DESIGN AND DEVELOPMENT OF A LABORATORY FOR THE STUDY OF PEMFC SYSTEM FOR MARINE APPLICATIONS

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***Abstract* – Climate change is driving the introduction of strict emission limits in the shipping sector favoring the introduction of alternative fuels, among which hydrogen. While the storage energy density of this energy vector is a key challenge that makes way to a variety of different solutions, from fossil fuel reformers to sodium borohydride systems, fuel cell systems are unilaterally considered the future ideal energy converters. Nevertheless very few fuel cell marine applications are available worldwide, none of them is related to a ship application, mainly because of the high power requirements. Fuel cells are relatively new in the shipping sector, up to now no civil industrial system has been commercialized yet while military applications rely only on the U212 submarine of the Italian and German Navy. The lack of favorable niche markets coupled with the strong conservative and traditional design principles held back the investment for optimized marine systems. For this reason, present and past projects made use of conveniently adapted automotive technologies into pilot demos, with particular focus on Proton Exchange Membrane Fuel Cell (PEMFC). However, ships requirements are largely different from automotive ones, not only for the power size that are in the range of MWs instead of kWs. On the other side, in order to take advantage of large scale production as well as of the modularity of fuel cell technology, the integrations of automotive or stationary based fuel cell subsystems, already available on the market, inside a dedicate modular marine system seems to be the solution pursued by many shipbuilders and contemplated by regulatory authorities. In hybrid system configurations, fuel cells are considered in combinations with batteries, another important technology under development, in order to take advantage of the superior energy performances of fuel cell systems and the highly power discharge dynamics of batteries. The need of fuel cell power systems for ships is pushing towards the creation of knowledge that requires laboratories able to challenge the abovementioned issues in order to give answers to shipbuilders and at a lower level also to rule makers.**

***Index Terms – Laboratory; PEM fuel cell; Cogeneration; Marine*.**

I. NOMENCLATURE

BoP	Balance of Plant
CVM	Control Voltage Monitoring
DER	Distributed Energy Resources
DMFC	Direct Methanol Fuel Cell
ECA	Emission Control Area
E-Hub	Energy Hub
EMSA	European Maritime Safety Agency
FC	Fuel Cell
FCS	Fuel Cell System
ICE	Internal Combustion Engine
IMO	International Maritime Organization
MFC	Mass Flow Controller
MH	Metal Hydride
MSC	Maritime Safety Committee
OEM	Original Equipment Manufacturer
PEMFC	Proton Exchange Membrane Fuel Cell
SOA	State Of the Art
SOFC	Solid Oxide Fuel Cell

II. INTRODUCTION

Regulations are setting to change common practice in marine power generation under the pressure of pollutant emissions reduction. The International Maritime Organization (IMO) is already imposing tight emission limits on Particulate Matter, SO_x and NO_x that for emission control areas (ECAs) are difficult if not impossible to be meet with traditional diesel engines and bunker fuels [1]. Fuel cell systems (FCS) are considered among the most promisign technologies able to reduce pollutants emissions and increase efficiencies [2]. The shipping fuel cell (FC) propulsion technology state of the art (SOA) is poor due to variuous reasons, among which the absence of prescriptive rules for the installation of alternative systems and lack of regulations on ships environmental impact, in particular on greeenhouse gasses (GHGs) [3][4].

A recent review of fuel cell systems for marine applications [5] showed the potentials of this technology coupled with different fuels while the European Maritime Safety Agency (EMSA) commissioned to DNV-GL a study [6] on the use of fuel cell in shipping that further distinguished the most suitable fuel cell technology for marine applications among which PEMFC result to be the most mature one. In parallel, the TESEO project "High Efficiency Technologies For On-Board Energy And Environmental Sustainability" [7] investigated among all the use of PEMFC for the development and demonstration of an electrical generator of 260 kW output power for marine application, that has been designed and built by Fincantieri with the technical support of the University of Genoa. Due to the relevance of the topic, the prototype has been designed inside a container with a high flexible electric architecture to permit the future continuation of the studies. The exploitaion of the system research potential required the outfitting of a dedicated laboratory that has been modeled considering past experiences, technology SOA, ships and rule requirements.

The HI-SEA (Hydrogen Initiative for Sustainable Energy Application) Joint Laboratory represents the first large scale PEMFC test rig especially dedicated to the study of FC application onboard ships and for marine application in general. The goal of the laboratory is to define the best design for a modular FC system for ship application able to guarantee the maximum life spam of FC stacks without omit performance.

