Feasibility analysis of an innovative naval on-board power-train system with hydrogen- based PEMFC technology

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Abstract. The maritime transportation sector is one of the main contributors to global emissions of greenhouse gases (GHGs), volatile organic compounds (VOCs), particulate matter (PM), hazardous air pollutants, NOX and SOX. In particular, it is estimated that the CO2 emissions in this sector are about 1 Gt every year.
The International Maritime Organization (IMO) adopted stringent emission limits in its Tier III regulation, most notably on NOX and SOX emissions and pledged to reach a reduction in greenhouse gas (GHG) emissions from international shipments by at least 50% by the year 2050, compared to 2008 emissions. For emission control areas (ECAs) these requirements are particularly strict and will be difficult to meet with traditional diesel engines and bunker fuels. Therefore, ship owners need to adopt solutions to bring emissions within these and other future limits by means of environmentally friendly fuels and high efficiency propulsion technologies. In this context, hydrogen and fuel cells play a crucial role, thanks to their low criteria pollutant and GHG emission.
This paper presents a techno-economic feasibility study for replacing the conventional diesel engine powertrain, usually employed in Ro-Pax ferries, with an innovative system based on polymer electrolyte membrane fuel cell (PEMFC) technology. The ferry is actually powered by four diesel engines, which deliver a total output of 37.8 MW. The ferry also has two auxiliary engines which give an output of 4.0 MW and also two 2.0 MW bow thrusters for its manoeuvring. The energy analysis has allowed to define the hydrogen consumption for each cruise, as well as the optimal size of the innovative propulsion system. In particular, The PEMFC powertrain is sized at the same maximum power output as the main diesel engine and, thanks to the modular architecture of fuel cells and their flexible performance at partial load, the auxiliary engines are not contemplated. Moreover, in order to identify the best solution in terms of ship's weight and space requirements, two hydrogen storage solutions based on compressed hydrogen technology and

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liquefied hydrogen technology, have been analyzed and compared. The economic assessment has been carried out by estimating the CAPEX and OPEX for each H2 storage technology by considering short-term, mid-term and long-term scenarios (from 2020 to 2050).

1 Introduction

Although maritime transport is typically viewed as an environmentally friendly transport mode, it is one of the largest greenhouse gas (GHG) emitting sectors of the global economy, responsible for around 1 Gt of CO2eq every year [1,2]. As matter of fact, the global emissions from the maritime sector is responsible for 10–15% of anthropogenic sulfur (SOx) and nitrogen oxide (NOx) emissions, as well as approximately 3% of the carbon dioxide (CO2) emissions [3]. The International Maritime Organization (IMO) has set ambitious goals to reduce, and eventually eliminate, greenhouse gas (GHG) emissions from international shipping [4]. The decarbonization of maritime sector will require changes in on-board energy storage and in energy conversion systems. Therefore, a range of technical and operational measures based on the introduction of carbon-free fuels, both on ships and in ports, can contribute to reducing emissions [5-8].

New renewable fuels and new energy conversion technologies, like the fuel cells can pave the way for the decarbonization in the maritime sector [9-12].

In Europe the interest in the maritime sector decarbonization is high. FCs and H2 have been demonstrated in e.g. submarines, small in-land and near coastal vessels, proving the viability of the technology. In addition, demonstration projects on small ferries are under construction. Larger vessels are generally at the design study stage and a range of fuels and fuel cell types are currently being tested.

Demonstration projects (i.e. MARANDA, FLAGSHIPS, ShipFC, H2PORTS) are underway to highlight the viability of H2 to power ships using FCs and modified combustion engines and several studies are available in the current technical literature.

Dall'Armi et al., propose a process simulation study to analyze the peak shaving services that a hybrid PEMFC/Li-ion battery propulsion system can provide to a small RoRo vessel and a passenger ferry. They also evaluated different compressed hydrogen storage solutions depending on the cruise duration [13].

