

Comparison of different plant layouts and fuel storage solutions for fuel cells utilization on a small ferry

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HIGHLIGHTS

- Overview of marine fuel cells projects.
- H₂ and PEM fuel cells considered for the propulsion of a small RoRo ferry.
- Different operative profiles analyzed.
- Energy efficiency improved by 10% compared to diesel oil.
- Zero local emissions.

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ABSTRACT

In the path towards the decarbonization of the maritime sector, Low Temperature Polymer Electrolyte Membrane Fuel Cells (LT-PEMFC) fed by hydrogen are gaining attention as they could guarantee zero local emissions propulsion. In this study, a process simulation model is implemented to analyze the influence of peak shaving in a hybrid LT-PEMFC/lithium-ion battery power plant for the propulsion of a small size RoRo car and passenger ferry in different operative conditions. Results show that battery peak shaving could allow a reduction of FC installed power of up to 72%. As for compressed H₂ storage, the results show that for sailing time in the range of 5–10 min, Type I cylinders at 250 bar are a viable option. For longer routes, Type III cylinders at 350 bar or Type IV cylinders at 700 bar should be considered in order to avoid excessive reduction in the pay-load.

Introduction

The restrictions to shipping emissions imposed by the International Maritime Organization (IMO) and other bodies [1], together with the demanding energy efficiency requirements introduced by IMO since 2011, require rethinking the entire

process of ship design, from hull design to route optimization. In particular, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) have the purpose of reducing energy inefficiencies and, therefore, both greenhouse gases (GHG) and pollutant emissions [2].

As for GHG, further restrictions introduced in 2018 aim to reduce the total annual shipping emissions by at least

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50% by 2050 compared to 2008 [3,4]. Moreover, the Norwegian Parliament adopted a resolution to halt GHG emissions of cruise ships and ferries in Norwegian fjords within 2026 [4].

With regards to pollutant emissions, in order to comply with MARPOL Annex VI limitations on nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate (PM), fuel choice and power generation system technology are of particular concern. Since 2016, all vessels sailing in Emission Controlled Areas (ECAs) must comply with the very low SO_x and NO_x limits set by the Tier III standards. The limit of fuel's sulphur content by weight is 0.10% (0.50% outside ECAs). Maximum allowed NO_x emission, depending on the engine's rated speed, is $2.0 \div 3.4$ g/kWh ($7.7 \div 14.4$ g/kWh outside ECAs) [3,5,6]. Moreover, all new ships sailing in Baltic Sea and North Sea after January 2021 will have to reduce NO_x emissions by 80% with respect to actual levels, as new NO_x ECAs will be established [7].

The choice of alternative fuels in shipping depends on many aspects. They are technical (fuel properties and pre-treatment requirements, maintenance, engine adaptation, bunkering infrastructure), economical (fuel price, investment and operational costs), environmental (emissions, life cycle performance), safety and ethical related (availability, politics, public opinion, etc.) [8].

The choice of power generation system depends on the selected fuel and on the design specifications of the system itself (i.e. efficiency, off design operation, operative profile of vessel, technology maturity, emissions, market availability, etc.). To date, they are mostly based on Internal Combustion Engines (ICEs) fed by Heavy Fuel Oil (HFO) and its derivatives. Though being a cheap and market ready solution, the high levels of pollutant and GHG emissions of HFO fed ICEs represent a big obstacle for future installations, even when coupled with emission abatement systems (i.e. Selective Catalytic Reduction-SCR and scrubbers). Therefore, alternative fuels and power generation systems are gaining ever more attention [9]. In particular, Liquefied Natural Gas (LNG) fed ICEs have been demonstrated to be an effective solution to pave the way towards sustainable shipping and have started to be implemented on board [10,11]. More recently, also Fuel Cells (FC) have seen growing interest in the marine sector, given their high efficiency and the possibility to generate power without emissions [12]. Among different types of FC, Solid Oxide Fuel Cells (SOFC) are mainly studied for long-range ships installations, as they are not sensitive to fuel impurities and can therefore be fed by high density fuels instead of H_2 [13,14]. Low Temperature Polymer Electrolyte Membrane Fuel Cells (LT-PEMFC), on the contrary, require pure H_2 as input. If H_2 is stored in its pure form, the low volumetric density of the storage system could hamper LT-PEMFC utilization for long distance shipping [15]. The research on high-density H_2 storage systems and relative refilling process, and the development of both physical and chemical solutions are therefore essential to improve the overall system effectiveness and potentially extend FC usage to long-distance operations [16,17].

Nevertheless, being the FC technology with the highest maturity to date [18], LT-PEMFC could represent a viable solution for short-distance shipping.

To obtain an overall improvement of the ships energy efficiency, the choice of fuel and power system must take into account also the specific operative profile of the vessel. For this purpose, different methodologies can be used, defined, for example, in Ref. [19] as: model-driven approach, data-driven approach and hybrid-approach. The model-driven approach, chosen in this paper, allows gaining general information while easily evaluating the influence of different parameters on the overall energy performance of a ship. Other literature studies that follow this approach are for example [20–23]. Han et al. [20] propose a dynamic analysis of a hybrid LT-PEMFC/battery powertrain for a small size boat, following a model-driven approach on a typical operative profile of the vessel. An improved energy management system for the same vessel and operative profile is proposed by Bassam et al. in Refs. [21,22]. Wu et al. [23] follow a model-driven approach for determining the best design and operation of a hybrid LT-PEMFC/battery propulsion system for a coastal ferry. Data-driven approach is gaining attention in recent years: sailing parameters (i.e. speed, load allocations, route, etc.) are optimized, based on ship operational and environmental big-data, to reach an objective as the best energy efficiency value [24,25]. However, big-data are not always available on board and the results of such an approach have relevance only for the specific case. The hybrid-approach merge model-driven and data-driven ones by utilizing measured data as input of a built up model. In this way it is possible to calculate and optimize also performance parameters that cannot be measured on board [26].

Another important aspect to consider is the need to hybridize LT-PEMFC with energy storage systems. As reported in several studies on LT-PEMFC powertrains for mobility applications [27–30], the inclusion of an energy storage in the system allows to improve the system dynamics and efficiency.

In the first part of this paper, a comprehensive analysis of projects on the application of FC in the marine sector is presented, in order to point out the development lines and to assess the industrial interest in the topic.

The second part describes the process simulation model of a hybrid LT-PEMFC/batteries power plant, fed with H_2 stored in compressed form. This powertrain is installed on board of a small size RoRo car and passenger ferry used for short distance voyages. The model is utilized for analyzing different configurations and operative strategies. In particular, the influence of operative profiles and batteries peak shaving on the daily H_2 consumption is analyzed and compared to the reference case of MGO fed ICE.

Overview on marine fuel cells projects

A comprehensive and up to date overview of marine and inland water FC projects developed since 2000 is presented in this section, updating and revising some other previous documents available in the literature [12,15,31]. The research has been limited to projects for which information is freely available in English on the web and for which at least two data among FC type, FC rated power and logistic fuel are available.

The data of the considered projects are presented in [Tables 11 and 12 in Appendix](#). For each project data have been

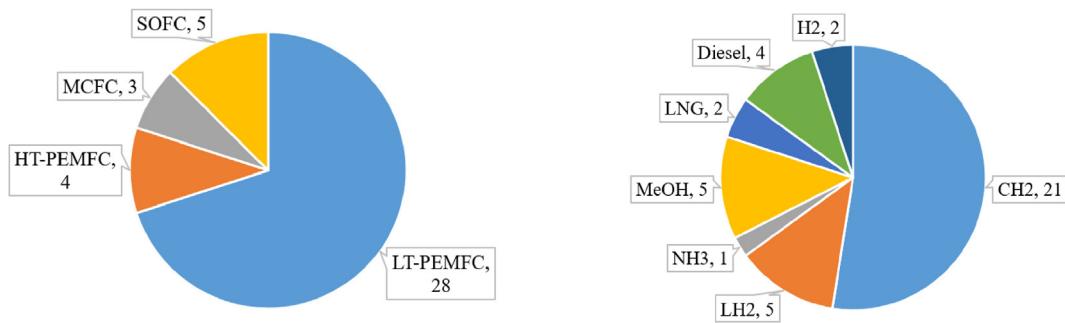


Fig. 1 – FC type (left) and logistic fuel (right) chosen in the projects of Tables 11 and 12

collected on FC type and installed power, FC purpose, batteries type (if any) and capacity, and type of vessel. More in detail, Table 11 refers to “operative” projects in which the vessel/pilot plant successfully operated at sea at least one time or in which the vessel is currently under construction. Table 12 reports information on “non-operative” projects in which the vessel/pilot plant is still a feasibility study or in which the vessel/power plant design and development was not the main target of the project.

The overview as a whole demonstrates that there is a growing interest in marine FC applications (more than 15 projects started after 2017), even though the number of operative projects is still limited (17 out of 44 considered in this study).

