A FEASIBILITY STUDY FOR ZERO-EMISSION PASSENGER BOATS FOR INLAND WATERWAYS BASED ON HYDROGEN FUEL CELLS

Massimo Rivarolo*[1], Giaime Niccolò Montagna[1,2], Thomas Lamberti[2], Stefano Barberis[1]

[1]Thermochemical Power Group, University of Genoa, via Montallegro 1, 16145 Genoa, Italy

[2]h2boat, Via Antonio Cecchi 4/4, 16129 Genoa, Italy

*Corresponding Author: massimo.rivarolo@unige.it

ABSTRACT

As environmental concern is growing, decarbonization of maritime sector and reduction of pollutant emissions is a key-point, in particular in ports, inland water and for navigation nearby urban areas. Today the largest part of ships in operation still employs internal combustion engines fed by oil products for propulsion and energy generation onboard. Hydrogen and Fuel Cells can represent a promising solution for zero-emission propulsion, in particular for small size applications (up to 2 MW), where they can offer considerably higher efficiency compared to traditional engine solutions. Short-sea and inland navigation vessels can represent promising applications, also to avoid the use of excessive volume onboard for H_2 storage, needed for long navigation routes (i.e. weeks in case of deep ocean).

The present paper aims to investigate hydrogen fuel cell and compressed hydrogen (CH2) tanks (350 bar) solutions for inland navigation for two different passenger vessels operating on Italian lakes, considering both the technical and economic aspects. The analysis is performed in two subsequent steps: (i) first, a steady-state multi-criteria approach is adopted to compare the hydrogen based solution with the traditional one (engines fed by diesel oil) from emissions, costs, volumes and weights standpoints, considering the constraints related to the vessel type and dimensions; (ii) then, a time-dependent techno-economic analysis is performed considering the ships operating profile, determining the optimal size for energy generation modules and their best energy management strategy, aiming at annual costs minimization for both the case studies. The analysis is performed on real vessels energy demands by employing two software tools, HELM (Helper for Energy Layouts in Maritime applications) and W-ECoMP (Web-based Economic Modular Program), both developed by the authors' research group. The proposed approach has general validity and can be applied to different ships typologies, also considering different technologies for energy generation and storage onboard.

1 INTRODUCTION

At the end of 2022, almost the totality of the transportation sector worldwide is still powered by fossil fuels, resulting in strong impact in terms of pollutants (i.e. SOx, NOx, particulate matter) and GHGs, with a contribute of about 8.5 Gtons CO_2 /year on a total of roughly 36.8 Gtons in 2022, as reported by the International Energy Agency (IEA) [1]. The maritime transport is one of the most impacting, responsible for nearly 3 Gtons/year. In fact, almost the totality of ships in operation today are propelled by Internal Combustion Engines (ICEs) fed by fossil fuels, mainly Heavy Fuel Oil and Marine Diesel Oil (MDO), since many practical advantages, such as the already available infrastructure, the high energy density and the well-developed and established technologies on-board. In the last 25 years, the IMO introduced new normative aimed to reduce the pollutant emissions of greenhouse gases in maritime sector [2][3]: in order to respect emission limits, new strategies to increase efficiency, reducing fuel consumption, are worthy of investigation [4]. Restrictions are particularly applied inside

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the Emission Controlled Areas (ECA), as well in ports and inland waters. In 2018, the IMO released a long-term strategy, revised and updated in 2023 [5], aimed to: (i) reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008 levels; (ii) reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008 levels.

To reach such ambitious results, the utilization of carbon-free fuels is a key-point, together with high efficiency technologies for power generation onboard. Proton Exchange Membrane Fuel Cells (PEMFC), directly fed by hydrogen, are one of the most promising solutions thanks to many advantages, such as high efficiency, low noise and vibrations, zero emissions both in terms of GHG and other pollutants, fast start-up time and quick answer to load variations. The utilization of PEMFC for maritime transport has been investigated widely in the last years, focusing on many aspects related to technologies review [7], feasibility studies [8], experimental campaigns [9] and control [10]. At the same time, the most important manufactures have already developed specific products for this kind of application, with installed power up to hundreds kW, aiming to MW size [11-14]. The growing interest in the use of PEMFC in maritime sector has been demonstrated in many national and international research projects as well, such as *Maranda*, *Hyship*, *RiverCell, ZEMSHIP, Flagships, H2Ports, Hi-Sea, TecBia, HFC Marine, Elektra*, reported in Table 1.

