.7% at 46% of load factor and 54.5% at 46% of load factor for the methanol-SOFC module and ammonia SOFC module, respectively.

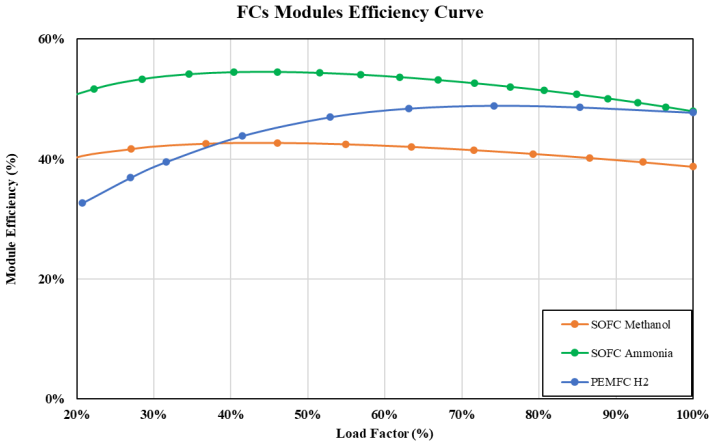


Figure 5. PEMFC and SOFC Modules Net Efficiency Curves

The adopted energy management strategy of the fuel cell-based systems in following the power demand is based on two criteria: 1) the number of modules (N_M) used to satisfy the power demand is calculated as the integer of the ratio between the required power and the module rated power and 2) as consequence, only 1 module operates, if necessary, at partial load (N_M -1 modules work always at full load).

In order to evaluate the performances of the conventional and innovative powertrain systems, in Step 3 a numerical algorithm is developed. In Figure 6, the workflow of the developed algorithm is depicted. Starting from the input data (the total installed power, the mission profile and the performance maps of the ICEs and the FCs power units), the numerical algorithm allows to estimate some performances, environmental and technical indicators such as the total fuel amount (consumed per trip), the emissions, and the fuel volume (related to a trip). The performance maps of the conventional engines are given from the construction manuals and from ref. [16] for the Ro-pax and the cruise ship, respectively.

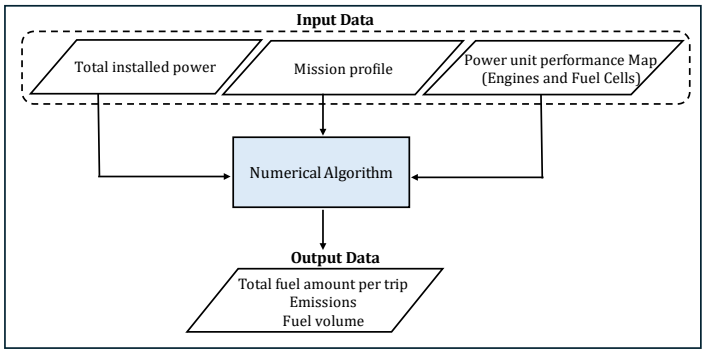
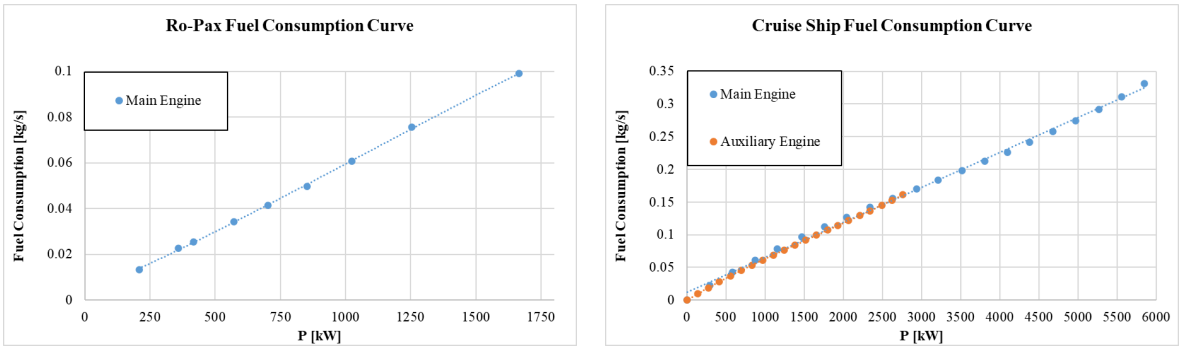