Rivarolo et al., present the development of a PEMFC-based system for a 200 people ferry using a time-dependent thermo-economic analysis to determine the optimal operating conditions for the fuel cell that minimize operating costs [14].

Choi et al [15] developed a PEMFC-battery hybrid propulsion system for a tourist boat, and demonstrated the reliable operation in the coastal waters of South Korea.

Jeong et al [16] analyzed a hybrid propulsion system consisting of a LNG-fueled combustion engine and a hydrogen-fueled PEMFC.

Based on this background, it is possible to affirm that there is a great interest in developing hydrogen-based powertrain on-board ships, even if several issues, from technical and economic points of view, have to be furtherly and deeply analyzed.

In this work a techno-economic feasibility study for replacing the conventional diesel engine powertrain usually employed in ro-pax ferries (about 38 MW) with an innovative power system based on polymer electrolyte membrane fuel cell (PEMFC) technology, is presented. The hydrogen consumption for each cruise, as well as the optimal size of the innovative propulsion system is performed by means of the energy balance analysis. In particular, the PEMFC powertrain is sized at the same maximum power output of the main diesel engine and, thanks to the modular architecture of fuel cells and their flexible performance at partial load, the auxiliary engines are not contemplated. Moreover, in order to identify the best

solution in terms of ship's weight and space requirements, two hydrogen storage solutions based on compressed hydrogen technology and liquefied hydrogen technology, are analyzed and compared.
The economic assessment is carried out by estimating the CAPEX and OPEX for each H_2 storage technology by considering short-term, mid-term and long-term scenarios (from 2020 to 2050).

2 Ro-Pax Description and Operation

The case study refers to a Ro-Pax ferry, a large ship widely used for reaching the islands (Fig. 1). It is designed as two ships in one, both a passenger/vehicles ferry and a cargo transporter, with three large freight decks, loaded by a single stern door and a car deck, loaded via a side ramp.
The selected Ro-Pax is able to accommodate 1,360 passengers and 1,380 vehicles. It has a length overall (LOA) of 215.44 m, a beam of 31.88 m, a draught of 6.04 m and shows a carrying capacity of 59,925 Gross Tonnage. The Ro-Pax operates short-distance voyages, with a cruise duration of 12 hours, an average speed of 17.2 knots, travelling for 211.0 nm [17].

Fig. 1. Typical layout of Ro-Pax ferry [18].

The ferry is powered by four Wärtsilä 9L46C main diesel engines (MEs), which have a total power output of 37.8 MW, and two Wärtsilä 9L32 auxiliary engines (AEs), which give an output of 4 MW. It is equipped with two bow thrusters, two stabilizers and twin rudders [19]. In particular, the main engine is used for propulsion during navigation, where the load demand has an almost constant trend, while the auxiliary engine is used during docking and in-port operation and to meet the electricity needs on board during the cruise. Table 1 provides the detailed specifications of the Ro-Pax ferry.

Table 1. General characteristics of Ro-Pax ferry [17].

IMO	9208629
Flag	Bahamas [BS]
Gross Tonnage(tons)	59,925.0
Length Overall (m)	215.44
Engine Room Volume (m^3)	1,660.0
Fuel Room Volume (m^3)	1,000.0
Fuel Mass Capacity (ton)	1,025.0
MEs Mass Capacity (ton)	116.5 x 4
AEs Mass Capacity (ton)	54.2 x 2

The load profile of the Ro-Pax ferry, that considers both the power needed for the main engine (ME) and the auxiliary engines (AEs), is depicted in Fig.2.

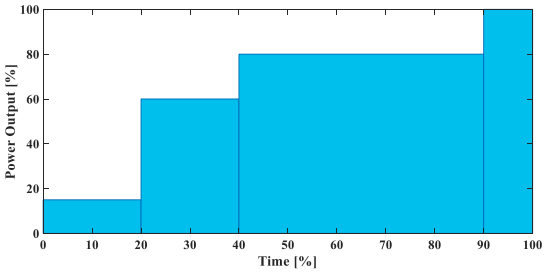

Fig. 2. Ro-Pax ferry load profile

3 Power-Train System Based On PEMFC Technology

The feasibility analysis for replacing the diesel-based power-train system with a PEMFC-based one has been assessed taking into account the size of components, the weight and space requirements.