Projects in which FC are considered as the main power plant on board refer to small size boats or passenger ferries, while larger ships are generally considered if FC are used as Auxiliary Power Unit (APU). Even though data on power plant layout are available only for a selection of the considered projects (29 out of 44), 18 projects encompass batteries for peak shaving purposes.

Fig. 1 reports the share of FC types and logistic fuels in the projects for which such information is available (40 projects out of 44). Data labels in the left and right figures indicate the FC type or fuel utilized, respectively, and the relative number of projects. Projects not included in Fig. 1 are all non-operative (FCSHIP, DESIRE, NEW-H-SHIP, e5Tug). In particular, FCSHIP is a feasibility study that includes considerations on SOFC, LT-PEMFC and MCFC for two different applications, but only a concept design was developed. DESIRE focuses on the development and testing of a Diesel fuel reformer for feeding MCFC and LT-PEMFC. The NEW-H-SHIP project is aimed to the identification of technical barriers for FC and H₂ on board utilization. Lastly, e5Tug regards the utilization of H₂ FC and batteries for peak shaving in a tug.

From Fig. 1 it emerges that the majority of projects and studies utilizes LT-PEMFC, that is the most mature FC technology available today, at least in sectors other than shipping. Fig. 1 also shows that hydrogen is, to date, the preferred logistic fuel. In 21 projects, H₂ is stored in compressed form, hereinafter referred to as CH₂. Among the CH₂ projects, ten are operative. Also liquefied hydrogen, referred to as LH₂, has been gaining attention (5 projects in the last 4 years) due to the significant reduction of the fuel storage volume. In two cases,

where the fuel type/storage was not the focus of the project, the label in Fig. 1 is “H₂”.

With reference to fuels other than hydrogen, five projects out of 40 utilize methanol (MeOH), mostly to feed high temperature PEM fuel cells (HT-PEMFC). In fact, HT-PEMFC tolerate in input a reformat gas with few percent of CO impurities [32,33].

LNG projects reported in Fig. 1 refer to cases in which LNG is the only logistic fuel taken into account. Besides these, other two projects (Rivercell and Pa-x-ell [34,35] reported in Tables 11 and 12) can use LNG as optional fuel to MeOH.

With reference to low sulphur Diesel oil, it is used in three projects out of 40, two of which (SchibZ and MultiSchibZ) refer to the same on board demonstrator. In these cases, SOFC and Molten Carbonate Fuel Cell (MCFC) are implemented. Other two non-operative projects (DESIRE and FCSHIP), not included in Fig. 1, encompass Diesel oil as one of the possible logistic fuels.

As for ammonia, NH₃, the non-operative ShipFC project is the only one that considers it as logistic fuel, here used to feed SOFC.

Table 1 and Table 2 report, respectively, countries and partners involved in marine FC projects. From Table 1 it is evident that Germany and Norway are the leading countries in this sector. Norway, in particular, has been leading the way in recent years. Nine over 11 projects led by Norway use H₂ as fuel.

Table 2 reports the names of partners involved in three or more projects of the 44 analyzed. In particular, DNV GL and Wärtsilä are (or have been) the most frequently involved, with seven and five projects, respectively.

Table 1 – Number of marine fuel cell projects per country (leading partner).

Country	N° projects	Country	N° projects
Germany	12	Belgium	1
Norway	11	Canada	1
USA	5	Finland	1
France	3	Italy	1
Netherlands	3	South Korea	1
UK	3	Sweden	1
Iceland	2	Switzerland	1
Japan	2	Turkey	1

Table 2 – Number of projects per partner. Only partners involved in three or more projects are taken into account.

Partner	N° projects	Partner	N° projects
DNV GL	7	Germanischer Lloyd	3
Wärtsilä	5	Lloyd's Register	3
Ballard power Systems	4	Meyer Werft	3
SerEnergy A/S	4	Norled	3
Hamburg University of Applied Sciences	4	Sandia National Laboratories	3
Det Norske Veritas	3	TU Berlin	3
DLR	3	TU Delft	3
Fincantieri S.p.A.	3	University of Genova	3
Lürssen	3		

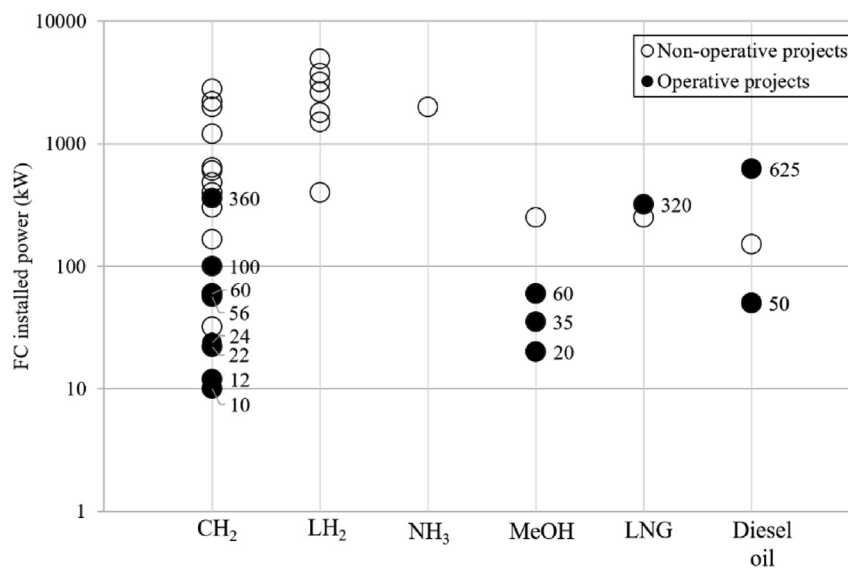
**Fig. 2 – FC installed power vs. logistic fuel in marine fuel cells projects. Numbers in the chart area refer to FC installed power of operative projects (see Tables 11 and 12).**

Fig. 2 refers to the same 40 projects of Fig. 1, and shows the values of FC installed power sorted by the corresponding logistic fuel. Different markers are used for *operative* and *non-operative* projects. It can be noticed that the *operative* projects have a FC installed power lower than 400 kW, with the only exception of the naval project US-SSFC in which a 625 kW MCFC module was tested for a short period on board. For *operative* projects using LNG, Diesel oil or MeOH as logistic fuel, this limit also depends on the high cost, to date, of the referred FC systems, i.e. SOFC, MCFC and HT-PEMFC. If SOFC or HT-PEMFC are used, the low technology maturity of such systems is also an issue [12]. Moreover, MW size plants on board entail increased complexity and volume of the system.

Overall, from the projects analysis, it can be inferred that the technologies on which today there is more experience are LT-PEMFC fuelled by CH₂. Nevertheless, the utilization of a low energy density fuel as CH₂ implies big storage volume that affects the payload and the ship design. On these bases, it can be useful to assess the possibility to utilize these technologies in such applications where the energy required for a typical sailing service is relatively low and the introduction on board of bulky fuel storage is possible. In particular, the possibility to install the storage system in an open deck is, today, the preferred solution in terms of safety. From this standpoint,

small size short range RoRo car and passenger ferries can be an interesting ship segment to be considered. Moreover, small RoRo passenger ferries spend most of the total sailing time in coastal or very sensitive areas where it is relevant to investigate zero local emissions solutions [11]. Obviously, the fuel tank volume is a critical issue in this type of ship as well, therefore tools to support the design and the operation of the power plant system can be useful.

In this context, the next section describes the process simulation model of a small size RoRo car and passenger ferry powered with LT-PEMFC, and its utilization to determine the CH₂ on board storage volume. Different operational profiles have been analyzed in order to evaluate the sailing distance range in which a CH₂+LT-PEMFC would be applicable.

Table 3 – Main characteristics of the selected ferry.

Length	42	m
Breadth	9.4	m
Gross tonnage	100	t
Installed propulsion power	2 × 206	kW
Installed auxiliary power	2 × 28	kW
Service speed	8–9	knots

Case study and simulation model description

The main characteristics of the typical small size RoRo car and passenger ferry chosen as case study are reported in Table 3, while Fig. 3 shows its current daily operational profile [17].

The considered reference plant layout encompasses two ICEs, running on MGO. Hybrid solution with batteries for peak shaving has been analyzed for CH₂+LT-PEMFC configuration. Plug-in with on shore power has not been considered given the high travel frequency of the vessel, as shown in Fig. 3. Fig. 4 shows a simplified schematic of the main components included in the plant. The main engine is either LT-PEMFC or ICE, depending on the selected plant architecture. A Diesel generator is always present for emergency purpose. A constant efficiency of 95% has been assumed for inverters and converters. A DC bus is considered to efficiently connect FC and batteries [36,37].

The efficiency curves as a function of engine load for ICEs and LT-PEMFC are reported in Fig. 5 and Fig. 6 respectively. The experimental data on ICE curve (Fig. 5) have been elaborated from Ref. [38] for small engines (<2000 kW). Experimental data on LT-PEMFC curve (Fig. 6) refer to a commercial 120 kW PEM FC stack and have been elaborated from Ref. [39].