Table 1: National/international research projects with PEM fuel cells and hydrogen for maritime applications

Project name	PEM Fuel Cell size	Time period	Vessel type	Reference
HYSEAS III	600 kW	2018-2022	RoPax ferry	[15]
FLAGSHIPS	1200 / 400 / 600 kW	2019-2023	Container cargo ship /self-propelled barge/ Passenger and car ferry	[16]
H2PORTS	70 kW	2019 -2023	-	[17]
HFC MARINE	200 kW	2018-2020	Ferry	[18]
ELEKTRA	300 kW	2017 - 2019	Canal tug	[19]
ZEMSHIP	96 kW	2007 - 2014	Inland passenger boat	[20]
TecBia	144 kW	2018-2022	Research vessel	[10]
HI-SEA	250 kW	2017 - 2022	-	[9]
MARANDA	165 kW	2017-2022	Research vessel	[22]
MF Hydra	400 kW	2020-2025	Ro-Pax ferry	[21]
HyShip	3 MW	2021 - 2024	Coastal goods-carrying RoRo	[23]

In 2018, ships calling at European Union and European Economic Area ports emitted around 140 million tons of CO_2 and inland navigation accounted for 13.5% of the EU's GHG emissions [24]. The use of hydrogen fuel cells on vessels represents an important step towards zero emission navigation and has been investigated in many research projects recently. However, the application to several kinds of vessels for inland waterways represents an important innovation. On 1st March 2023, the *RH2IWER* (Renewable Hydrogen for Inland Waterway Emission Reduction) Horizon European Project has been started. The project aims to create a solid basis for the acceleration of hydrogen fuel cell powered vessels in inland waterway shipping by demonstrating six commercially operated vessels [25]. The demonstrative vessels include container, bulk and tanker vessels with installed power in the range 0.6 – 2 MW. The project also includes the study of replication potential in different EU scenarios, considering passenger ferries operating in Italian lakes. In this context, the present paper aims to perform a feasibility study for the retrofitting of a passenger ferry operating in Lake of Garda (Italy). The vessel is powered with internal combustion engines fed by MDO and represents an interesting case study for retrofitting with hydrogen and fuel cells, targeting zero emissions.

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2 METHODOLOGY

The analysis is performed in two subsequent steps, by using two in-house software developed by the Authors' research group. For both the steps, data related to the vessel (i.e. installed power, autonomy, energy demand profile) are considered. First, the HELM tool is adopted to compare the hydrogen-based solution with the traditional one (engines fed by MDO) considering multi-criteria, i.e. emissions, costs, volumes, weights and environmental impact. This analysis allows to understand if PEMFC is a promising solution for the vessel under analysis. considering the constraints related to the vessel type and dimensions. In the second step, a time-dependent analysis is carried out considering the ship's operating profile, determining the size for energy generation modules (PEM Fuel Cells, batteries, hydrogen storage system) and the best energy management strategy, aiming at annual costs minimization.

2.1 Steady-state analysis

The goal of the HELM software is to compare different technological solutions for the power generation on maritime applications, and it can be used to aid the ship design process, both for newly built vessels or retrofitting. This comparison is based on various parameters, following a multi-criteria approach outlined by the flow chart in Figure 1. Starting from a large number of inputs (vessel features, energy requirements, energy systems efficiency), the software compares the different solutions in terms of both power units and related fuel storage. From the energy requirements, the software calculates the absolute values in terms of several criteria (weight, volume, cost and emissions) for each technology by means of maps, developed through a deep and detailed market investigation and private communication by different companies. Comparing the different solutions, and considering different relevance depending on the application characteristics, a score is assigned to each solution for each criterion and a total score is calculated, allowing the comparison analysis and determining the most promising solutions for the specific vessel application. As Eq. (1) shows, for the i-th criterion, all the solutions are analysed and their values (i.e. in terms of volume) are compared with the best one for the specific criterion. According to the application and vessel type, a relevance R is assigned. For more details about HELM algorithm, the reader is referred to [26].

$$S_{ij} = coeff_i \cdot \frac{v_{best_i}}{v_{ij}} \cdot R_i \qquad (1)$$

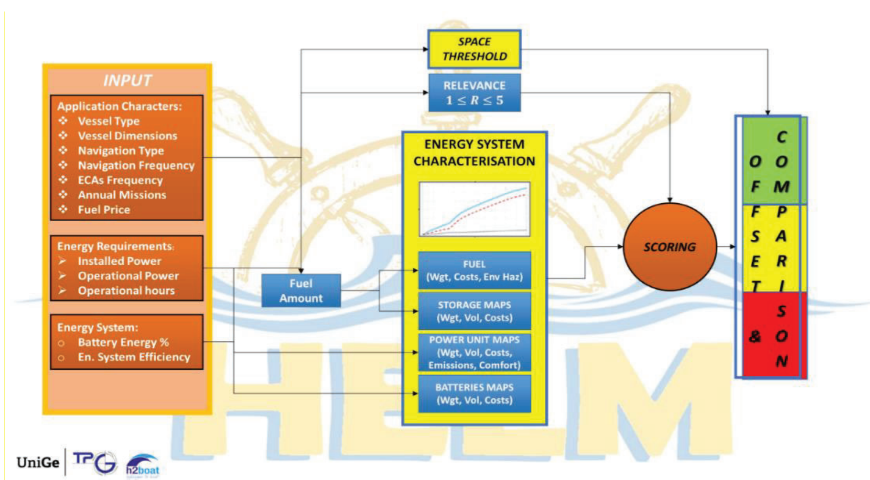

Figure 1: HELM flowchart

2.2 W-ECoMP

W-ECoMP is an in-house software developed by the Thermochemical Power Group (TPG) at the University of Genoa in the last twenty years to perform thermo-economic analysis of different energy