For the proposed power-train system, a 100 kW PEMFC module (depicted in Fig. 3), developed by Ballard [20,21], has been selected. Table 2 summarized the PEMFC module's characteristics.

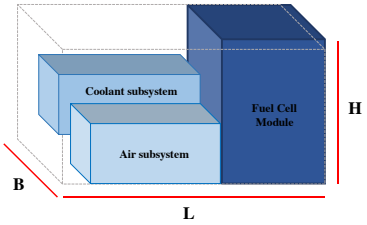

Fig.3. 100 kW PEMFC module design [20,21]

The PEMFC has been sized as the same nominal power capacity of the reference main diesel engine (i.e., 37.8 MW). Consequently, a PEMFC power-train system made up of 378x100 kW units has been employed. Thanks to the modular configuration of this power unit (378 modules x 100 kW each), the auxiliary engines have been not contemplated, considering that the power requirements during docking and in-port operations can be satisfied thought the PEMFC power unit, with a great advantage on the size-reduction of the on-board power-train system.

Table 2. 100kW PEMFC module characteristics [20,21]

	Fuel Cell Module	Coolant Subsystem	Air Subsystem	PEMFC (added margin 5 mm each side)
L (m)	0.869	0.737	0.676	1.616
B (m)	1.200	0.529	0.418	1.210
H (m)	0.506	0.379	0.352	0.516
Mass (kg)	285.0	44.0	61.0	390
Power density (kW/ton)	-	-	-	256
Volumetric Power density(kW/m^3)	-	-	-	99

For storing hydrogen on-board, two alternative hydrogen storage solutions have been taken into account:1) cryogenic tanks; 2) high pressure tanks. In particular, gaseous hydrogen has been considered both at 350 bar and 700 bar, at ambient temperature.
Table 3 summarizes the main characteristics of the selected storage technologies, whereas in Fig. 4 shows the schematic configuration of the PEMFC-based power-train system.

Table 3. Main characteristics of the considered storage systems

	350 bar Compressed H_2	700 bar Compressed H_2	Liquefied H_2
Ref.	[22]	[23]	[24]
External Diameter (mm)	408.4	460.0	3,000
Length (mm)	2,100.0	1,359.6	18,000
Empty Weight (kg)	81.0	87.5	29,650
Internal Volume (m^3)	0.20	0.13	76

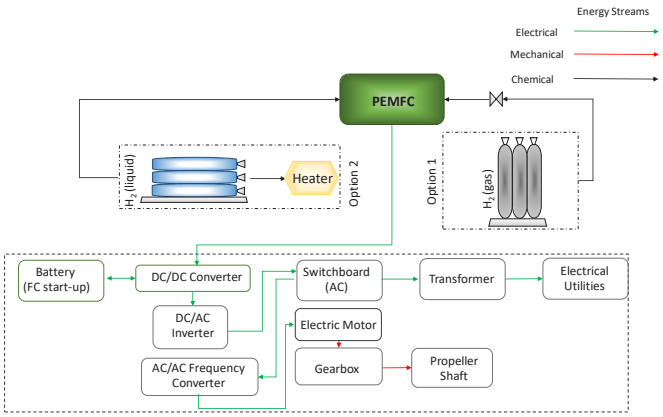

Fig. 4: Configuration of the on-board power-train system with hydrogen-based PEMFC

As shown in Fig. 4, a DC/DC converter is applied after the PEMFC for regulating the voltage provided by the PEMFC. Besides, a DC/AC inverter is needed, since the electric motor is supplied in AC. It is connected to AC/AC converter for regulating the voltage.
The AC switchboard allows to supply the electrical utilities, so that, according to the different type of load, a transformer is also considered.
The electric power needed for the electric motor is regulated with a frequency converter, which allows to operates for the so the entire range of speeds. The electric motor is connected to the propeller shaft by means of a gearbox.
The efficiencies of these components have not been considered in this analysis.

