The RESHiP Project: Renewable Energy for Ship Propulsion

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Abstract. In recent years the acknowledgement of the relations between the emissions of exhaust gas, in particular CO_2, and their effects on climate and environment has grown to a wide level. Many countries and international organizations have begun to work to mitigate the problem and drive the society towards more sustainable sources of energy. Shipping is no exception and in 2018 the IMO – International Maritime Organization set the ambitious goal of reducing the CO2 emissions of the shipping industries of at least 50% within 2050, compared to the levels of 2008. This has introduced the need to research and develop new, sustainable energy sources and power systems for ships. The RESHiP projects is aimed to identify a type of ship which would be suitable for an early adoption of a carbon free or carbon neutral fuel and a matching power generation system, tailored on specific routes. A small ferry powered by a hybrid combination of liquid hydrogen-fuelled fuel cells and Lithium-ion batteries has thus been identified. A mathematical model was developed to optimize the usage of fuel cell and batteries based on the ship operative profile. A multi objective optimization was implemented to minimize system performance degradation. To support the mathematical model a 7 kW PEMFC power generating unit was assembled and relevant data have been analysed. Following a regulatory framework research and in lack of comprehensive prescriptive rules, the design of the ferry and the prototype was done in accordance with the alternative design approach based on the risk assessment methodology, reaching a level of confidence appropriate to award an approval in principle.

Keywords. hydrogen, fuel cell, alternative fuels, alternative design, zero-emission, hybrid

1. Introduction

Like most, if not all industries, shipping has been pushed toward a reduction of its environmental impact, including emissions of harmful, ozone depleting and greenhouse gases. In recent years the focus has shifted toward the reduction of CO_2 emissions, which are believed to have a substantial impact in the global warming phenomenon and other unfavorable changes in the climate. The International Maritime Organization (IMO) and other regulatory bodies have or are expected to introduce requirements to push for the "decarbonization" of the current fleet and newbuilding [1,2]. Due to the ambitious goals which have been or are expected to be set, the development and optimization of current technologies based on hydrocarbon fuels and rotating machinery are not expected to be enough. New technologies such as carbon free fuels [3], Fuel Cells (FC) [4,5], hybrid technologies [6] are of particular interest to achieve the decarbonization goals but are expected to have a deep impact on the ship design, construction and operation, as well as the ports and fuel supply chain. The adoption of these new technologies is likely to start from the vessels which, due to their characteristics, are the most suitable from the cost and feasibility prospective. On top of that, the type and details of alternative fuel, power and energy storage systems, arrangements on board would also be subject to a detailed analysis to identify the optimal solution. At present day there are few rules and regulations available in the marine sector to cover many of the possible future fuels and power generation and storage technologies, introducing therefore further challenges to be addressed to ensure the safety and reliability of these installations [5,7]. The aim of the REShiP (Renewable Energy Ship Propulsion) project is to identify a suitable vessel and route, a zero-carbon fuel and optimized power generation technology and develop that into a forerunner basic design in compliance with the applicable rules and making use of the available risk assessment work to fill the gaps and ensure the maximum safety.

2. Identification of suitable ship and routes

The most suitable ship type to be developed and arranged with an alternative energy generation system has been identified through an analysis on ship emissions during normal operation phases and on navigation areas of different ship types.

Based on the project aim, ship pollutant and greenhouse gas emissions have been evaluated by specialized institutes during main operation phases (docking, cruising and maneuvering) [8]; the higher emissions have been detected when the vessels are in port, during docking and maneuvering activities. The ships that are found to operate most of the time in latest mentioned conditions are ferries and small passenger vessels which are normally restricted in coastal areas, where pollutant emission requirements are generally more stringent [9].

A secondary analysis has been made on the ship operating profiles, required ship energy, and ship space availability on board. Different ferry dimensions and power requests have been considered in order to identify which could be the most suitable ship design to implement the alternative generation approach. Due to the functioning of the innovative system, the energy analysis outlined that the operating profile with a higher variability, i.e. the one reported in Figure 1, would help to obtain the maximum efficiency from the alternative system. Ship characteristics were evaluated through a decision matrix which assigns positive feedback in case the analyzed ship presents sufficient space on board to arrange the new generation system, highly variable operating profile or limited power demand; on the contrary a negative appraisal was given in case ship characteristics do not match with above mentioned power and spatial requirements, then a null value in assigned when the vessel's data do not particularly affect the choice. The summary of the multi objective analysis is summarized in Table 1.