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systems in time-dependent conditions, controlling the different generators to find out the best operational strategy. The software has been applied to many plants, such as poly-generative energy districts [27], power-to-hydrogen [28] and distributed generation onboard ships [29]. W-ECoMP employs a genetic algorithm for the minimization of the objective function, which represents the plant annual variable costs, as shown in Eq. (2), where *c* are specific costs, *F* is the fuel consumption and *E* the electrical energy. Virtual flows represent terms related to not satisfied constraints in the problem (i.e. not satisfied energy demands), thus they should be reduced to zero.

$$C_{var} = F_i \cdot \sum_{i=1}^{N} c_{fuel,i} + c_{el} \cdot E_{acq} + c_{virt} \cdot \left(F_{virt} + E_{virt} + Q^*_{virt}\right) \quad (2)$$

It is also possible to perform a size optimization of one or more components in the plant layout: in this case, the objective function represents the sum of variable and fixed annual costs. The software has a modular approach: each prime mover (i.e. ICE, fuel cell, gas turbine) is described by off-design curves and cost functions. Off-design curves are dimensionless and are extrapolated from real data provided by the manufacturers or by experimental campaigns performed by the authors' research group within the last twenty years. Cost functions are calculated from market/literature data, integrated with real data by the producers, when possible. Figure 2 shows the W-ECoMP flowchart. For more details about W-ECoMP, the reader is referred to [29][30].

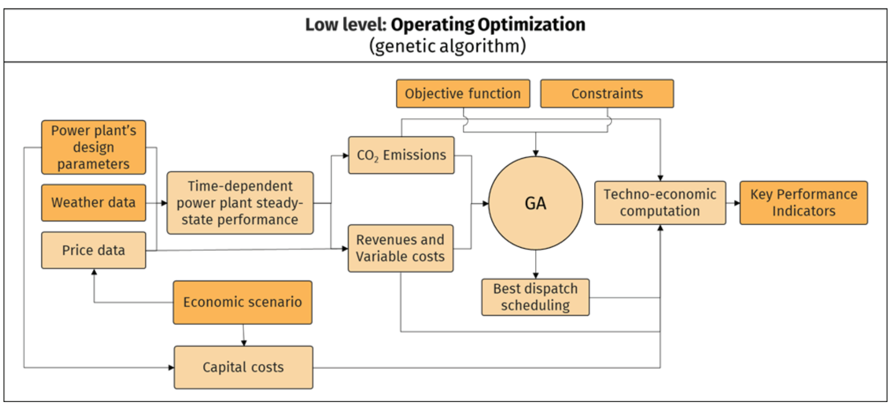

Figure 2: W-ECoMP flowchart

3 CASE STUDY

The presented case study is the *Tonale* [31] passenger and car ferry boat, operating on the Lake of Garda (Italy), built in 1986. The vessel can host till 1,000 people, plus 50 cars. As many inland vessels, it has the characteristics of the symmetrical longitudinal profile, with twin bows, to reduce the manoeuvring time also in small harbour; thus, there are two twin vertical thrusts, one per each bow, with two installed MTU 12v 550 kW diesel engines [32], each one with 37% max efficiency. The vessel sails in the Garda lake daily from April to October from 8:30 to 18:40 and it is docked for the night in Desenzano harbour. The vessel's route is reported in Table 2. To follow the goal of the project and investigate on alternative solutions to reduce the emissions, in particular on PEMFC-CH2, the energy analysis has been done on a single day navigation. Starting from the information of the *Tonale* route, the average velocities have been calculated and used to estimate the required powers (effective to move the ship and at brake) and fuel consumption in each village connection. The other data used for the analysis are the engine efficiency, the propulsion line efficiency (around 45% for vertical thrust) and the ship resistance, estimated through the geometrical parameters. The values related at each route are reported in Table 2 and the sum of the consumptions is compared with the daily fuel consumption provided from the owner (about 1400 l/day) to validate the estimation.