Model description: peak shaving strategy

For the configurations that encompass PEMFC and batteries for peak shaving, it is assumed that at each time step t the power supply matches the power demand P_{demand} :

$$P_{engine}(t) + P_{batt}^+(t) - P_{batt}^-(t) + P_{pgin,d}(t) + P_{pgin,n}(t) = P_{demand}(t) \quad (1)$$

where:

- P_{engine} : power of the main engine. In this LT-PEMFC case is $P_{engine} = P_{FC}$;
- $P_{batt}^+(t)$ and $P_{batt}^-(t)$: output/input battery power, respectively;

- $P_{pgin,d}(t)$: plug-in power during the day, always null in the considered case study;
- $P_{pgin,n}(t)$: plug-in power during the night, always null in the considered case study.

As for LT-PEMFC, it is assumed that they cover the average power demand, constant during the day in order to avoid high degradation rates [23,40]. Hence:

$$P_{FC, hyp} = \frac{P_{average}}{\eta_{conversion}} \quad (2)$$

where $P_{average}$ is the average power demand of the ferry and $\eta_{conversion}$ is assumed to be constant and equal to 95%. The subscript *hyp* indicates a hypothesized quantity, which is subsequently redefined in the model. Assuming that all the stacks operate at the same load, and that each stack has an installed power $P_{FC,stack}$ of 120 kW:

$$n_{FC,stack} = \text{int} \left(\frac{P_{FC,hyp}}{\text{load}_{hyp} * P_{FC,stack}} \right) \quad (3)$$

$$\text{load} = \frac{P_{FC,hyp}}{n_{FC,stack} * P_{FC,stack}} \quad (4)$$

$$P_{FC} = n_{FC,stack} * P_{FC,stack} * \text{load} \quad (5)$$

$$\eta_{FC} = f(\text{load}) \quad (6)$$

where $n_{FC,stack}$ is the PEMFC stack number and η_{FC} is their efficiency. The last one is calculated as function of power load from the characteristic curves in Fig. 6.

As for the batteries, at each time step t the energy stored in the battery E_{acc} is calculated as:

$$E_{acc}(t) = E_{acc}(t-1) + (\eta_{batt} * P_{batt}^-(t) - (1/\eta_{batt}) * P_{batt}^+(t)) * dt \quad (7)$$

where η_{batt} is the battery charging/discharging efficiency, assumed to be constant and equal to 92% [22]. The batteries State of Charge (SOC) is:

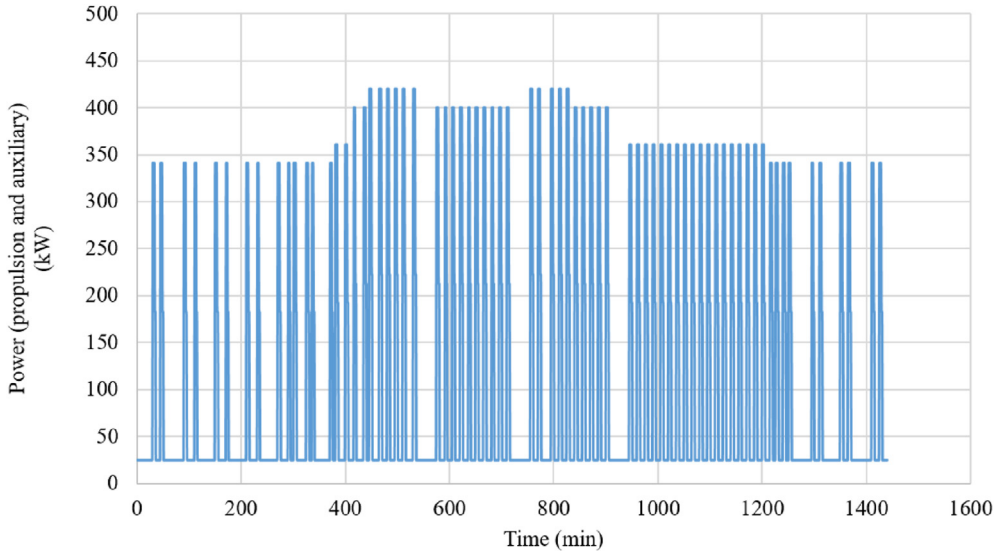


Fig. 3 – Typical operational profile of the considered vessel.

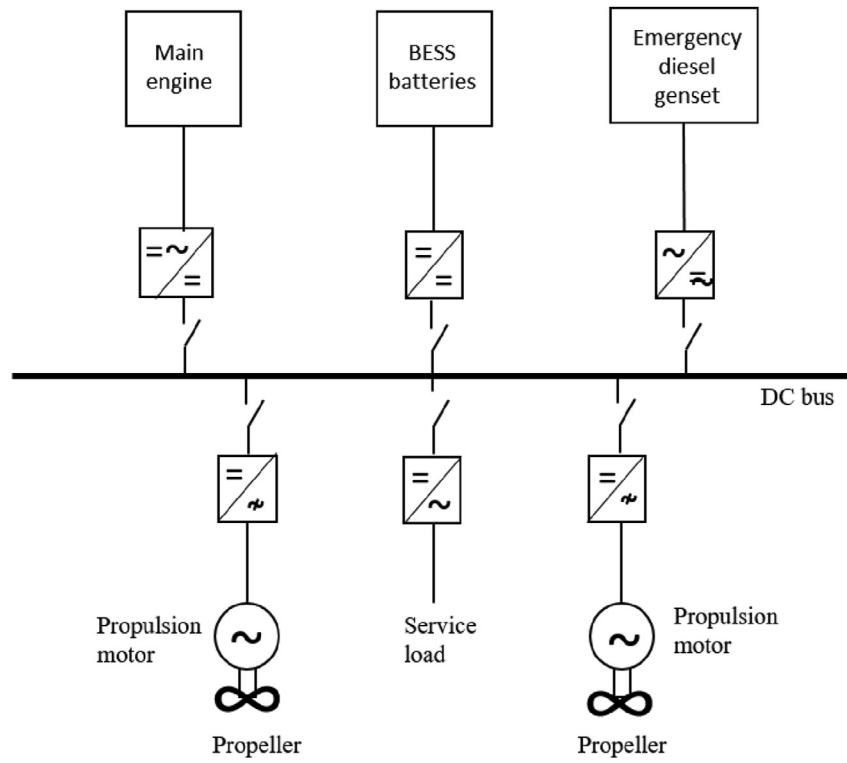


Fig. 4 – Simplified schematic of the main components included in the plant.

$$SOC(t) = \left(\frac{E_{acc}(t) + |\min(E_{acc})|}{E_{batt}} + (1 - DOD) \right) * 100 \quad (8)$$

$$SOC_{min} < SOC(t) < SOC_{max} \quad (9)$$

where DOD is the Depth of Discharge of the batteries, and SOC_{min} and SOC_{max} are imposed in accordance with best strategies to maximize Li-ion batteries lifetime [41]. It is assumed that SOC is at its maximum at the first departure of the day. E_{batt} is the energy capacity of the battery, calculated as:

$$E_{batt} = \frac{\max(E_{acc}) - \min(E_{acc})}{SOC_{max} - SOC_{min}} * 100 \quad (10)$$

At each time step, the C-rate of batteries is calculated as the ratio between the charge/discharge current and the nominal rated capacity Ah_{design} :

$$Crate(t) = \frac{SOC(t) * E_{batt}}{100 * V_{batt} * Ah_{design}} \quad (11)$$

$$Crate(t) < Crate_{max} \quad (12)$$

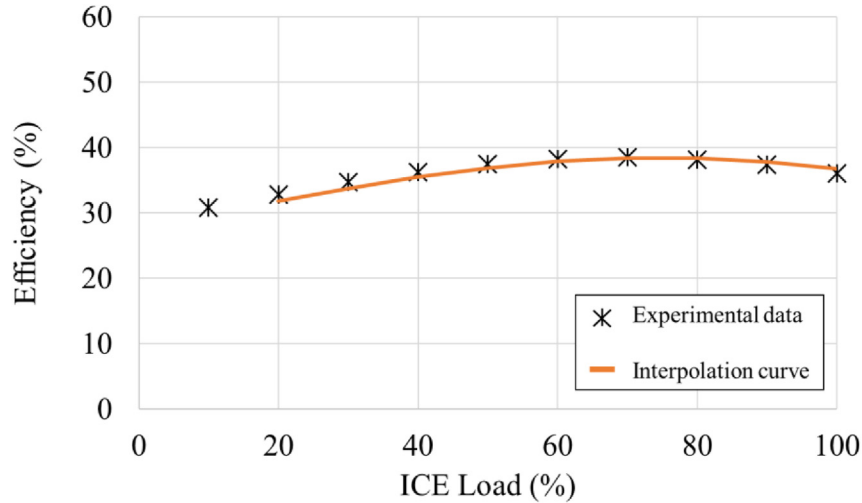


Fig. 5 – Characteristic curve of ICE. Experimental data and interpolation curve used in the simulation model [38].