The results outline that suitable ship dimension, based on the study purpose, are included in the length range of 60 - 90 m. Hence, a ferry size of about 80 m has been considered for the basic design of the innovative vessel.

Table 1. Multi objective decision matrix.

Ship type	Spatial availability onboard	Power demand	Operating profile	Score	Results
Ship 1 (L_{OA} = 42m)	-	+	+	1	Not suitable
Ship 2 (L_{OA} = 58m)	0	+	+	2	Suitable
Ship 3 (L_{OA} = 90m)	+	0	+	2	Suitable
Ship 4 (L_{OA} = 138m)	+	-	0	1	Not suitable

3. Identification of suitable fuel and power generation system and energy system optimization

Once determined the type of ship, i.e. a medium size ferry, the analyses focused on determining the most suitable alternative fuel and power system. Three low-carbon or zero-carbon fuels have been considered in the analysis, namely Natural Gas (NG), hydrogen (H_2) and ammonia (NH_3). NG is already used in shipping, and it is often referred to as the fuel for the transition towards greener shipping [10]. H_2 and NH_3 have been considered as they could potentially guarantee zero-emission navigation and are addressed today as the most promising zero-carbon fuels for future shipping [11]. As for the power system, both solutions based on Internal Combustion Engines (ICE) and Fuel Cells (FC) have been taken into account. Among the different types of FC, Polymer Electrolyte Membrane FC (PEMFC) have been considered, as they are today the most mature technology and have already been implemented on board of ships [12]. Table 2 illustrates the power plant configurations considered for the analysis. It can be noticed that in case NG or NH_3 were used in PEMFC based systems, a fuel processing unit would be needed to obtain H_2 for feeding the PEMFC: a cracker in the case of NH_3 and a reformer in the case of NG.

Table 2. Main characteristics of the selected fuels, storage systems, and relative power systems considered in the analysis. (● = applicable/considered; ○ = not applicable/not considered).

		MGO*	NG	H_2	NH_3
Fuel storage considered	Liquid	●	●	●	●
	Compressed gas	○	●	●	○
Power system considered	ICE-based	●	●	○	●
	PEMFC-based	○	●	●	●
	Fuel processing unit**	○	●	○	●

*reference case

** fuel processing unit in case the fuel is used in PEMFC-based power generation systems

Among the considered options, particular attention has been given to PEMFC based solutions where either H_2 or NH_3 are used as fuel, as these solutions could guarantee the navigation of the ferry with zero local emissions. To this extent, the use of NH_3 as logistic fuel onboard would guarantee easier storage conditions than H_2. Nonetheless, the use of NH_3 would imply the use of a cracking unit to obtain H_2 for feeding PEMFC: while crackers are market ready solutions for stationary applications, marinized solutions are not yet available. Moreover, H_2 obtained from the cracking process may not satisfy the purity requirements of PEMFC, hence resulting in PEMFC poisoning and performance degradation [13]. In addition, NH_3 is a toxic substance and regulations are not yet considering its use as fuel onboard [14]. The use of H_2 implies difficult storage conditions onboard, and also in this case regulations are not yet including the possibility to use H_2 as fuel onboard [15]. However, differently from NH_3, H_2 is not a toxic substance, and it can be directly used to feed PEMFC without the risk of poisoning the membranes. For these reasons, H_2 fed PEMFC has been selected as the most suitable power plant configuration for the REShiP ferry. It has been considered to store H_2 in liquid form (LH_2 – Liquid H_2) to achieve higher volumetric energy density with respect to compressed H_2 storage. A hybrid powertrain has been considered where PEMFC are coupled with an Energy Storage System (ESS). Indeed, hybrid powertrains allow to (i) decrease the installed power of PEMFC onboard, (ii) to use PEMFC in the best operating conditions and (iii) to shave the peaks in the power demand of the vessel [16]. In particular, Lithium-Ion Batteries (LIB) have been considered as ESS as they can reach higher gravimetric energy density with respect to other types of ESS [17], and have already been implemented on board of ships [18]. Despite the advantages of hybrid PEMFC/LIB powertrains, an Energy Management Strategy (EMS) needs to be assessed to determine the optimal power allocation between PEMFC and LIB [19], possibly ensuring the minimum performance degradation of the system over time [20]. To address such issues, a multi-objective optimization model has been developed to define the ferry EMS that concurrently minimizes investment/operation costs and PEMFC degradation. The model has been developed with a mixed-integer linear programming approach, and is able to optimize the design and operation of the ferry energy system over a typical operating day. An extensive description of the methodology along with the set of equations describing the optimization model is available in a previous study by the authors [21]. The optimal sizes of PEMFC and LIB resulted to be of 600 kW and 657 kWh, respectively, while the daily H_2 consumption resulted to be of about 500 kg. Figure 1 shows the optimal operation of the ferry over a typical day of operation.