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Table 2: Daily navigation profile and energy consumptions

Route	Start [h]	Arrive [h]	Distance [km]	Av Velocity [km/h]	Effective Power [kW]	Required Power [kW]	MDO cons [l]
Desenzano-Sirmione	08:30	08:50	5,6	16,8	328,3	729,6	66,8
Sirmione-Garda	08:50	09:35	13	17,3	365,1	811,3	163,8
Garda-Bardolino	09:35	09:50	3,5	14	177,0	393,4	29,8
Bardolino-Cisano	09:50	09:58	2,4	18	415,0	922,2	32,3
Cisano-Lazise	09:58	10:10	3,4	17	341,8	759,5	41,4
Lazise-Sirmione	10:10	10:57	11,6	14,8	214,0	475,5	109,8
Sirmione-Desenzano	10:57	11:20	5,6	14,6	204,4	454,2	51,7
Desenzano-Sirmione	11:35	12:00	5,6	13,4	154,3	342,9	44,0
Sirmione-Lazise	12:00	12:40	11,6	17,4	369,9	821,9	147,2
Lazise-Bardolino	12:40	12:58	4,7	15,7	259,0	575,5	49,4
Bardolino-Garda	12:58	13:15	3,5	12,4	116,5	258,8	23,3
Garda-Bardolino	14:15	14:30	3,5	14	177,0	393,4	29,8
Bardolino-Lazise	14:30	14:47	4,7	16,6	314,5	698,8	54,8
Lazise-Peschiera	14:47	15:20	7,8	14,2	184,9	410,9	68,0
Peschiera-Lazise	15:30	15:58	7,8	16,7	322,7	717,0	92,2
Lazise-Cisano	15:58	16:10	3,4	17	341,8	759,5	41,4
Cisano-Bardolino	16:10	16:20	2,4	14,4	194,7	432,6	21,5
Bardolino-Garda	16:20	16:35	3,5	14	177,0	393,4	29,8
Garda-Bardolino	16:55	17:10	3,5	14	177,0	393,4	29,8
Bardolino-Cisano	17:10	17:20	2,4	14,4	194,7	432,6	21,5
Cisano-Lazise	17:20	17:32	3,4	17	341,8	759,5	41,4
Lazise-Sirmione	17:32	18:18	11,6	15,1	230,1	511,4	114,3
Sirmione-Desenzano	18:18	18:40	5,6	15,3	237,6	527,9	56,2
Total	-	-	130,1	-	-	-	1360,1

4 ANALYSIS AND RESULTS

4.1 Feasibility study and pre-dimensioning

The preliminary investigation of the diesel ICE replacement to reduce the emissions is performed with a steady-state analysis through the use of the HELM software, able to compare the energy systems in terms of technology, cost and emissions. HELM multi criteria algorithm needs several inputs to properly define the case study, related both to the vessel features (type, dimensions, route) and to the energy demands (installed power, autonomy, average efficiency). The considered values for the *Tonale* ferry boat are shown in Table 3. An operational power of 1000 kW is assumed, considering the highest power demand of 922 kW, reported in Table 2. About the characterization of the energy systems, the ICE-MDO efficiency is assumed 35% while the PEMFC's average one is assumed 50%, based on market data; storage pressure for CH2 is 350 bar. In case of propulsion utilization, the fuel cell system needs a small battery to manage power request in the transients and not compromise the FC. In this case the batteries absorb the fluctuation and the power peaks. Since the case study is a ferry boat for inland navigation, environmental relevance (GHG, NOx, the environmental hazard) has the highest value due to the strong interest in emission reduction and environmental protection in the touristic area of the

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Garda lake; on the other hand, the cost relevance is minimum as the project has public funds to support the investment; weight and volume relevance values strongly depend on the vessel typology.

Table 3: Steady-state inputs analysis

Vessel Type	Length [m]	Beam Hull [m]	Beam Upper [m]	High Hull [m]	High Upper [m]	Installed Power [kW]	Max Power [kW]	Op hours [h]	Nav Freq	Nav Type	Annual Mission
Pax Ferry	54	10,8	10,8	2,9	9	1100	1000	8,5	Medium	Inland	210

REL Costs	REL Volume	REL Weight	REL NOx	REL GHG	REL Env Haz
1	3	2	5	5	5

The analysis has been performed for the 8.5 operational daily hours, considering the refuelling at the end of the navigation day. The results are shown in Figure 3 in terms of total scores, considering the five criteria (volume, weight, cost, emissions -GHG, NOx- and environmental hazard). In general, PEMFC fed by hydrogen are the most promising solution thanks to their zero emissions in terms of both GHG and NOx; in terms of cost, the ICE-MDO is the best solution, due to the high maturity and market diffusion. Comparing the different storage systems for H_2, in terms of cost and weight, the CH2 is the most promising solution for hydrogen storage, although the volume score is much lower than the ICE fed by MDO. LH2 would be promising as well, however the management onboard due to the cryogenic system and the boil-off would be complicated, also considering the vessel dimensions.