III. FUEL CELL SYSTEM TEST RIG

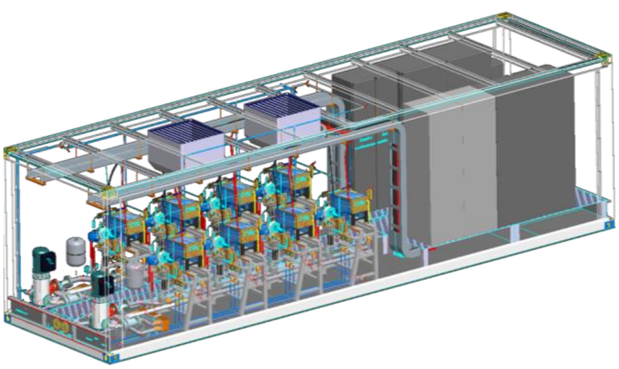

Figure 1. PEMFC FCS test rig

The first and main objective of the FCS test rig, developed during the TESEO Project [7] was the definition of the best design and size of a modular PEMFC system for ship application. The goal was achieved towards the development of a high flexible system able to demonstrate the feasibility of the technology in a simulated relevant environment, namely a ship fuel cell room. Moreover, the test rig has been designed in order to be easily transported (inside a 30 ft container, Figure 1) and integrated into a laboratory able to simulate a ship infrastructure. In order to permit the investigation of the best electric and fluid architecture a mixed configuration has been adopted connecting two symmetrical branches composed by 4 stacks in series, Figure 2. Each stack (L1) has been integrated with BoP components that integrate also an air Mass Flow Controller (MFC) able to control the air flow in order to simulate the behavior of different blowers specification (L2). Each branch is autonomous, with dedicated DC/DC converter and cooling system (L3). The chosen technology for the test rig is the commercial PEMFC, characterized by metallic bipolar plates and open flow field with 30 kW of nominal power at 1 A/cm^2.

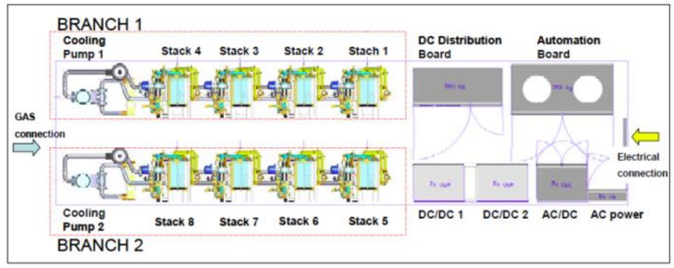

Figure 2. FCS test rig configuration

The DC/DC converter is able to work with the tension of 3 or 4 connected stacks enabling the simulation of a single stack fault on each branch permitting the control of the output tension and current. The DC/DC can also be bypassed in order to directly connect the FC to the electric load. Moreover, the 60 kW AC/DC rectifier together with the controllable electric load permit the simulation of any kind of battery packs, enabling the assessment of the optimum balance between FC and battery dimension as a function of the operational profile and the optimal integration of PEMFCs in a DC grid. Different operational profiles can be tested to investigate the possibility to utilizing PEMFC system to power only auxiliaries or propulsion.

IV. MATURATED EXPERIENCE

Few tests have been conducted during the TESEO project due to time constraints. No significant data have been published but important experience have been registered and later used to design the HI-SEA laboratory, in particular for the definition of important parameters to be supervised and of safe control procedures. At the end of the project, the following observation were made:

- Cooling water conductivity. After the system shot down the cooling water was analyzed and found with conductivity values higher than the accepted value, 5 µS/cm. The problem was related to the use of an inappropriate glycol.
- Standby monitoring (air to the cell). The lack of air flow measure of the stacks didn't permit the identification of a faulty air MFC.
- FC module insertion in series. When a series of fuel cell stacks is supplying high currents, the insertion of a stack has to be avoided in order to prevent possible FC damage.

- Purge system temporization. If the purge pipes of various operating stacks is combined into a single pipe, the former should be properly dimensioned or the stacks purge time should be correctly synchronized in order to avoid the counter pressure.
- DC/DC control. A properly defined control is required to permit the simultaneous current supply by systems connected in parallel.
- Electric load control for simulation. The electric load resistance should be properly sized and controlled in order to simulate an electric load without falling into control interference between the DC/DC converter and the electric load.