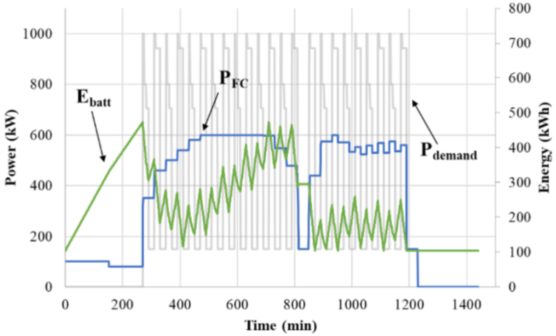

Figure 1. Optimal operation of the hybrid PEMFC/LIB powertrain over a typical operating day of the ferry as resulting from the MILP optimization model described in a previous study by the authors [21]. E_{batt} refers to the energy stored in the LIB at each time step.

4. Basic design of the ship for the alt-fuel system

The double ended ferry is designed to be propelled by a H_2 – PEMFC system. Figure 2 reports the design of the ferry. The design of the system does not have any direct regulatory framework, and the alternative design approach was adopted, using the risk assessment method to study and minimize the risks associated with the installation of the innovative system.

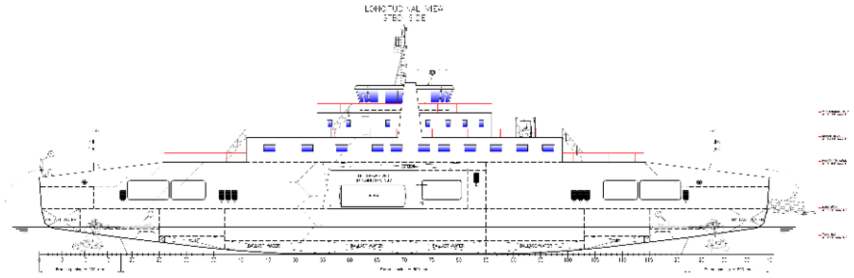

Figure 2. REShiP ferry longitudinal view with side opening for LH_2 tank.

The design of the plant involves rethinking the classic engine room arrangement. The ship's propulsion is full electric, and the heart of the electric power generation are the PEMFC powered by H_2 stored in liquid form and transformed into gaseous form by a vaporizer. The ferry transverse section is reported in Figure 3, where it is reported the detail regarding the H_2 loading. Indeed, the H_2 storage is contained in a 20 ft container and is designed to be handled by a side crane installed on board for the loading and unloading operations. The storage container is provided with a flexible quick connection to the ship fuel supply piping system.

The FC are contained in machinery space below main deck underneath the LH_2 tank in order to minimize pipe runs. As there are no dedicated regulations, the IGF code has been used as a reference. The equipment arrangements are designed to minimize the risks associated with the operation of the system (e.g. suitable cofferdams around the H_2 storage). Access to hazardous areas is carried out by means of airlocks.

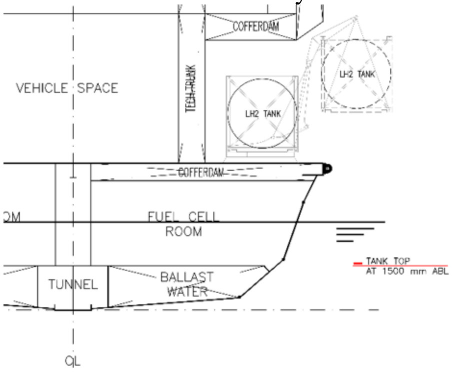

Figure 3. REShiP ferry transverse section, side loading detail.