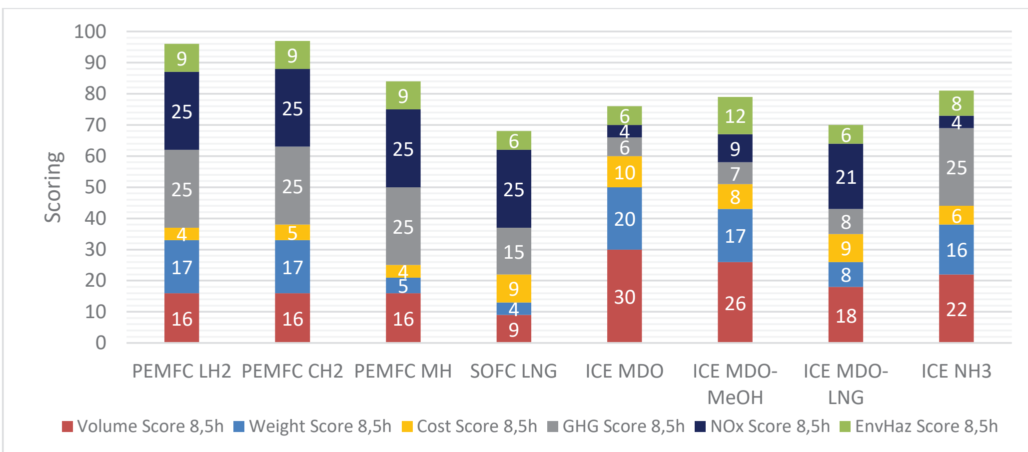

Figure 3: Steady-state analysis results (one day autonomy)

Considering all the parameters, PEMFC-CH2 results the best solution to retrofit the diesel engine, in particular thanks to the zero emissions, although the ICE-MDO has higher weight and volume scores, meaning that the H_2 system needs to be lighter and more compact. Thus, to obtain better volume and weight conditions, a sensitivity analysis is performed on the autonomy and a refuelling during the scheduled one hour stop (13:15 - 14:15 as shown in Table 2) is considered. In this scenario, the considered operational hours are 4.5. The results are reported in Figure 4. It is worth noting that the absolute difference in terms of score between PEMFC-CH2 and ICE-MDO are more significant compared to the previous scenario, as the disadvantage in terms of weight and volume vs ICE-MDO is lower, thanks to a significant reduction in terms of hydrogen storage onboard.

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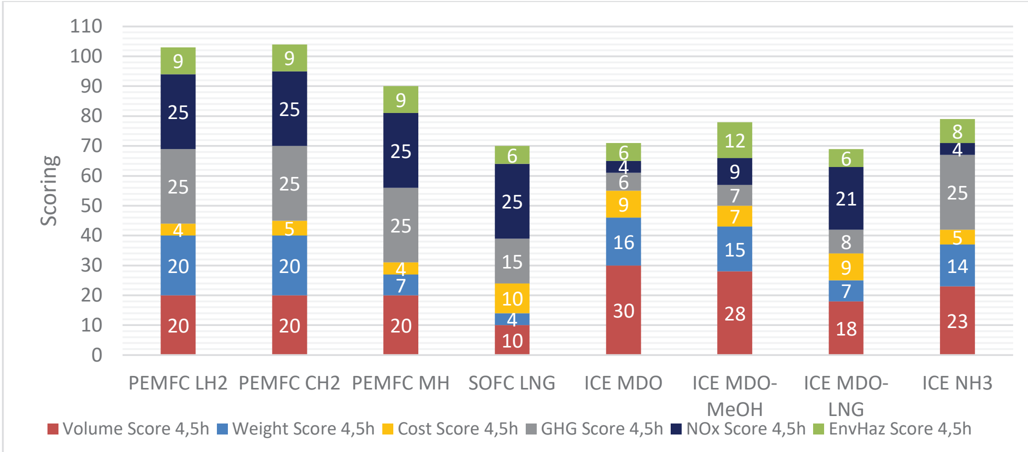

Figure 4: Steady-state analysis results (half day autonomy)

The main results are shown in Table 4 (volume and weight) and in Figure 5 (capital cost) in terms of absolute values for the two energy systems and their components, including power unit (PU), fuel, tank, battery (for PEMFC) and selective catalytic reduction (SCR, for ICE MDO). Reducing the operational hours, volume and weight are significantly reduced for the H_2 solution (from 60 m^3 and 19 tons to 45 m^3 and 12 tons), in particular thanks to storage volume (from 24.2 to 12.8 m^3) and batteries weight (from 9.9 to 5.3 tons) reductions. For the ICE-MDO solution, the storage influence is quite limited, due to high fuel energy density, thus results in terms of volume and weight are similar (27 m^3 and 16 tons for full day, 25 m^3 and 15 tons for half day). Moreover, the fuel cell system can reduce up to zero the emissions of diesel engine in the operational year: 1022 t of CO_2 and 12.05 t of NOx.