Figure 6. Workflow of the developed Algorithm

In order to estimate the total fuel amount consumed during the trip (according with the mission profile), the fuel consumption curves as function of the produced power should be defined. The relationship between the power and the fuel consumption is modelled as an n^{th} degree polynomial by applying a polynomial regression technique on the pairs (power, fuel consumption) of available dataset.
For the ICE-based power trains, a 3rd degree polynomial has been used:

$$C_i(P) = a \cdot P^3 + b \cdot P^2 + c \cdot P + d \quad (2)$$

where a, b, c and d are the coefficients of the fitting curve. The coefficients of determination, R-squared, for the fuel consumption curves are equal to 0.996 and 0.999 for the Ro-Pax and the Cruise Ship, respectively. Figure 7 show the fuel consumption curves for the main engine of the Ro-pax ship (figure 7a; the fuel consumption curve of the auxiliary engine is not calculated because it always works at 75% of its rated power), and those of the Cruise ship (Figure 7b).



(a) (b)

Figure 7. (a) Ro-Pax and (b) Cruise Ship Fuel Consumption Curves

For the FC-based power trains (Hydrogen-based PEMFC, methanol-based SOFC, ammonia-based SOFC), high R-squared values (0.999) are obtained by using a sixth-grade polynomial. Thus, the fitting curve is:

$$C_i(P) = a \cdot P^6 + b \cdot P^5 + c \cdot P^4 + d \cdot P^3 + e \cdot P^2 + f \cdot P + g \quad (3)$$

where a, b, c, d, e, f and g are the coefficients of the polynomial regressions calculated for each fuel cell.
In figure 8 the Fuel Consumption Curves are depicted. It can be noticed that, in order to compare the trends of the fuel consumptions of system configurations, characterized by different power train sizes, in the x-axis the load factor is used instead of the power.

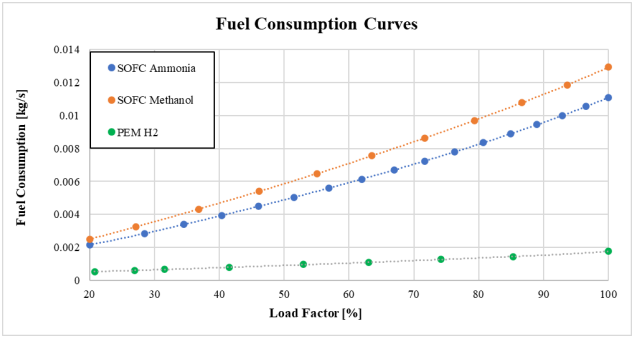


Figure 8. Fuel Consumption Curves for both the PEMFC and SOFC modules

The total fuel amount F_{TOT} (kg) consumed during each trip (for all powertrain configurations), is calculated as the sum of the fuel consumptions (related to each power demand) during each time step Δt_i of the trip (t_i represents the initial value of the mission time interval, while t_f is the final one):

$$F_{TOT} = \sum_{t_i}^{t_f} C_i(P) \cdot \Delta t_i \tag{4}$$

The average trip efficiency $\overline{\eta}$ is calculated as in eq. 5:

$$\overline{\eta} = \frac{\sum_{t_i}^{t_f} P_i(t) \cdot \Delta t_i}{F_{TOT} \cdot LHV} \tag{5}$$

where $\sum_{t_i}^{t_f} P_i(t) \cdot \Delta t_i$ is the total energy demand, and the $F_{TOT} \cdot LHV$ is the total supplied energy (LHV is the lower heating value of the fuel). By taking into account the total fuel amount per trip, the emissions (kg), in terms of CO_2, NO_x, SO_x, and PM are calculated, by using eqs. 6-9:

$$CO_2 = F_{TOT} \cdot f_{CO_2} \tag{6}$$
$$NO_x = F_{TOT} \cdot f_{NO_x} \tag{7}$$
$$SO_x = F_{TOT} \cdot f_{SO_x} \tag{8}$$
$$PM = F_{TOT} \cdot f_{PM} \tag{9}$$

where $f_{CO_2}, f_{NO_x}, f_{SO_x}, f_{PM}$ are the specific emission factor.
In Table 3, the characteristics and emission factors of the Marine Diesel Oil (MDO) and the Heavy Fuel Oil (HFO) are summarized [17] [18]. MDO is the selected fuel for the Ro-pax ship, while HFO is used in the cruise ship.

Table 3. MDO and HFO Characteristics [17], [18]

Type of fuel	Lower calorific value [kJ/kg]	Density [kg/m³]	State	Emission Factors [kg/kg]
MDO	42,700	900	Liquid (At ambient T and p)	$f_{CO_2} = 3.206$ $f_{NO_x} = 0.05488$ $f_{SO_x} = 0.00215$ $f_{PM} = 0.00095$
HFO	40,200	991		$f_{CO_2} = 3.114$ $f_{NO_x} = 0.07726$ $f_{SO_x} = 0.04773$ $f_{PM} = 0.00725$

The fuel specifications, for hydrogen, ammonia, and methanol are listed in table 4 [17], [19]. It is possible to note that hydrogen and ammonia do not produce any emissions [20] while for the methanol the CO_2 emissions are estimated by applying the eq. 6.

Table 4. Specifications of Hydrogen, Ammonia, and Methanol [17], [19]

Type of fuel	Lower calorific value [MJ/kg]	Density [kg/m³]	State	Emission Factors [kg/kg]
H_2	120	23.3	compressed at ambient T and 350 bar	-
		39.3	compressed at ambient T and 700 bar	
Ammonia	18.8	602	liquid at ambient T and 10 bar	-
Methanol	20	792	liquid at ambient T and p	$f_{CO_2} = 1.375$

Considering the ratio between the total fuel amount during navigation and the fuel density (ρ_{fuel}), the fuel volume (V_{fuel}), is calculated as:

$$V_{fuel} = \frac{F_{TOT}}{\rho_{fuel}} \tag{10}$$

3. Results and discussion

This study aims to evaluate the feasibility of the fuel cell technology, fed with low or zero-carbon fuel, in supporting maritime decarbonization. Therefore, the analysis is focused on the evaluation of the environmental impact of these alternative configurations. Therefore, results of the proposed methodology, in terms of total fuel amount, average trip efficiency, and emissions, are summarized in Table 5 and Table 6 for the ICE configurations and FC configurations, respectively.

Table 5. Performance and environmental results for the selected ships in the ICE configurations

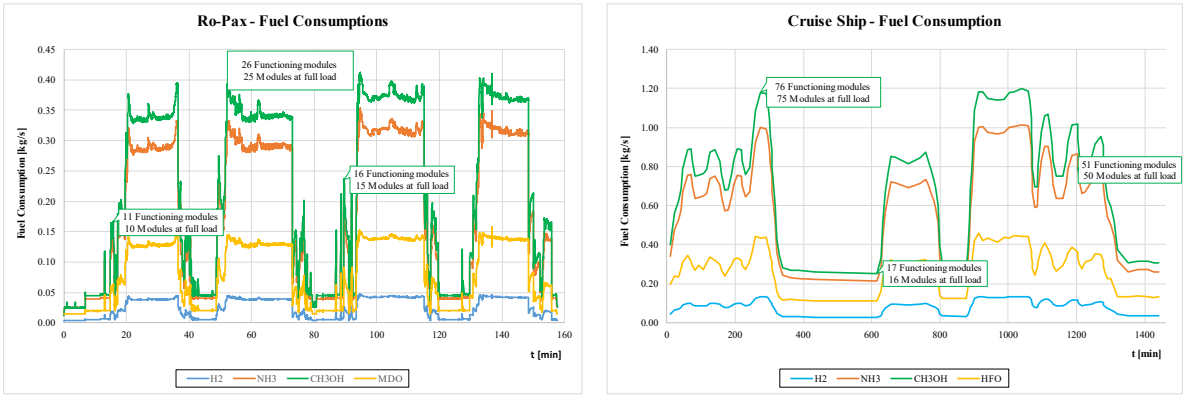
ICE Powered Ships			
Ship Type		**Ro-Pax**	**Cruise Ship**
Fuel type		MDO	HFO
Total installed power [kW]		4,238	34,400
Total Fuel amount [kg]		784	22,087
Average Trip Efficiency (%)	Main Engine	35.6	28.7
	Auxiliary Engine	43.5	41.8
CO_2 emissions [kg]		2,513	68,778
NO_x emissions [kg]		43.0	1,706
SO_x emissions [kg]		1.70	1,054
PM emissions [kg]		0.74	160