5. Design and prototyping of the fuel cell

The prototype of the fuel cell system was built by Cenergy at its facility located in Basovizza, AREA Science Park. The prototype is powered by H_2 in gaseous form and guarantees a power of 5 kWe, the stack has the possibility of reaching a maximum power of 7 kWe. Electricity is produced in the PEMFC stack in which the redox reaction between H_2 and oxygen contained in the ambient air takes place. Figure 4 shows the main components of the prototype.

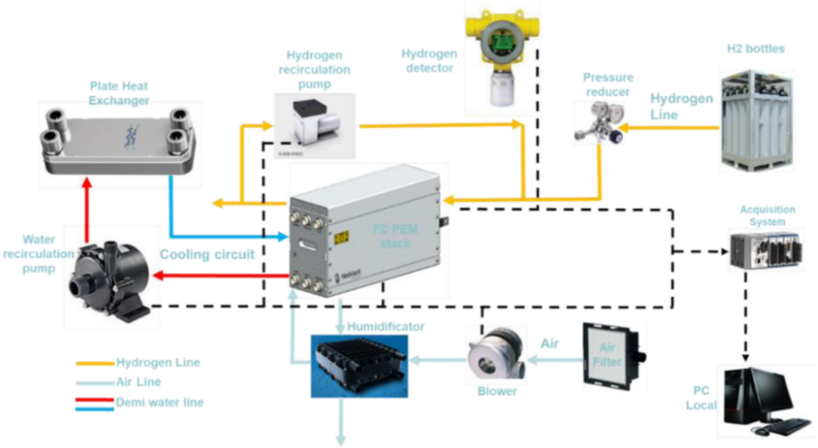

Figure 4. Diagram of the main components of the prototype.

In summary we distinguish: a H_2 circuit, an air circuit, and a water circuit. The H2 circuit is composed of a pressure reducer that allows to regulate the hydrogen pressure at the stack inlet; a recirculation pump that guarantees the correct stoichiometric ratio and the correct humidification of the stack membranes; PRVs that protect the system from eventual overpressures. The air circuit consists of a filter and a blower that sucks air from the environment; a humidifier and two condensate collectors that allow the proper humidification of the membranes of the chimney. The cooling water circuit is composed of a recirculation pump, a heat exchanger and two proportional valves that allow the distribution of the flow between the heat exchanger and a by-pass to ensure the correct temperature of the cooling water entering the cell. All three circuits are equipped with manual and solenoid valves for managing flows and measuring instrumentation (temperature, pressure, flow rate, etc.). The P&ID of the system is shown below in Figure 5.

The prototype is controlled by a National instrument CompactRIo PLC connected via ethernet to a PC. The system receives and records all the data coming from the measuring instruments, also checking that they are within the operating ranges foreseen for the functioning of the prototype and, if necessary, sends alarm signals and/or takes corrective action. Furthermore, the system sends the signals to the various components necessary to control the prototype, allowing the start-up, production of electricity and shutdown of the system to be managed from a PC. The plant has four operating modes: (i) stand by, (ii) electricity generation (including also the start-up phase of the system), (iii) manual control, and (iv) shut-down. In addition, alarm status and the emergency shut-down modes can be activated at any time. The operating modes are initiated and managed by the monitoring and control system, which allows the automatic execution of various operations.