Table 4: Volume and Weight absolute values for PEMFC-CH2 and ICE-MDO

	hours [h]	**PU Vol [m^3]**	**Store Vol [m^3]**	**Bat Vol [m^3]**	**Noise Ins Vol [m^3]**	**SCR Vol [m^3]**	**PU Wgt [t]**	**Store Wgt [t]**	**Bat Wgt [t]**	**Noise Ins Wgt [t]**	**SCR Wgt [t]**	**Fuel Wgt [t]**
PEMFC CH2	8.5	10.9	24.2	6.9	-	-	4.4	5.4	9.9	-	-	0.5
ICE MDO	8.5	16.4	3.5	0	0.9	6.2	11.8	0.5	-	0.9	0.8	2.4
PEMFC CH2	4.5	10.9	12.8	3.6	-	-	4.4	2.8	5.3	-	-	0.2
ICE MDO	4.5	16.4	1.9	-	0.9	6.2	11.8	0.2	-	0.9	0.8	1.2

Figure 5 shows the capital expenditure (CAPEX) split for the two solutions: the CAPEX for the PEMFC-CH2 is about 5.5 M$, ten times higher compared to the MDO-ICE. It is worth noting that for both the systems, the main CAPEX is the PU, in particular the PEMFC represents 93% of the investment (96% in case of 4.5 h autonomy). Although the complex nature of the H_2 at ambient condition, the storage represents only the 2% of the entire investments for 8.5 h of operativity, 1% in case of half day. For the ICE-MDO solution, the engine represents about 53%, the SCR and the noise insulation systems account for the remaining part, while the diesel tanks are almost negligible.

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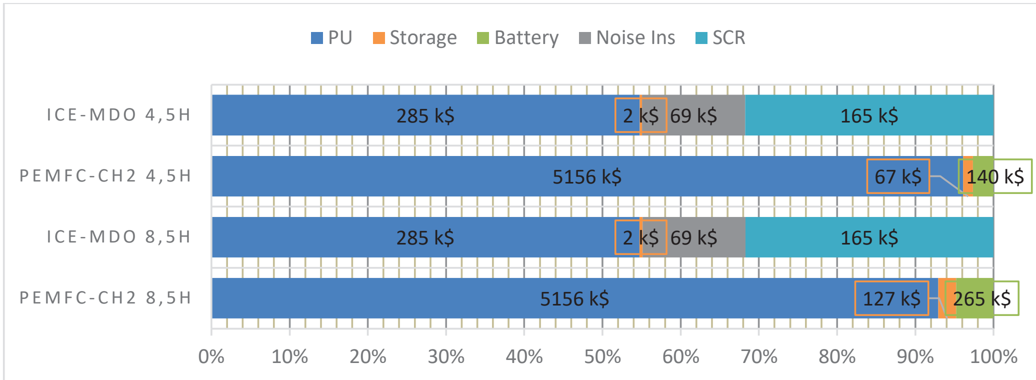

Figure 5: Capital cost influence of each system component for ICE-MDO and PEMFC-CH2

4.2 Time-dependent analysis

The steady-state analysis has given good results to consider PEMFC-CH2 as a promising solution for inland navigation, reaching zero emissions. To have a deeper comparison among the two systems, a time-dependent investigation has been carried out through the W-ECoMP software, considering the energy demand for the operational daily profile of the *Tonale*. The main input data required by the software are the power demand vs time, the time period, and the plant layout. From the data reported in Table 2, the energy profile has been defined: the daily navigation is 8 h and 25 min, analysed with a time step of 300 seconds, due to the short route duration and the high frequency of changing in energy request. The plant layout depends on the characteristics of the PU. In first case, two 550 kW engines are installed; in the second, five 200 kW PEMFC systems are installed, basing on the products available on the market [11][12]. To preserve the fuel cell by fast power fluctuation and power peaks, an hybrid solution has been considered, including a small battery package to avoid stress and excessive degradation on PEMFC modules. The innovative solution layout is shown in Figure 6.

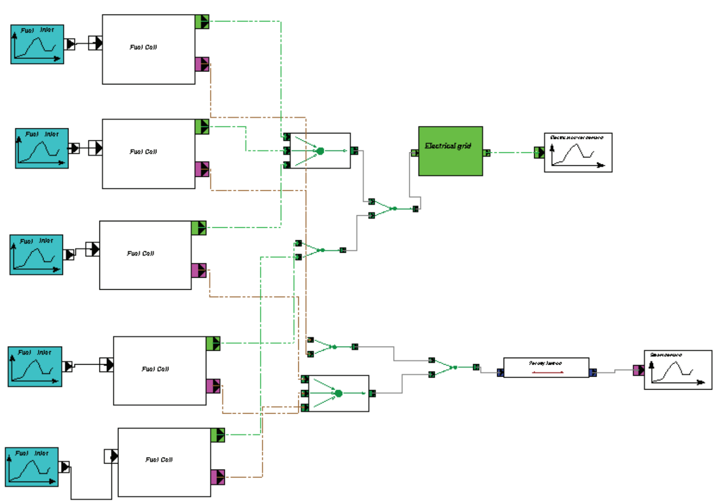

Figure 6: Plant lay-out in W-ECoMP, PEMFC alternative configuration

The goal of the software is to optimize the fuel consumption and the annual cost, thus the off-design curves for both ICE and PEMFC, already implemented in W-ECoMP, shown in Figure 7 as dimensionless curves, have been considered. Nominal efficiencies (at maximum power) are 37% for ICE and 48% for PEMFC and the minimum off-design is 25% for ICE installed on-board and 10% for PEMFC. Performance data include the auxiliaries and are provided by manufacturers [11][12].