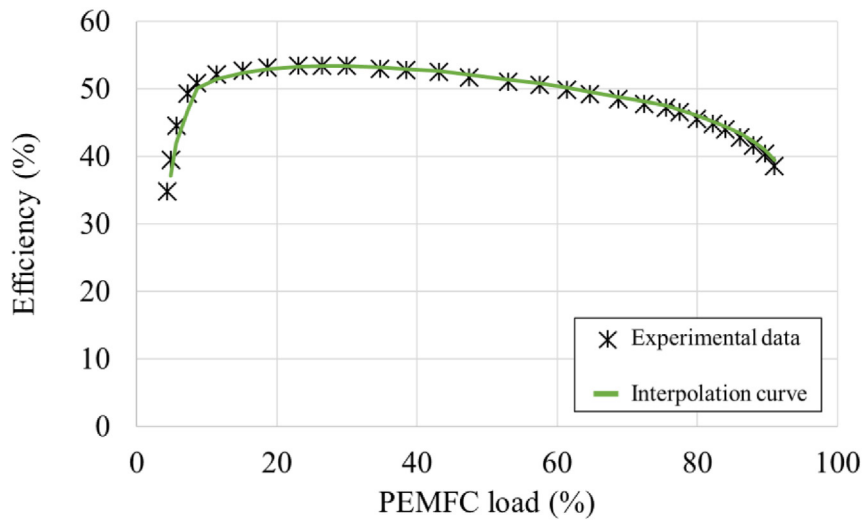


Fig. 6 – Characteristic curve of PEMFC. Experimental data and interpolation curve used in the simulation model [39].

where V_{batt} is the rated voltage of the battery pack. If $Crate$ exceeds the peak value, $Crate_{max}$, the capacity of the battery is increased.

For the considered case study, Li-ion batteries have been considered. Table 4 reports the main characteristics for the chosen batteries, with reference to commercial products available for marine applications [42].

The H_2 consumption for 24 h of operation is determined as:

$$M_{H_2} = \frac{\int_{T_0}^{T_{end}} P_{FC}(t) dt}{LHV_{H_2} * \eta_{FC}} \quad (13)$$

where LHV_{H_2} is the Lower Heating Value of H_2 (120 MJ/kg). The overall efficiency of the system is therefore calculated as:

$$\eta_{tot} = \frac{\int_{T_0}^{T_{end}} P_{demand}(t) dt}{M_{H_2}} \quad (14)$$

Model description: no peak shaving strategy

If no peak shaving is provided by batteries, and assuming that no plug-in power is supplied to the ferry neither during the day nor in the night, the main engine (either PEMFC or ICE) must fulfill the power demand at each time step t:

$$P_{engine}(t) = P_{demand}(t) \quad (15)$$

At each time step, the efficiency of the engine η_{engine} is calculated as function of the engine load (Figs. 5 and 6):

$$\eta_{engine}(t) = f(load(t)) \quad (16)$$

$$load(t) = \frac{P_{engine}(t)}{P_{engine,max}} \quad (17)$$

where $P_{engine,max}$ is the installed power of the main engine, fixed at 110% of the maximum P_{engine} if FC are considered. If ICE is the main engine, reference is made to the currently installed power of the ferry (see Table 3), divided by an electrical efficiency of 95%.

The fuel consumption (either H_2 or MGO) for every 24 h of operation and the global efficiency of the system are therefore calculated as.

$$M_{fuel} = \frac{\int_{T_0}^{T_{end}} P_{engine}(t) dt}{LHV_{fuel} * \eta_{engine}} \quad (18)$$

$$\eta_{tot} = \frac{\int_{T_0}^{T_{end}} P_{demand}(t) dt}{M_{fuel}} \quad (19)$$

where LHV_{fuel} for MGO is equal to 42.7 MJ/kg.

Emission calculations for the reference scenario

For the reference MGO + ICE scenario, CO_2 , NO_x , SO_x and PM local emissions for 24 h of operation are determined based on the fuel consumption. Table 5 reports the emission factors used in the calculations for MGO + ICE plant layouts, while for CH_2+LT -PEMFC there are no local emissions [43]. The last

Table 4 – Li-ion batteries characteristics.

Parameter	Value	Unit
C-rate peak	6C	h^{-1}
C-rate continuous	3C	h^{-1}
Voltage single pack	1000	V
Nominal rated capacity single pack	60	Ah
Maximum state of charge (SOC)	90	%
Depth of discharge (DOD)	80	%

Table 5 – Emission factors for MGO fuel [43,44].

Substance	Emission factor	Emission reduction with SCR and scrubber
CO_2	3206 g_{CO_2}/kg_{fuel}	–
NO_x	48.96 g_{NO_x}/kg_{fuel}	85%
SO_x	2.64 g_{SO_x}/kg_{fuel}	97%
PM	1.02 g_{PM}/kg_{fuel}	70%

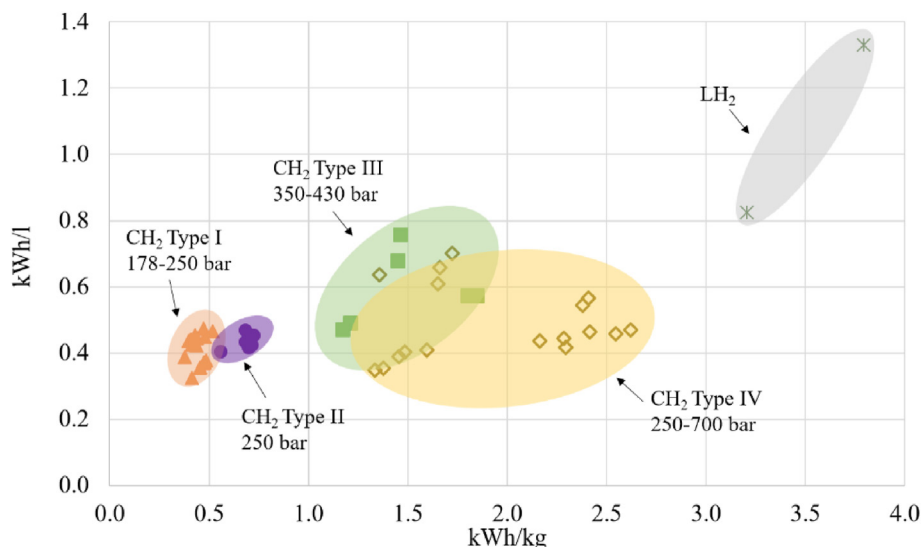


Fig. 7 – Volumetric and gravimetric energy density of CH₂ and LH₂ containment systems. Points in the diagram refer to the analyzed market solutions [45–50].

column of Table 5 reports the reduction in percentage of CO₂, NO_x and SO_x emissions obtainable with SCR and scrubber, as reported in Ref. [44].

H₂ storage solutions

For CH₂+LT-PEMFC configurations, the required volume and weight of the fuel storage system have been evaluated. Different types of available CH₂ cylinders [45–50] have been analyzed in order to define the typical energy densities for the storage systems considered in the simulations. Fig. 7 shows the results of such analysis, while Table 6 reports the energy density values assumed in the calculations.

Gravimetric energy densities in Table 6 refer to the weight of empty cylinder. Volumetric energy densities refer to the external volume of the cylinders. Type I cylinders at 250 bar have been considered because they have, today, the largest market share. In any case they cannot tolerate pressure higher than 300 bar [51]. In order to overcome the problem of the high weight of such tanks, Type IV composite cylinders at 250 bar have also been considered. Type III cylinders at 350 bar, though more expensive than Type I cylinders, have been already implemented on board of CH₂ fuelled vessels and thus represent a short term solution. Lastly, Type IV cylinders at 700 bar have been considered as they are, to day, the solution with the highest volumetric energy density.

Table 6 – Gravimetric and volumetric energy densities assumed for the different types of CH₂ cylinders.

	Type I at 250 bar	Type IV at 250 bar	Type III at 350 bar	Type IV at 700 bar
Gravimetric energy density (kWh/kg _{tank})	0.29	1.32	1.08	1.58
Volumetric energy density (kWh/l _{tank})	0.29	0.29	0.39	0.65

In order to take into account the effective volume occupied by the cylinders once installed on board, a utilization factor of 50% has been introduced. The utilization factor is defined as the ratio between the cylinders external volume and the actual volume occupied on board by the containment system.

Definition of operative profile

In order to determine the applicability of a CH₂+LT-PEMFC on the vessel in different operative conditions, simulations have been performed for three typical power profiles, further referred to as Case 1, Case 2 and Case 3. Table 7 reports travel data for each case. Maneuvers of entry/exit from the port have not been included in the operative profiles.

Fig. 8 shows the single trip power demand of Case 1, which refers to the current operational profile of the ferry. Auxiliary power demand is 25 kW, constant during the 24 h. Propulsion power demand is determined according to the vessel speed data. In Case 1, the total travel time is 5 min, three at full power and two at half power load. The ferry operates 24 h nonstop, seven days per week.