4 Hydrogen Consumption Assessment

The hydrogen consumption (HC) in each load condition (i) is calculated as reported in [25]:

$$HC(i) = \frac{L_f(i) \cdot W_{PEMFC}}{LHV_{H_2} \cdot \eta(i)} \quad (1)$$

where, W_{PEMFC} is the nominal power of the PEMFC system, L_f is the load factor of the Ro-Pax ferry (Fig. 2), LHV_{H_2} represents the hydrogen lower heating value (120 MJ/kg), and η is the PEMFC efficiency (calculated from the polarization curve provided by the manufacturer). Therefore, considering the fuel cell operation during the cruise (12 hours), the total hydrogen consumption (THC) has been calculated:

$$THC = \int_0^{t_f} \frac{L_f(i) \cdot W_{PEMFC}}{LHV_{H_2} \cdot \eta(i)} dt \quad (2)$$

5 Economic Assessment

The economic assessment has been carried out comparing the PEMFC-based and diesel-based powertrain systems. In particular, the Capital Expenditure (CAPEX), as well as the Operational Expenditure (OPEX) for each H_2 storage technology, have been estimated, considering different cost scenarios: current, near-term, mid-term, long-term and target scenario (ranging from 2020 to 2050).
Table 4 summarizes the assumed investment costs for the selected technologies, in each considered scenario.

Table 4. Investment costs for the plant components

Investment costs	Unit	Current Scenario	Near-term Scenario	Mid-term Scenario	Long-term Scenario	Target Scenario
PEMFC [20,26,27]	$/kW	960.0	350.0	170.0	130.0	92.4
Evaporator*[28]	k$	200.0	190.0	180.0	160.0	145
GH_2 storage [29,30]	$/kg	600.0	333.0	300.0	266.0	166.0
LH_2 storage [31-33]	$/kg	165.0	165.0	150.0	110.0	70.0

*Only needed for LH_2

6 Results and Discussion

Considering a PEMFC average efficiency equal to 45%, the overall hydrogen consumption during one cruise is calculated equal to 15.9 tons. By assuming a fuel margin percentage of 10% for safety conditions, the hydrogen to be stored on-board is 17.5 tons.

6.1 Technical analysis

In order to verify the feasibility replacement of the conventional diesel engine powertrain with the proposed one, the engine room and the fuel room characteristics (see table 1) have been taken into account. In particular, the weights and volumes of the powertrain systems have been calculated for ensuring the compatibility with the available space on the ferry.
Considering the number of the PEMFC units (378) and the geometric parameters of each unit (see table 3), the new power unit allows to reduce the volume and weight of the engine room, with respect to the reference diesel-based solution of about 51.1% and 74.3% respectively, as reported in Table 5 (for the Diesel powertrain system data refers to both the MEs and AEs [34,35]). Therefore, both an additional volume, as well as a saved weight, is available for storing hydrogen. In particular, the overall available volume in the engine room is 879.1 m^3 and the saved weight is 426.6 tons.

Table 5. Powertrain systems: weights and volumes comparison

Data	Diesel powertrain system [34,35]	PEMFC powertrain system [20,21]
Volume (m^3)	780.9	381.8
Weight (tons)	574.3	147.7

With referring to the calculation of volume and weight for the selected hydrogen storage solutions (gaseous, GH_2, and liquid, LH_2, hydrogen storage), the main hydrogen properties, in terms of Gravimetric Energy Density (kWh/kg) and Volumetric Energy Density (kWh/m^3), have been taken into account (Table 6).