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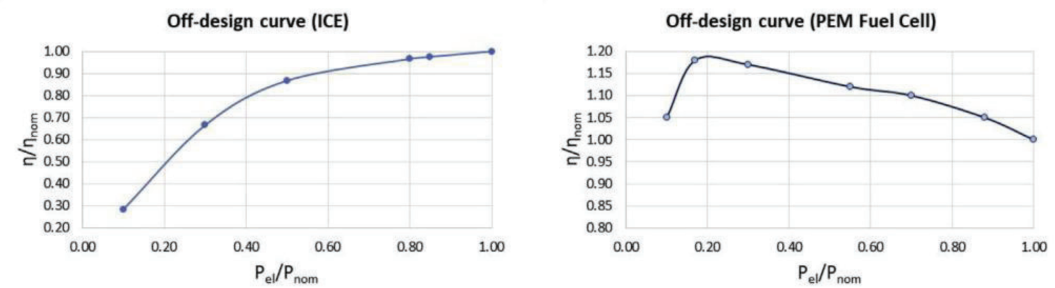

(a) (b)

Figure 7: Off-design curves in W-ECoMP for ICE (a) and PEM Fuel Cell (b)

The power management for each operative period is reported in Figure 8: it can be noted that PUs management follows the demand profile. To avoid PU shutdown, both the engines and the PEMFCs often work in off-design conditions. It is worth noting that PEMFCs are active also during the stop in the harbour for battery charging purpose.

(a)

(b)

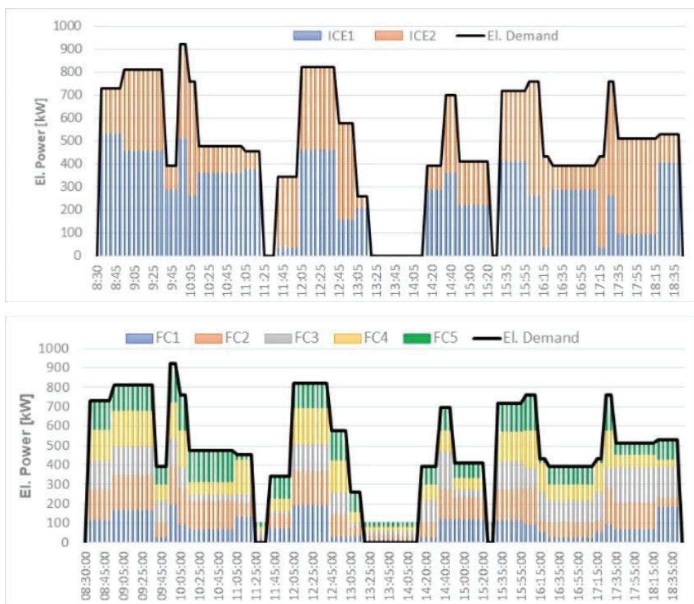

Figure 8: Energy management strategy in case of ICE (a) and PEM Fuel Cell (b)

To underline the advantage of PEMFC for the considered application, the efficiency values over time (both in percentage) for each PU vs operating time are reported in Figure 9. It can be noted the variation among the highest and lowest efficiency values, which is limited for the PEMFC (48-55% range) while the ICE suffers the low power level where its efficiency decreases, leading to larger variation (21-37% range). Due to the navigation profile, with short routes and many docking, a good performance also at low power level is important. The plot underlines the strong difference in terms of efficiency values, in particular for off-design conditions. Thanks to their characteristics, PEMFC are able to work at goof performance even at low energy-load (i.e. when total vessel demand is lower than 300 kW). Average efficiencies on the daily profile are 30% for ICEs and 51.3% for PEMFCs, respectively, corresponding to fuel consumptions of 1311 kg for MDO and 315 kg for CH2 (670 kg and 170 kg considering half day only).

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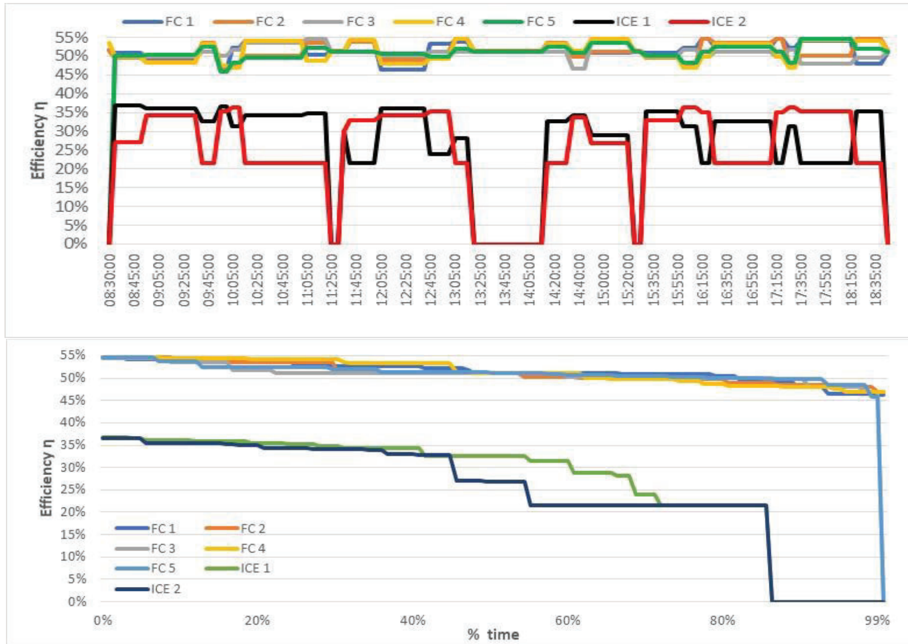