Table 7 – Number of trips per day, travel distance, travel duration and time spent at harbour between two consecutive voyages for the different operational profiles considered.

	N° trips per day	Single trip distance (km)	Single trip sailing duration (no harbour) (min)	Time spent at harbour between two consecutive voyages (min)
Case 1	72	1.4	5	15
Case 2	41	5.6	20	15
Case 3	19	16.7	60	15

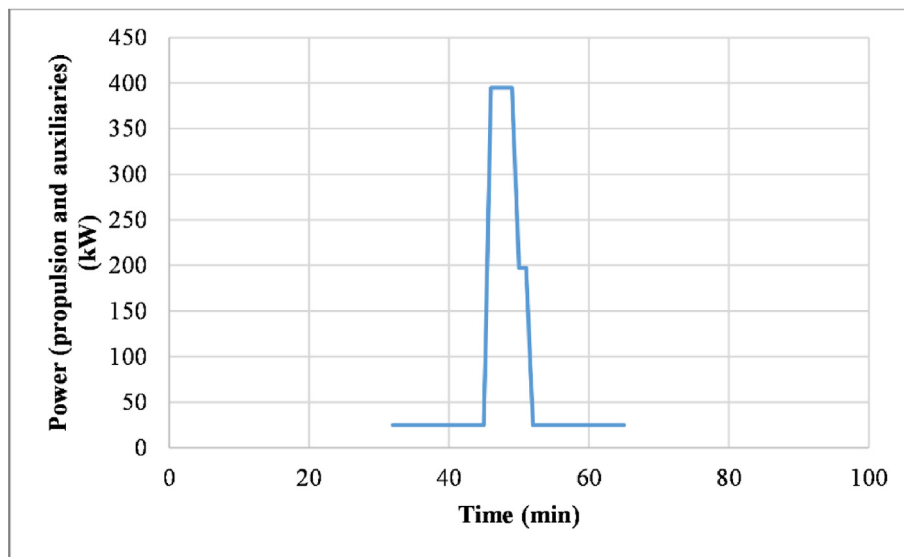


Fig. 8 – Single trip power demand profile in Case 1.

Fig. 9 and Fig. 10 show, respectively, propulsion and auxiliary power demand for Case 2 and Case 3. In both cases, it is assumed that the vessel operates 24 h a day, seven days a week. As in Case 1, the auxiliary power demand is considered to be 25 kW, constant during the 24 h. Sailing time has been extended to 20 min and 60 min in the two cases.

The next paragraph reports the simulation results obtained with the different plant architectures evaluated for Case 1, Case 2 and Case 3 operative profiles.

Simulation results

Simulation results for the reference case MGO + ICE without SCR and scrubber are reported in Table 8. Consider that the

emissions reported in the table represent also the emissions avoided when opting for CH₂+LT-PEMFC propulsion system, with CO₂ and NO_x savings of up to 4109 kg/day and 62.8 kg/day, respectively (see Case 3).

Table 9 and Table 10 report the main simulation results for CH₂ + LT-PEMFC plant architecture with and without peak shaving. In all the scenarios shown in Table 9, FC systems increase the overall efficiency by 10–15% with respect to MGO + ICE architecture reported in Table 8.

Batteries peak shaving leads to H₂ consumption reduction only in Case 1, although also in this case the reduction is negligible (2%). However, in all cases, peak shaving allows a reduction of the FC installed power leading to an overall simplification of the system. In particular, in Case 1 number of FC stacks is reduced from four to two stacks and in Case 2 the

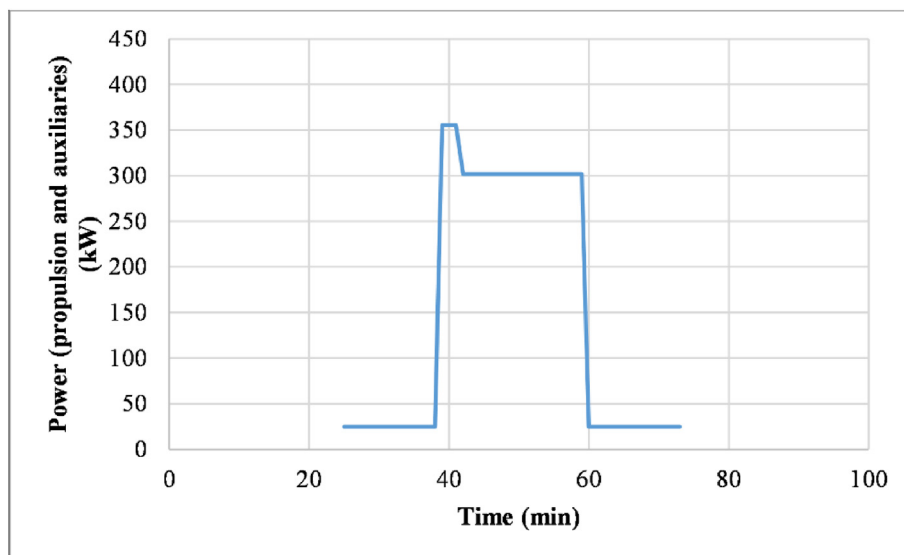


Fig. 9 – Single trip power demand profile in Case 2.

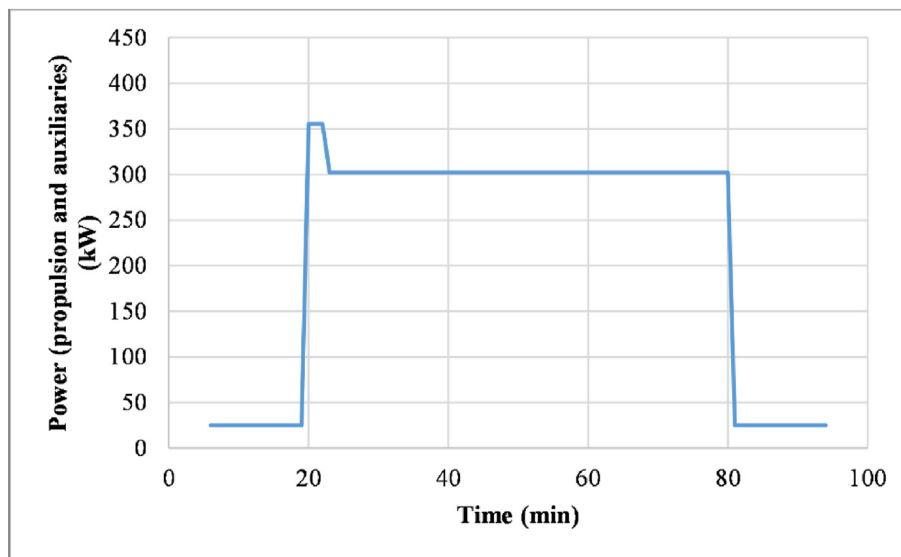


Fig. 10 – Single trip power demand profile in Case 3.

Table 8 – Simulation results for the reference case MGO + ICE without SCR and scrubber.

Operative profile	MGO consumption (kg/day)	MGO consumption (m ³ /day)	CO ₂ emissions (kg/day)	NO _x emissions (kg/day)	SO _x emissions (kg/day)	PM emissions (kg/day)	Overall LHV efficiency (%)
Case 1	581	0.684	1864	28.5	1.53	0.59	35.5
Case 2	1032	1.214	3308	50.5	2.72	1.05	37.6
Case 3	1282	1.508	4109	62.8	3.38	1.31	38.0

number of FC stacks is reduced from four to three. In Case 3, instead, the number of FC stacks does not change. However, it must be pointed out that these results refer to FC stacks with a fixed rated power of 120 kW. Indeed, in Case 3 the maximum FC load is reduced from 75% without peak shaving to 54% with peak shaving, meaning a potential reduction of FC installed power from 360 kW to 260 kW. In general, it can be inferred that peak shaving is beneficial especially for operative profiles as the one proposed in Case 1, with short and frequent voyages. Thanks to the peak shaving, in such cases the FC installed power can be reduced up to 72%. Further analysis

should take into account different sizes of FC stacks according to the specific operative profile. The trade-offs between the partial load operations to increase FC efficiency, the FC stack rated power and the capital cost of the plant should also be evaluated.

Table 10 reports the simulation results with reference to the calculation of H₂ storage system volume and weight. Volumes take into account a utilization factor of 50%, as defined in the previous section. It can be noticed that the utilization of the small size RoRo ferry for covering short and frequent routes (Case 1) potentially allows the use of

Table 9 – Simulation results for CH₂+LT-PEMFC plant architecture with and without peak shaving. Rated power of single FC stack assumed to be 120 kW.