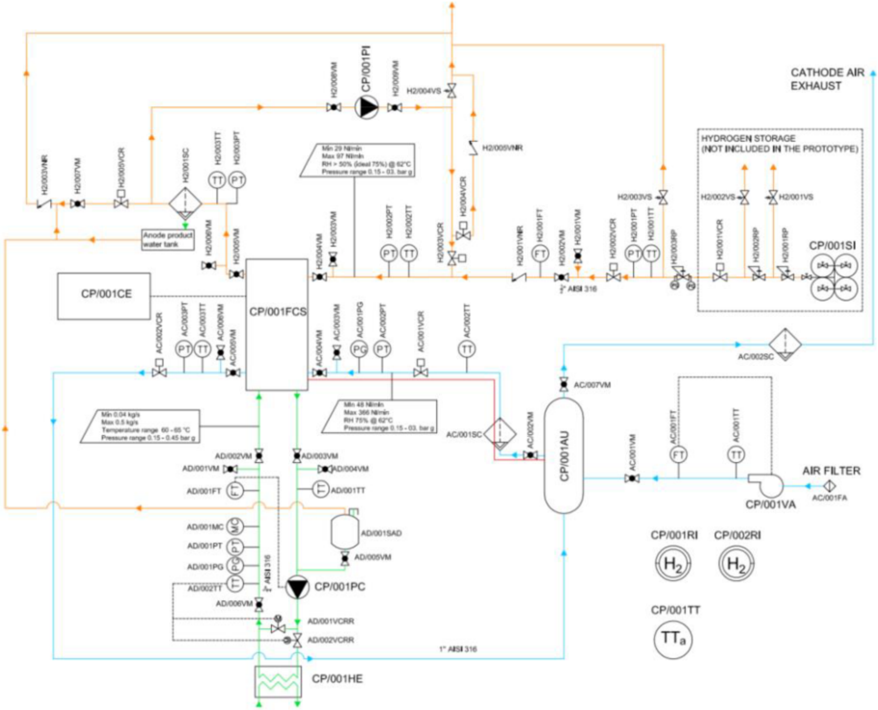

Figure 5. P&ID prototype plant.

The monitoring and control system therefore allows to: (i) operate devices such as, for example, remotely operated valves and flow controllers, following a control logic defined according to the state of the system; (ii) adjust the auxiliaries of the stack such as demineralized water recirculation pump, H_2 recirculation pump and air blower; (iii) check that the status of the connected devices and check that the value of the monitored quantities are compatible with the expected operating mode and, if not, report it to the operator or initiate corrective actions; (iv) record and display data from the system in real time; (v) activate alarms; (vi) turn off the system in an emergency.

6. Regulatory, safety and risk assessment aspects

6.1. Regulatory drivers

The IMO is introducing several regulatory drivers, through MEPC – Marine Environmental Protection Committee – circulars which are in the process of being incorporated in the MARPOL – International Convention for the Prevention of Pollution from Ships – Annex VI, related to reduction of emissions from ships. One of particular importance is the Energy Efficiency Design Index (EEDI) to evaluate the CO_2 emission of each newly design ship in the scope of the MARPOL convention in relation to its transportation work, It allows to evaluate and rank the environmental performances of the ship. The next step is to limit the maximum allowed values f and progressively decrease them over the upcoming years. In order to meet these requirements, it is believed that actions based solely on the development and optimization of existing ship propulsion technologies such as fossil fuel fed engines, propeller and hull shapes, etc.; will not be enough, thus pushing to consider alternative fuels which contain a limited amount or no carbon at all, like H_2 .

6.2. Safety aspects of hydrogen

H_2 at atmospheric temperature and pressure is a light, odourless, colourless and non-toxic gas. It is highly flammable and easily forms explosive mixtures with air. Its liquefaction temperature is approximately -253°C at atmospheric pressure and its critical point is approximately -240°C at 13 bar. In order to improve the energy density for its use as fuel, it is either compressed at several hundred bar, liquefied at cryogenic temperature or a combination of the two. H_2 forms flammable mixtures with air in the range from 4% to 75% and the ignition energy can be as low as 0.017mJ, i.e. more than ten time less than natural gas. This makes a H_2 release very likely to catch fire in lack of appropriate safety provisions, which would include (i) hazardous area categorization & use of explosion-proof devices and appliances, (ii) gas detection, (iii) fire detection, (iv) ventilation, and (v) process monitoring of H_2 system. H_2The liquid to gas expansion ratio of H_2 ad atmospheric pressure is in excess of 800 to 1, higher than natural gas. This implies that any leak of LH2 can be expected to turn into a large amount of vapors, hence introducing the need to provide ample release paths and/or suitable relief arrangements for enclosed spaces and containment system where a leak cannot be excluded. In its vapor state, at atmospheric pressure and temperature, the density of H_2 is abt. 0.085 kg/m3, making it significantly lighter than air and therefore buoyant. This effect can be exploited to enhance safety - as leaked gas may be expected to go upward - by providing suitable release paths from enclosed spaces to the atmosphere, which should be kept free of obstacles such as beams, or pockets as far as practicable. Regarding the risk and management of leaks, the approach with LNG and other gases is mostly based on prevention, with the use of double wall piping. This approach has been considered for H_2 as well, however, it has been found that due to the small size of the H_2 molecule and the characteristics of the fuel cell system, some minor leaks were difficult to rule out. The design of the system and arrangements on board, therefore, is based on the conservative assumption that certain parts of the system cannot be considered or rendered totally gastight.