Figure 9: Efficiency comparison for ICE and PEM Fuel Cells

4.3 Energy systems on-board sizing

The steady-state and the time-dependent analyses describe a feasible scenario to substitute the diesel engine with the H_2 system, in particular for an inland application as the *Tonale* ferry. A preliminary sizing of the energy systems has been performed with an appropriate selection of the PU and CH2 tank via a market research. Nowadays, the commercialized PEMFC modules ready for maritime application have the maximum power of 200 kW [11-14]; thus, five modules are needed to satisfy the *Tonale* load demand. To preserve the fuel cell by the frequent fluctuations and picks of power during the propulsion and furthermore to increase the readiness of the plant, an hybrid system is considered with a battery pack, 100 kW power is considered. The total weight and volume of the five PEMFC systems are nearly 5 tons and 7 m^3 , which is similar to the two ICEs installed on board (4.6 tons and 8 m^3) [12].

As far as the CH_2 storage system is concerned, the sizing is based on the W-ECoMP results in terms of daily fuel consumption, which is 313 kg H_2. The 350 bar tanks available on the market have different construction and material characteristics: nowadays, the most available on the market is in aluminium linear with glass fibre reinforcement (type 3). The chosen tank [33] weights 132 kg and can store 6.2 kg of H_2 , with 2.6 m length and 425 mm diameter. Considering a system of 52 tanks, that guarantees 320 kg of H_2 storage, the total rack weight is 7 ton, and the volume 25 m^3. It is worth noting that CH2 tanks at 700 bar start to be available on the market too: in this case, the needed amount of H_2 can be stored in a rack of 20 m^3 and weight of 6 ton.

5 CONCLUSIONS

In the present paper, a feasibility study has been performed to investigate a zero emission solution for propulsion on inland navigation vessels, represented by PEM fuel cell fed by hydrogen, stored in compressed tanks (CH2). A passenger vessel operating on the Garda lake in Italy has been considered as case study, based on the navigation profile and on the vessel's energy demands. In the first phase, the HELM multi-criteria tool, developed by the authors, has been employed to compare possible alternative solutions to the one installed on the real vessel (ICE fed by MDO), considering technical (weight, volume), economic and environmental criteria, also related to the applicative scenario and the kind of vessel. This first analysis allowed to identify PEMFC-CH2 as a promising solution. Then, a

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time-dependent analysis has been performed throughout the use of the W-ECoMP software for time-dependent analysis of energy systems, developed by the authors' research group as well. Starting from the operational daily profiles, the retrofitting of the two installed ICE-MDO (550 kW each) with five commercial 200 kW PEMFC modules has been investigated. The time-dependent analysis, performed thanks to the off-design maps implemented in the software, has shown a significant improvement in terms of average efficiency (from 30% to 51%) in case of hydrogen PEMFC solution. Hydrogen daily consumption has been calculated in nearly 315 kg for one complete navigation day. From these outputs, a sizing of the alternative energy solution has been estimated for both fuel cells and hydrogen storage systems. Thanks to the vessel's features (limited installed power and limited autonomy), the obtained results are promising in terms of volume and weight: retrofitting the ICEs with PEMFCs leads to similar volumes, while the penalty due to the hydrogen storage is not excessive, thanks to the limited required autonomy. Although more detailed studies are necessary, the solution can be worthy for the proposed vessel, or similar ones, and will be investigated in deeper detail in the next future.

NOMENCLATURE

CAPEX Capital Expenditure

CH2 Compressed Hydrogen

ECA Emission Controlled Areas

GHG Greenhouse Gas

HELM Helper for Energy Layout in Maritime applications

ICE Internal Combustion Engine

IEA International Energy Agency

IMO International Maritime Organization

MDO Marine Diesel Oil

NOx Nitrogen Oxides

PEMFC Proton Exchange Membrane Fuel Cell

PU Power Unit

RH2IWER Renewable Hydrogen for Inland Waterway Emission Reduction

SCR Selective Catalytic Reduction

TPG Thermochemical Power Group

W-ECoMP Web-based Economic Modular Program

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