Operative profile	Scenario	H ₂ consumption (kg/day)	N° of fuel cell stacks 120 kW each (-)	FC load max (%)	Average power demand (kW)	Overall LHV efficiency (%)
Case 1	Peak shaving	149	2	45.7	102	49.1
	No peak shaving	152	4	83.0	102	48.3
Case 2	Peak shaving	288	3	57.3	192	48.0
	No peak shaving	276	4	75.0	192	49.8
Case 3	Peak shaving	359	4	54.0	241	48.3
	No peak shaving	343	4	75.0	241	50.5

Table 10 – H₂ volume and cylinders volume and weight for CH₂+LT-PEMFC plant architecture with and without peak shaving. Storage volume values include a space utilization factor of 50%.

Operative profile	Scenario	H ₂ volume (m ³)		H ₂ energy (kW/h)	Type I cylinder (m ³)		Type I cylinder (kg empty)		Type IV cylinder (m ³)		Type IV cylinder (kg empty)	
		250 bar	350 bar		250 bar	700 bar	250 bar	700 bar	250 bar	700 bar	250 bar	700 bar
Case 1	Peak shaving	8.47	6.38	4971	17	17	17	17	17	17	3759	3153
	No peak shaving	8.64	6.51	5071	17	17	17	17	17	17	3835	3216
Case 2	Peak shaving	16.36	12.34	9608	33	33	33	33	33	33	7265	6094
	No peak shaving	15.68	11.83	9207	31	31	31	31	31	31	6963	5840
Case 3	Peak shaving	20.4	15.38	11 976	41	41	41	41	41	41	9057	7596
	No peak shaving	19.49	16.69	11 442	39	39	39	39	39	39	8653	7258

Type I cylinders at 250 bar, the cheapest and most mature technology available today. Indeed, the relatively low storage pressure achievable with Type I cylinders (<300 bar), though being an advantage in terms of safety and energy required for CH₂ compression, limits the utilization of such tanks to operative profiles with low energy demand. Therefore, Type I cylinders at 250 bar are not suitable for Case 2 and Case 3. In addition, if Type I cylinders are considered, it must be noted that the low gravimetric energy density of such tanks lead to high weight of the storage system on board. A possible solution to this issue could be the utilization of lighter tanks, for instance Type IV, at 250 bar. The latter, though requiring the same volume of Type I cylinders, allow for a reduction of the system weight of 78%. Type IV cylinders at 250 bar, however, do not solve the storage issue for Case 2 and Case 3, where the high volume required by the CH₂ containment system could not be bearable in terms of payload reduction.

As a consequence, storage pressure must be higher for longer ferry routes. Table 10 shows that if Type III cylinders at 350 bar are chosen for Case 2, the storage volume would be 24% lower than the Type 1 solution. As for Case 3 operative profile, if Type IV cylinders at 700 bar are used a volume reduction of 39% compared to Type III at 350 bar can be achieved. The 700 bar solution, however, though being state of the art technology for automotive applications, have not yet been applied on board of vessels and have higher costs than other types of cylinders.

Conclusions

In the paper an overview on 44 marine FC projects is presented. The analysis pointed out how operative FC installations (17 out of 44 projects) have installed power lower than 400 kW. Accordingly, if FC systems are used for propulsion purposes, they refer to small size vessels. LT-PEMFC have the largest utilization (28 projects) mainly using compressed hydrogen as logistic fuel (21 over 28). For these reasons, it has been chosen to analyze, using a process simulation model, the applicability in terms of fuel storage volume for a CH₂+LT-PEMFC power plant used in a 40 m long RoRo car and passenger ferry. Configurations with and without Li-ion batteries for peak shaving have been analyzed.

Three typical operative profiles, with sailing time of 5–20–60 min and named Case 1-2-3 respectively, have been considered. For each scenario, CH₂ storage volumes have been determined for different types of cylinders.

The simulation results show that the CH₂+LT-PEMFC power plant can potentially increase the overall system efficiency of more than 10% points with respect to the reference case of MGO fed ICE. Moreover, the proposed energy system could guarantee zero local emission propulsion, with a reduction of CO₂ emissions up to about 4000 kg/day (Case 3, longer travel duration) with respect to the reference case.

In the considered hypothesis, batteries peak shaving solution allows a reduction of the FC installed power. This advantage is evident for Case 1, where the number of FC

stacks is reduced from four to two units, with an overall reduction of FC installed power of about 72%. It is concluded that battery peak shaving is especially convenient for vessels that operate short and frequent voyages. With regards to CH₂ storage on board, the results show that the most mature solution, Type I cylinders at 250 bar, is feasible only for short distance operative profiles (Case 1, sailing time 5 min). For longer travel times, i.e. Case 2 and 3, Type I cylinders at 250 bar would lead to storage volumes that could not be bearable in terms of payload reduction. Type 4 cylinders at 700 bar represent instead an interesting solution for sailing times up to 60 min (Case 3). Such solution, however, suffers of high costs and low technology maturity in the maritime sector. Further analyses are required to study the trade-offs between the FC stacks rated power, capital costs and the fuel economy obtainable at FC partial load operation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 11 – Operative marine fuel cell projects.

Project name	Country and period	Vessel and project description	Energy system, logistic fuel, fuel storage	Partners and funding	Ref.
Water Go Round Golden Gate Zero Emission	USA end in 2020	Speed ferry length 21 m. Batteries in hulls to provide boost power to reach peak speed of 22 knots. Ship is under construction	360 kW LT-PEMFC 100 kWh en. storage CH ₂ 264 kg (12 × 22 kg), 250 bar; up to two days of operation.	Golden Gate Zero Emission Marine, Switch Maritime, California Air Resources Board, Bae Systems, Bay Area Quality Management District, Bayship, Hexagon Composites, Hydrogenics, Incat Crowther, Marsec, Port Of San Francisco, Red And White Fleet, Palmet Johnson Power Systems, Sandia Labs	[52,53]
Greenfuel project,	Germany end in 2017	Small size river ferry; FC charge batteries that power electrical motors for propulsion and auxiliary electrical loads (lights/galley stove). Vessel successfully operated in 2016.	35 kW HT-PEMFC 100 kWh en. storage MeOH	Innogy, Serenergy	[54,55]
Busan tourist boat	South Korea, end in 2016	Tourist boat, length 20 m. If power demand <40 kW FC alone supply the power. Ship operated in 2016 at a maximum speed of 7.5 knots; estimated that from 7.5 knots to 15 knots the power output should increase from 86 kW to about 688 kW.	56 kW LT-PEMFC 47 kWh Li-ion battery CH ₂ 14 type III cylinders, 25 kg of H ₂ in total; 350 bar	No data found	[56]
Hydrogenesis	UK, since 2012	Small passenger boat 12 passengers, 11 m length. The vessel was tested under seasonal operating conditions on a six month trial.	12 kW LT-PEMFC no data on en. storage CH ₂ 350 bar; tank filled every 4 days.	Bristol Hydrogen Boats, A Local Consortium Formed By The Directors Of Bristol Packet Boat Trips, Number Seven Boat Trips And Auriga Energy, Air Products	[57,58]
MultiSchiBZ (e4ships consortium)	Germany 2018-20	Follow up of SchiBZ project on large cargo ship MS Forester; the main goal is to optimize the reforming process in order to introduce LNG as fuel.	50 kW SOFC Low Sulphur diesel (15 ppm),	ThyssenKrupp Marine Systems Hülsebusch, Öl-Waerme-Institut, LUH-IfT, LUH-IfES, Rosswag, Sunfire, TEC4FUELS, ZBT Total budget: 9.838.072 €, Funds: 7.164.821 €	[59,60]

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Table 11 – (continued)