It can be noted that the average trip efficiency of the Cruise ship is less than 30%, even if the efficiency at rated condition is close to 45%; this is due to the mission profile for which the engines work often at partial load. On the contrary, with referring to the Ro-pax ship, the average trip efficiency is equal to 35.6% because the main engines operate more time at rated power.
By analysing the results concerning the FC-based power trains, it is worth noting that the average trip efficiencies are always higher than 38%; in particular, the best performances are obtained for the H2-based PEMFC configurations (46.8 % and 47.4%). Moreover, it can be highlighted that the average trip efficiencies are high also for the Cruise ship, thanks to the high efficiencies of fuel cells at partial loads. In terms of emissions, the methanol SOFC system avoid about the 5% of CO_2 in both ships.

Table 6. Performance and environmental results for the selected ships in the fuel cell configurations

FC Powered Ships						
Ship Type	**Ro-Pax**			**Cruise Ship**		
Fuel type	H_2	CH_3OH	NH_3	H_2	CH_3OH	NH_3
Total installed power [kW]	4,300	4,307	4,302	34,400	35,059	35,018
Total Fuel amount [kg]	237	1,737	1,491	6,532	47,997	41,217
Average Trip Efficiency [%]	46.8	38.8	48.1	47.4	38.8	48
CO_2 emissions [kg]	-	2,388	-	-	65,996	-

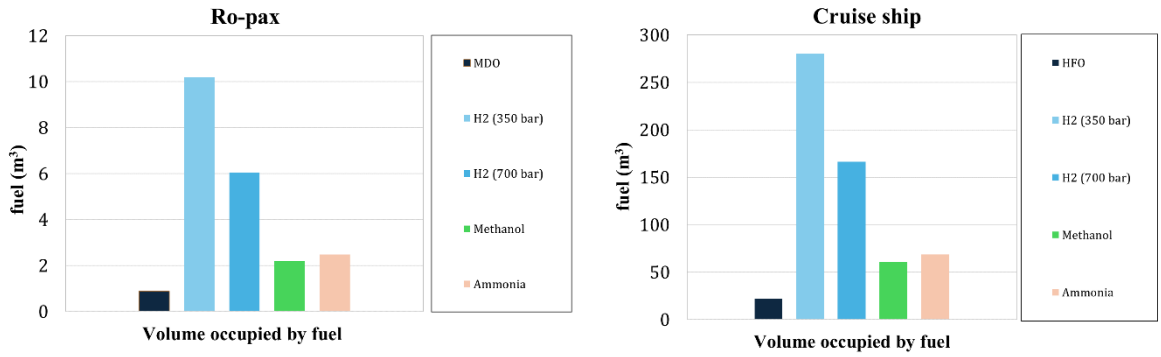
Figure 9 shows the fuel consumption trends estimated with respect to the mission profiles of the ships and for all the powertrains analysed.



(a) (b)

Figure 9. Fuel consumption for the Ro-pax (a) and the cruise ship (b) in the different powertrain configurations.