6.3. Regulatory framework

As of today, few rules are available in the maritime industry to cover the use of H_2 as fuel. In particular the IMO IGF code, even though applicable to any gas or low flash point fuel, is focused on the use of natural gas. While class and statutory rules cover diesel engines, including dual fuel natural gas/diesel, the installation of fuel cells poses another significant challenge, as they differ substantially both from rotating machinery and from batteries. Some of the rules and standards considered are (i) Lloyd's Register (LR) Rules and Regulations for the Classification of Ships, (ii) LR Rule Proposal N°2020/1 – Rules for fuel cell power installation, (iii) IGF CODE (Part A), (iv) CCC6/INF.17 – Amendment to the IGF Code and development of guidelines for Low-flashpoint fuels, and (v) IEC 60079-10-1 – Classification of areas – Explosive Gas atmospheres. Since the use of such fuel and power generation system would significantly deviate from the standard requirements of SOLAS – the convention for the Safety Of Life At Sea –, compliance should be achieved by filing a request for an "Alternative

Design”. In this case, the safety of the design should be demonstrated to be in principle equivalent to a similar ship with “traditional” arrangements. In order to do so, a risk assessment approach has been used to analyze, develop and ensure the safety of the design.

6.4. Risk assessment

The risk assessment process has been carried out following the LR Risk Based Design “RBD” [22] (now updated to Risk Based Certification, RBC) procedure – a tool to support the alternative design through the most appropriate risk assessment techniques (HazId, FMEA). It consisted of three main steps: (i) design screening: an initial workshop, based on a questionnaire, aimed to identify major issues or showstopper as early as possible in the project development; (ii) HazId or Hazard Identification: this has been the core of the work, where the risks arising from the installation of the H_2 containment system, piping and fuel cell installation were identified, ranked and alterations/upgrades were recommended in order to improve the safety of the system; (iii) FMEA or Failure Mode Effect Analysis on the H_2 fuel system: the FC/H_2 system has been considered too complex to be handled by a single HAZID workshop, therefore a FMEA study has been conducted to evaluate deeper the details of design and operation of the system and identify potential failure mode which could impact the safety of the ship. Recommendations were made to improve the design where needed.

The work mentioned above, together with a thorough review of the system and ship design document, are meant to ensure that the project has reached a satisfactory level of safety which would allow for the issue of an Approval in Principle by LR.

7. Conclusions

The proposed study presents the main outcomes of the REShiP project, an Italian research project for the design of a hybrid PEMFC/LIB ferry with liquid hydrogen as fuel. The project has seen the collaboration of academic and industrial partners for the design of the ferry and the optimization of the energy management of PEMFC onboard. A 7 kW PEMFC prototype has been developed to obtain experimental data useful for the future onboard PEMFC installations and for the experimental validation of the mathematical models of the ship energy system. The ship design has been thoroughly revised by the Lloyd’s Register, partner of the REShiP project, and the prototype has undergone an extensive risk assessment procedure. It has been concluded that the project has reached a satisfactory safety level which would allow to issue an Approval in Principle by Lloyd’s Register. From a ship design perspective obtaining the Approval in Principle preliminarily demonstrates the feasibility of the project and defines the areas of action to improve the level of safety of the vessel.It is believed that the REShiP project laid solid foundations for future developments in the design and development of marine PEMFC systems, and could be useful for future academic and industrial studies addressing this type of innovative ship propulsion systems. Future developments of the REShiP project will include additional experimental tests to obtain detailed data on specific phases of cells operation and transients, e.g. load variations. Lastly, an important aspect that remains to be explored is the scalability of the prototype, in order to obtain a flexible system that is easily adaptable to different vessels.

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