Project name	Country and period	Vessel and project description	Energy system, logistic fuel, fuel storage	Partners and funding	Ref.
Kamine boat	Japan, 2015-18	Small size boat, 16.5 m long, 17 tons, 50 kW installed for propulsion; boat was successfully tested under maritime loads and conditions.	60 kW LT-PEMFC 60 kWh Li-ion battery CH ₂	Yanmar Co Ltd, National Maritime Research Institute, Japan Ship Technology Research Association	[61,62]
Nemo H2	Netherlands, 2008-11	Boat passenger fluvial operation, 88 passengers. First operation in 2009, but then never operated as public transport due to lack of fueling infrastructure.	60–70 kW LT-PEMFC 55 kW Lead acid battery CH ₂ 350 bar, 24 kg	Fuel Cell Boat Bcv, TU Delft, Ministry Of Economic Affairs, City District Amsterdam North	[63]
SMART H2	Iceland/Canada, 2007-10	Whale watching boat 155 passengers, 125 ton; Fuel cells APU to allow ICEs switch off during whale watching; First operation in 2008.	10 kW LT-PEMFC CH ₂	Icelandic New Energy, Ballard Total cost of project estimated to be 6.5–8 M€	[31,64,65]
METHAPU Undine	Sweden, 2006-10	Car carrier Undine. APU demonstrator successfully tested on board.	20 kW SOFC demonstrator (250 kW APU) MeOH	Wärtsilä Finland Oy, Wärtsilä Corporation, Lloyd' S Register, Wallenius Marine, Universita' Degli Studi Di Genova, Det Norske Veritas Total budget: 1.930.300 €, EU contribution: 1.000.000 €	[66,67]
Race for water	Switzerland, 2015-21	Small boat. Length 30 m, breadth 16 m. PV panels (512 m ²) charge batteries and power a desalination unit that produces water to obtain H ₂ through an electrolyzer (50 bar), then compressed to 350 bar 41 m ² self-piloting kite enhances the propulsion. Still ongoing.	60 kW LT-PEMFC 745 kWh Li-ion battery CH ₂ 350 bar, 200 kg;	Breguet, Plastic Omnium, Etia Ecotechnologies, Skysails Yacht	[68]
Pa-X-ell (e4ships consortium)	Germany 2009-16	Cruise ferry MS Mariella, length 177 m, breadth 28 m; in operation since summer 2016; FC cover hotel load; absorption refrigeration cycle coupled with FC to recover waste heat. FC on sun deck.	60 kW HT-PEMFC MeOH tank filled by a tanker truck onshore.	Serenergy A/S, Fr. Lürssen Werft, DLR, Dnv Gl, Besecke, Carnival Maritime, Epea Internationale Umweltforschung Total budget: 23.503.238 €, Funds: 11.281.553 €	[69–71]
Energy observer	France, 2017-24	Catamaran, length 30.5 m, breadth 12.8 m 371 h of FC operation in 2018, with 48% power output (target 65% with heat recovery); still ongoing. H ₂ produced and compressed onboard;	22 kW LT-PEMFC 140 kWh Li-ion battery CH ₂ 62 kg, 8 cylinders at 350 bar; H ₂ +FC 1700 kg.	Accor, Thelem Assurances, Delanchy, Engie	[72]
ZEMSHIP FSC Alsterwasser	Germany 2006-13	Inland passenger ship 25.46 m long, 1.33 m draft, 5.36 m width, 2.65 m height over water. Up to 100 passengers. Ship was successfully operated.	100 kW LT-PEMFC Lead gel battery (360 A h, 560 V) CH ₂ 50 kg; 350 bar; 3 days of operation.	Proton Motors, M Gl, Alster Touristik, Linde, Hochbahn, Ujv, Hy Solutions, Hamburg University For Applied Sciences, Total budget: 5.158.348 €, EU contribution: 2.384.424 €	[73,74]
SchiBZ (e4ships consortium)	Germany 2009-19	Large size cargo ship MS Forester. FC for on board power supply in operation for >20 000 h; recovery of exhaust gas energy encompassed in the system.	50 kW SOFC Low sulphur diesel (15 ppm s)	Öl-Waerme-Institut, Sunfire, M&P, DNV GL, Leibnitz Universität, Rörd Brare Total budget: 13.687.446 €, Funds:8.072.158 €	[69–71,75]
Fellowship Viking Lady	Norway, 2003-18	Medium size off shore supply vessel. APU on board was	320 kW MCFC LNG	Eidesvik Offshore, Wartsila, DNV	[76–78]

Table 11 – (continued)

Project name	Country and period	Vessel and project description	Energy system, logistic fuel, fuel storage	Partners and funding	Ref.
		successfully operated with overall efficiency based on LNG LHV 52.1%.		Total budget: 21.000.000 \$ (115 million NOK), 55% covered by industry partners, 45% funding (Research Council of Norway, Innovation Norway, German federal ministry of Economics and technology)	
US-SSFC	USA, 2000-11	Naval application. MCFC tested on land and one module tested on board. PEMFC only concept design. Fuel processing unit to fuel PEMFC tested on land. Further scale up limited by volume and complexity.	2500 kW MCFC (625 kW tested on board) PEMFC concept Diesel	Office Of Naval Research (Onr, U.S. Department Of Defence)	[12]
Cobalt 233 Zet	Germany since 2007	Small sport boat. Originally only batteries, then partially replaced by fuel cells.	24 kW LT-PEMFC no data on en. storage, but included for peak shaving CH ₂	Zebotec, Brunnert-Grimm Germanischer Lloyd for certification	[12,79,80]

Table 12 – Non-operative marine fuel cell projects

Project name	Country and period	Vessel and project description	Energy system, logistic fuel, fuel storage	Partners and funding	Ref.
Aero 42	Norway, end in 2023	Pax ferry, length 42.8 m, breadth 11.8 m; 275 passengers. Installed propulsion power 2 × 1300kW; 90 kg of H ₂ + 403 kWh electrical energy for round trip.	2800 kW LT-PEMFC 672 kWh Li-ion battery CH ₂ 612 kg, 250 bar (4 × 154 kg tanks)	Wstcon Automation, Boreal, Arena Ocean Hyway Cluster, Brodrene Aa	[81,82]
e5 tug	Japan, end in 2022	Tugboat, 50 tons. Batteries are the main source of energy, FC auxiliary together with a LNG genset for open sea operation. Tug expected to be commercialized in 2022.	no data yet on energy system H ₂ (no data if compressed or liquid)	Tokyo Kisen Co., Ltd., e5 Lab Inc	[83]
Future Proof Shipping	Netherland/ Belgium, end in 2021	Retrofit inland container vessel (msc Maas), length 110 m, breadth 11.5 m electric propulsion; batteries for peak shaving, emergency, bridging power. Tests ongoing.	635 kW LT-PEMFC 300 kWh Li-ion CH ₂ ; 1160 kg of H ₂ per round trip; 300 bar; two storages above the battery room.	CCNR, Holland Shipyards Group, Future Proof Shipping, Interreg Northsea, Kwr Allied Waters	[84]
Norled-Ryfylke	Norway, end in 2021	Cars and pax ferry; length 82.4 m, breadth 16.8 m; 299 passengers, 10 trucks and 80 cars BLUE Energy optimization	400 kW LT-PEMFC no data on en. storage LH ₂ 150 kg daily consumption; cryogenic tank: multilayer-vacuum, 10 bar, 3.8 tons (about 20% ullage), standard approval DNV GL IGF code; holding time 15 days;	Linde, Ballard, Norled, Westcon Power And Automation, Open Bridge Partner, Sintef, Lloyd Register	[85,86]

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Table 12 – (continued)

Project name	Country and period	Vessel and project description	Energy system, logistic fuel, fuel storage	Partners and funding	Ref.
GKP7H2-MoZEEES program	Norway, since 2019	High speed ferry, length 30 m; 100 passengers;	on the top deck, together with FC 1200 kW LT-PEMFC no data on en. storage CH ₂ , 250 bar; storage on top roof	Norwegian R&D Institution Ife (Total Of 40 Partners). Total budget of MoZEEES program: 24.000.000 €	[87,88]
Zero V	USA, 2017	Zero V research vessel, length 52 m, breadth 17 m, draught 3.6 m; 15 days endurance. FC and batteries cover both propulsion and auxiliary load; propulsion: 2 × 500kW motors Concept design completed.	1800 kW LT-PEMFC no data on en. storage LH ₂ 1100 kg; 2 × 28800gal type C vacuum insulated tanks on top deck; 70.5% of stored H ₂ volume consumable	Sandia National Laboratories, Glosthen, The Scripps Institution Of Oceanography San Diego, Dnv Gl	[89]
Hornblower hybrid	USA, since 2012	Small size ferry 168 ft length, 40 ft width up to 600 passengers; diesel generator, batteries, wind, PV panels and FC included.	32 kW LT-PEMFC no data on en. storage CH ₂	Hornblower	[12]
NEW-H-SHIP	Iceland, 2004-05	In addition to PEMFC, feasibility study on the application of 625 kW MCFC fuel cells for APU on board.	feasibility studies on LT-PEMFC and MCFC no data on en. Storage no data on fuel storage	Leading partners: Icelandic New Energy Ltd, Norwegian Marine Technology Research Institute, Det Norske Veritas Germanischer Lloyd, Total budget: 544.874 €, EU contribution: 295.582 €	[90–92]
Humphry Marine (e4ships consortium)	Germany 2019-20	Inland speed boat; prototype currently undergoing testing and optimization phase in laboratory; the startup, based in Berlin, is investigating also the possibility to transfer the application on other boat types.	LT-PEMFC no data on en. storage H ₂ (no data if compressed or liquid)	TU Berlin, Dnv-Gl, Fsg Flensburgship Company, Hadag Seetouristik Und Fährdienst, Helm, Hoppecke Batteries, Meyer Werft, Neptun Werft, Pella Sietas, Serenergy A/S, Viking Technical, Zeppelin Power Systems	[93]
Zeff (part of Pilot-E scheme)	Norway, 2018-20	Small size fast ferry; length 37 m, breadth 14 m, 275 passengers; cruise speed 24–25 knots; five concepts proposed in 2019.	2200 kW LT-PEMFC 50 kWh en. storage, type under evaluation; CH ₂ ,	Selfa Artic, Lmg Marin, Hyon, Norled, Servogear	[94–96]
FCSHIP	Norway, 2002-04	Two vessels: River ferry (2 × 253 kW of installed power) RoPax 32 MW prop power, 3 MW APU. Design concepts developed.	LT-PEMFC/SOFC/MCFC: 400 kW for river ferry CH ₂ for river ferry 1 MW APU for RoPax Low sulphur diesel oil, LNG or LH ₂ for RoPax	Leading partners: Norwegian Shipowners Association, Ansaldo Fuel Cells Total budget: 2.545.501€, EU contribution: 1.402.563€	[97]
FLAGSHIPS (France)	Norway and France, 2019-22	Small size river push boat; new built prototype to be tested in 2021.	400 kW LT-PEMFC en. storage under evaluation CH ₂	Lmg Marin, Norled, CTF, Ada Shipyard For Building No Ships, ABB, Kongsberg Maritime, Greenstat, Westcon Power & Automation, Prototech, Nce Marine Technology, Ballard Europe, Pers-Ee Total budget: 7.000.000 €	[98,99]
FLAGSHIPS (Norway)	Norway and France, 2019-22	Medium size passenger and car ferry; 199 passengers, 60 cars or 6 trucks; prototype to be tested in 2021.	600 kW LT-PEMFC 0-500 kWh en. Storage, under evaluation CH ₂ 250 bar; 460 kg	Lmg Marin, Norled, CTF, Ada Shipyard For Building No Ships, ABB, Kongsberg Maritime, Greenstat, Westcon Power & Automation, Prototech, Nce	[98,99]