From a technical point of view, the required fuel volumes per trip are depicted in Figure 10. It is possible to observe that the lesser volumes are occupied by the MDO and HFO since fossil fuels have the highest volumetric energy density; with referring to the hydrogen and hydrogen carriers, it is worth noticing that 700 bar compressed hydrogen requires 67% and 58% more volume than methanol and ammonia, respectively.



(a) (b)

Figure 10. Volumes occupied by fuels for the Ro-pax (a) and the cruise ship (b)

Finally, from an economic point of view, the analysis is focused on the evaluation of the fuel costs and the savings due to the avoided CO_2 with respect to the EU ETS system that from 2024 introduces a carbon tax for CO_2 emitted by vessels with gross tonnages higher than 5,000. Table 7 summarizes the costs of the fuel per trip for all the studied configurations.

Table 7. Trip Expenditure for ship refuelling

Fuel	Fuel Cost [€/t]	Ro-Pax	Cruise Ship	
		Refuelling costs [€/trip]	Refuelling costs [€/trip]	Saving [€/trip]
MDO	695 [21]	545	-	-
HFO	386 [21]	-	8,525	-
H_2	6,860 [22]	1,627	44,810	4,585
NH_3	450 [23]	671	18,548	4,585
CH_3OH	545 [24]	947	26,158	185

Among the proposed alternative fuels, the ammonia solution is the most promising one, thanks to the lower refuelling cost compared to the costs of hydrogen and methanol: it is equal to 671€/trip and 18,548 €/trip for the Ro-pax and the Cruise ship, respectively.
Finally, considering the cruise ship (the GT is higher than 5,000), it is possible to estimate the savings due to the CO_2 avoided; by assuming a carbon price of 66.67 €/tCO_2 [25], the saving for the hydrogen and ammonia solutions is equal to 4,585 €/trip, while for the methanol one is only equal to 185 €/trip. Thus, it can be affirmed that, according to the current costs of the HFO, the saving does not compensate the higher refuelling costs of the proposed alternative fuels. However, this gap could be reduced in the medium scenario if the costs of the fossil fuels will increase (as expected) and the carbon price will rise too.

4. Conclusions

In order to promote the decarbonization of the maritime sector, the replacement of traditional fossil fuel propulsive systems with innovative ones powered by cleaner fuels (such as hydrogen and hydrogen carriers) is essential. In this context, the objective of this study was to perform a preliminary technical analysis, carried out by applying a properly developed code, to assess the performances and emissions of fuel cell power train-based propulsion systems installed on board medium and large size ships. The developed numerical code is a useful and flexible tool, easily applicable to analyse the feasibility of replacing conventional diesel engines with novel technologies, considering different vessel types, different mission profiles, and different fuel supplies.

Different fuel cell systems fed with hydrogen, ammonia, and methanol have been defined and proposed to replace the existing conventional diesel engines. The analysis, based on the estimation of energy and environmental performance indicators such as the fuel consumption and the emissions as well as technical and economic indicators such as the fuel volume (related to the consumption for 1 trip) and the trip fuel cost, has highlighted that:

- The trip fuel consumptions are the greatest for the SOFC fed with methanol (around 2-2.5 times the fossil fuel ones), and the lowest for the hydrogen configurations (about 3-4 times the fossil fuel ones).
- the average trip efficiencies are always higher than 38%; in particular, the best performances are obtained for the H_2-based PEMFC configurations.
- For the methanol-based configurations, according to the ships' mission profiles, the CO_2 emissions are reduced by about 5% compared to fossil fuel configurations.
- With referring to the hydrogen and hydrogen carriers, 700 bar compressed hydrogen requires 67% and 58% more volume than methanol and ammonia, respectively.
- The fuel volume required for the hydrogen solution at 700 bar is 6 times greater than the fossil fuel one. Methanol and ammonia occupy comparable volumes of around 2 to 2.5 times the fossil fuel ones.
- Among the proposed alternative fuels, the ammonia solution is the most promising one, thanks to the lower refuelling cost compared to the costs of hydrogen and methanol: it is equal to 671€/trip and 18,548 €/trip for the Ro-pax and the Cruise ship, respectively.

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