Table 6. Hydrogen fuel properties

Fuel Property	Units	GH_2 350 bar	GH_2 700 bar	LH_2
Hydrogen Low Heating Value	MJ/kg (kWh/kg)	120.0 (33.3)	120.0 (33.3)	120.0 (33.3)
Tank Gravimetric Energy Density	MJ/kg (kWh/kg)	6.3 (1.7)	6.5 (1.8)	17.3 (4.8)
Tank Volumetric Energy Density	MJ/m^3 (kWh/m^3)	1963.6 (545.5)	2666.7 (740.7)	7859.6 (2183.2)

Table 7 summarizes and compares the results in terms of weight and the volume for each proposed storage technology with the diesel system.

Table 7. Fuel storage systems: weights and volumes comparison

Data	Diesel Storage system	H_2 Storage system		
		350 bar GH_2	700 bar GH_2	LH_2
Volume (m^3)	78.3	971.3	666.3	436.3
Weight (tons)	65.4	512.0	275.6	119.2

By analyzing the data illustrated in table 7, it is possible to underline that:

- the volume of the hydrogen storage systems is 12.4, 8.5 and 5.6 times higher (for 350 bar GH_2, 700 bar GH_2, LH_2, respectively) compared to the diesel storage system;
- the weight is 7.8, 4.2 and 1.8 times higher (for 350 bar GH_2, 700 bar GH_2, LH_2, respectively) compared to the diesel storage system.

Furthermore, all the hydrogen solutions are suitable in terms of weight and volume (see Table 1) even if the number voyages (without refueling) are drastically reduced. As matter of fact, considering that the vessel has a fuel room with a volume of 1000 m^3, the number of voyages decreases from 12.8 (with the diesel), to 1.03, 1.5 and 2.3 considering the hydrogen storage systems (350 bar GH_2, 700 bar GH_2, LH_2, respectively).
Figs. 5-6, compare the weights and volumes of the hydrogen-based power train system (fuel cells and hydrogen storage tanks) with those of the conventional diesel engine system (MEs, AEs and diesel tank).

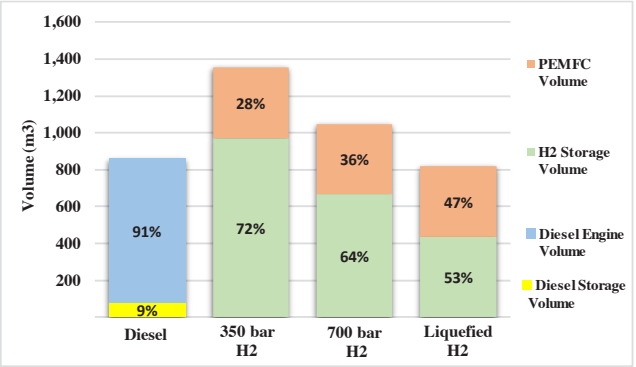

Fig.5: Total volume comparison for each case

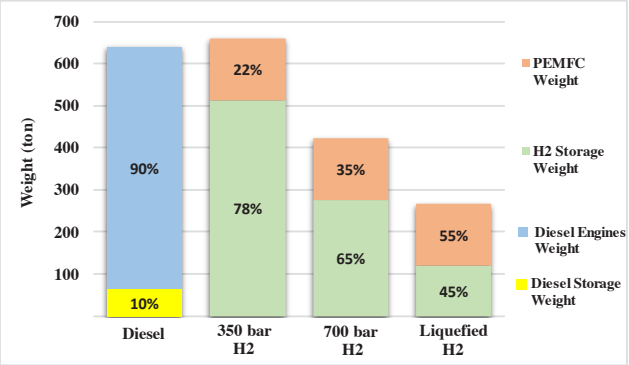

Fig 6: Total weight comparison for each case

It is worth noticing that on the Ro-Pax ferry the replacement of the diesel ICE with hydrogen-based power train causes an increase of the total occupied volume in all the analyzed hydrogen storage systems; on the other hand, the 700 bar GH_2 and LH_2 solutions involve a reduction in weight compared to the conventional solution.