Table 12 – (continued)

Project name	Country and period	Vessel and project description	Energy system, logistic fuel, fuel storage	Partners and funding	Ref.
Ulstein SX190 Zero Emission DP2	Norway, 2019-22	Offshore vessel, 99 m long, 23.4 m breadth, 6 m draught, 5000 tons; 2 × 1280 kW propulsion thruster and 2 × 750 kW tunnel thrusters.	daily consumption, 600 kg total capacity 2000 kW LT-PEMFC no data on en. storage CH ₂ Removable storage system for easier bunkering	Marine Technology, Ballard Europe, Pers-Ee Ulsteiin Design and Solutions, Dnv GI, Nedstack	[100,101]
FreeCO2ast (part of Pilot-E scheme)	Norway, 2018-21	RoRo freight and passenger ferry; length 122.7 m, breadth 22 m; first of four ships to enter in service in 2021.	3200 kW LT-PEMFC no data on en. storage LH ₂ total capacity 3500 kg	Havyard Group Powercell, Linde, Havila Kystruten, Norwegian Control Systems, Sintef Total budget: 9.150.000 €	[102–104]
Hyseas III	Scotland 2018-21	RoRo ferry, 16 cars, 120 passengers, length 120 m, breadth 10 m. The aim of the project is to operate the complete powertrain on land before 2021, then to implement it on board of the ferry.	700 kW LT-PEMFC Li-ion, no data on capacity 2000 kg H ₂ no data if liquid or compressed.	Ferguson Marine Ballard, University Of St Andrews, Kingsberg, Mcphy, DLR, Interferry, Orkney Ferries Total budget: 12.579.610 €, EU contribution: 9.276.373 €	[105,106]
FELICITAS	Germany 2005-08	Heavy duty applications: trains, truck and marine considered. SOFC were tested by simulations and partly by experimental tests, but never operated on board. Reformer for LPG was also studied;	250 kW SOFC + LNG 80 kW LT-PEMFC + CH ₂ evaluated	Leading partner: Fraunhofer Institute For Transportation And Infrastructure Systems Total budget: 12.559.523 €, EU contribution 7.943.597 €	[107]
DESIRE	2001–04	Study on diesel reforming process to feed fuel cells, which are not considered themselves in the study. The reference power is 250 kW. Fuel cells development was not considered in the project.	25 kW MCFC demonstrator also LT-PEMFC evaluated Low Sulphur diesel (F76 NATO)	Energy Research Center Of The Netherlands (Ecn) Ministries of defence of Netherlands, Germany, Turkey and UK financed the project.	[108,109]
MARANDA	Finland, 2017-21	Medium size research vessel (3000 kW installed propulsion power, 550 kW thrusters); FC for ship's electrical equipment and dynamic positioning during measurements.	165 kW LT-PEMFC en. Storage under evaluation CH ₂ 350 bar; 83 kg total capacity	Teknologian Tutkimuskeskus Vit Oy, Powercell Sweden Ab, Abb Oy, Omb Saleri, Pers-Ee, Suomen Ymparistokeskus, Swiss Hydrogen Sa, Total budget: 3.704.757 €, Funds: 2.939.457 €	[110,111]
Rivercell1 and Rivercell2 (e4ships consortium)	Germany 2017-21	River cruise ship; Hotel and propulsion baseload covered by fuel cells, batteries for load peaks, diesel gensets for high propulsion loads current status: system design, goal to reach production ready technologies.	250 kW HT-PEMFC no data on en. storage MeOH (LNG optional)	TU Berlin Dnv-GI, Fsg Flensburgship Company, Hadag Seetouristik Und Fährdienst, Helm Ag, Hoppecke Batteries, Meyer Werft, Neptun Werft, Pella Sietas Gmbh, Serenergy, Viking Technical., Zeppelin Power Systems Rivercell: Total budget: 4.177.941 €, Funds: 2.125.598€ Rivercell2: Total budget 3.632.331 €, Funds 1.852.793 €	[34,112]
Pa-X-ell 2 (e4ships consortium)	Germany 2017-21	Follow up project of Pa-x-ell. AIDAnova cruise ship (currently operating on LNG), length 300 m. FC supposed to cover hotel load of seagoing ship. Current status: system design, on board testing planned for 2021.	HT-PEMFC no data on FC power and en. storage yet MeOH (LNG optional)	Meyer Werft, Besecke, Carnival Maritime, DLR, Dnv GI, Epea Gmbh Patr Of Drees & Sommer, Fr Lurssen Werft Total budget: 11.542.077 €, Funds: 6.012.875 €	[35,113]

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Table 12 – (continued)

Project name	Country and period	Vessel and project description	Energy system, logistic fuel, fuel storage	Partners and funding	Ref.
Rødne E-Maran sluttraport	Norway, 2019-23	Three different vessels evaluated in the project: 1.130 passengers, 24 m length, 9.2 m breadth 2.145 passengers, 24 m length, 9.2 breadth 3.190 passengers, 28 m length, 10 m breadth Batteries charged by FC. Concepts ready, real application in 2022–2023	1.500 kW LT-PEMFC 2.625 kW LT-PEMFC 3.750 kW LT-PEMFC LTO en. storage, no data on capacity LH ₂ , Tanks placed on top deck, together with FC parts containing H ₂ ;	Maran, Echandia Marine, Fjellstrand, Scalesia, Maran Utvikling	[87]
SF-BREEZE	USA, 2015-19	Feasibility study of a speed ferry, length 33 m, breadth 10 m; 150 passengers. Only fuel cells to cover power demand of the vessel. Project ended; part of Golden Gate Zero Emission Marine (know-how for Water Go Round project).	4920 kW LT-PEMFC LH ₂ , 1200 kg	Sandia Laboratories, Hydrogenics, Gardner Cryogenics	[114]
ShipFC	Norway, 2020-25	Big size ship, Viking energy (previously the world's first LNG supplied vessel); pilot plant of 100 kW to be built at University of Strathclyde; Wärtsilä responsible for NH ₃ fuel system on board.	2000 kW SOFC no data on en. storage NH ₃	Nce Maritime Cleantech, Eidesvik Shipping, Equinor, Prototech, Yara, Wärtsilä Norway, Fraunhofer Imm, Sme Persee, University Of Strathclyde Glasgow; Total budget: about 10 M€	[115,116]
MC-WAP	Italy, 2005-11	Medium and large vessels individuated for possible applications for fuel cells APU. Tests were performed on an existing MCFC plant.	150 kW MCFC applied (500 kW designed) Diesel	Leading partners: Cetena, Fincantieri, Total budget: 15 947 620€, EU contribution: 9 899 413 €	[117,118]
Elektra and Elektra 2 (e4ships consortium)	Germany, 2017-24	Push boat, length 20 m, breadth 8 m, about 160 tons; accumulators harnessed for peak loads, photovoltaic module 2.7 kW peak; current status: ship design	300 kW LT-PEMFC 2.5 kWh Li-NMC CH ₂ 750 kg; removable structure for bunkering	Leading partners: TU Berlin, Ballard Elektra: Total budget: 1.552.239 €, Funds: 1.178.317 € Elektra 2: Total budget: 13.081.512 €, Funds: 7.973.475 €	[119,120]
Hynovar	France, 2016-21	Small size vessel, length 26 m, 200 passengers. Hybrid battery/fuel cell solution was also evaluated	480 kW LT-PEMFC CH ₂ 260 kg; 350 bar	Hyseas Energy, Bateliers De La Cote Azur, Engie Cofely, Cci Var	[121]

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