6.2 Economic Analysis

The economic assessment is carried out by estimating the CAPEX and OPEX for each H_2 storage technology, in all considered scenarios (from 2020 to 2050).
Table 8 summarizes the investment cost of the proposed PEMFC-based system in each considered scenario.

Table 8. CAPEX for the proposed power train systems

System Configurations	Unit	Current Scenario	Near-term Scenario	Mid-term Scenario	Long-term Scenario	Target Scenario
PEMFC& LH_2 storage	k$	39,818.0	16,365.0	9,226.0	6,997.0	4,861.0
PEMFC& GH_2 storage	k$	47,529.0	19,100.0	11,666.0	9,560	6,392.0
Diesel engine System*	k$	20,390.0	-	-	-	-

*The cost of diesel tanks is considered negligible

It is worth noticing how, in the current Scenario, considering an average specific capital cost of diesel engines equal to 478 $/kW [21], the proposed system is not comparable with respect

to the Diesel engine system. It becomes comparable and competitive in the other scenarios, because of forecasted cost reduction of PEMFC stack system [35].
For the OPEX, only the cost for the fuel consumption has been considered. In particular, the hydrogen consumption for one cruise (17.5 tons) and its average retail price (available for light duty and heavy-duty vehicles) on the market as a function of time have been taken into account.
Table 9 summarizes the Operational Expenditure (OPEX) of the proposed PEMFC-based system in each considered scenario.

Table 9. OPEX: H_2 VS Diesel for the different scenarios (for 1 cruise)

	Unit	Current Scenario	Near-term Scenario	Mid-term Scenario	Long-term Scenario	Target Scenario
Fuel costs						
H_2 average price [36]	$/kg	16.5	13.0	10.0	7.0	4.0
Diesel average price [30]	$/kg	0.5	0.8	1.0	1.1	1.3
OPEX						
H_2 consumption cost	k$	288.8	227.5	175.0	122.5	70.0
Diesel consumption cost	k$	32.7	52.3	65.4	71.9	98.0

Hydrogen price decreases from $16.5/kg to $4/kg over the time, while the diesel price increases from $0.5/kg to $1.3/kg [33,36].
It is worth noticing that that the fuel cell-based system is competitive from the operating cost perspective only at the target scenario (2050).

Conclusion

In this paper a techno-economic feasibility analysis, for integrating a polymer electrolyte membrane fuel cell (PEMFC) technology as a propulsion system on-bard ocean-going vessel, has been carried out. The ship selected in this study is a Ro-Pax ferry, a passenger/vehicles ferry and a cargo transporter, currently powered by four diesel engines, which have a total power output of 37.8 MW, and two auxiliary engines, which give an output of 4 MW.
The PEMFC system has been designed to completely replace the main diesel engine as well as the auxiliary engines with 378 units of 100 kW each.
Two different hydrogen storage technologies have been taken into account in this study: compressed gaseous hydrogen (at 350 bar or at 700 bar) and liquid hydrogen.
The results show that the PEMFC-based powertrain solution is characterized by 54.2% less space and 74.3% less weight compared to a diesel engine with the same power output, possibly allowing for additional space saving in the engine room.
As concerns the hydrogen storage technologies, it has been demonstrated that in terms of volume, the hydrogen storage systems are 12.4, 8.5 and 5.6 fold-higher for 350 bar GH_2, 700 bar GH_2, LH_2 compared to diesel storage system while 7.8, 4.2 and 1.8 fold-higher in terms of weight.
Moreover, it has been demonstrated that all the hydrogen solutions are suitable in terms of weight and volume, even if the number voyages (without refueling) are drastically reduced.
Finally, different economic scenarios, based on the predicted combined reduction in hydrogen fuel prices and increase in diesel prices, show that the PEMFC powertrain can become comparable with the reference scenario at a hydrogen price of $4.0/kg.

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