Moreover a number of parameters have been monitored in the new installation in order to enhance the interpretation of the phenomena.

V. HI-SEA Joint Laboratory

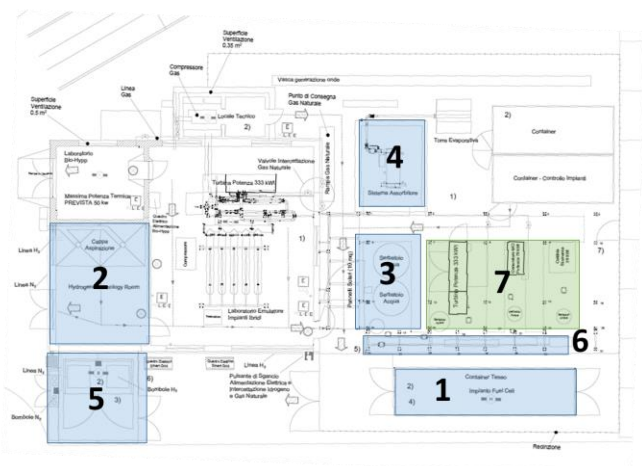

Figure 3. HI-SEA Laboratory plant

The HI-SEA laboratory presents a unique presence of facilities that make it suitable for the study of ships power generator systems. Referring to Figure 3:

1. PEMFC power systems, with 260 kW; 2. Dedicated space for test and analysis of 30 kW stacks and Metal Hydride (MH) hydrogen storage tanks; 3. Large heat storage systems; 4. Absorber chiller of 100 kWth; 5. Hydrogen storage; 6. Water cooling system; 7. Lab scale micro grid E-Hub [23], composed by a 100 kWe micro turbine, a 20 kWe cogenerated ICE and a 1 kWe photovoltaic solar panel system.

The laboratory gives the opportunity to study the behavior of the PEMFC systems in a grid with different sources of electrical and thermal power, enabling the development of design tools for smart grid controls. The presence of water storage systems with temperatures and flows measurement will enable to assess the potentiality of the PEMFC system for cogeneration. Moreover, the absorber chiller working temperature comply with the thermal output of the PEMFC and will permit to test at a real system size the coupling of the systems, an important achievement for the reduction of onboard air conditioning energy consumption. Finally, the equipped space will permit tests and analysis of single FC stacks and of Metal Hydride tanks, with the possibility to develop an optimum thermal integration between them. In the following a list of potential analysis that can be developed in the laboratory is reported:

- Definition of FCS marine requirements and related test protocols;
- ESS coupling (with FCS) and sizing;
- Co-generation;
- Tri-generation;
- Dynamic simulations;
- Diagnostic database and simulations;
- Reliability engineering;
- Design specification of case studies;
- Optimization;
- Safety;
- FC lifetime;
- System design and operation;
- Scientific dissemination;
- Training.

VI. Fuel cell systems for ships

On board ships electrical power is mainly used for auxiliaries, but the tendency towards the use of electricity for propulsion is increasing [8]. The majority of ships produce electricity using diesel generators (gen-sets) localized in few engine rooms that are characterised by higher efficiencies at partial load, while power is delivered to the users towards long cables penalized by transport losses. The traditional design approach allow the delimitations of zones where safety related issues like fire can be identified as a significant hazard [9][10]. At the same time, all outlet gases and inlet ventilation piping and casings are confined in a few astern zones. Conversely, fuel cells like batteries are modular systems that are not dependent on the size of the module and presents higher efficiency at partial load. As a result, FCSs can be distributed over the ship, increasing redundancy, reducing electricity transport costs and enabling Distributed Energy Resources (DER) concepts.

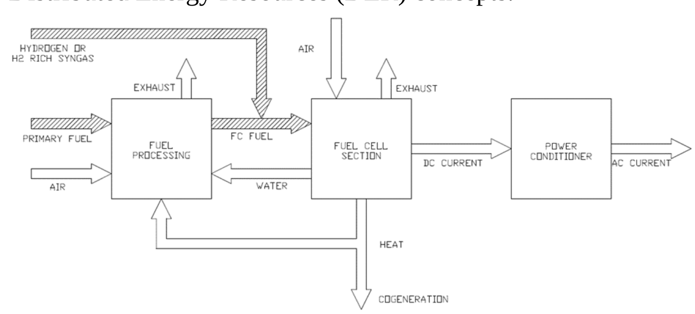

Figure 4. General scheme of FCS

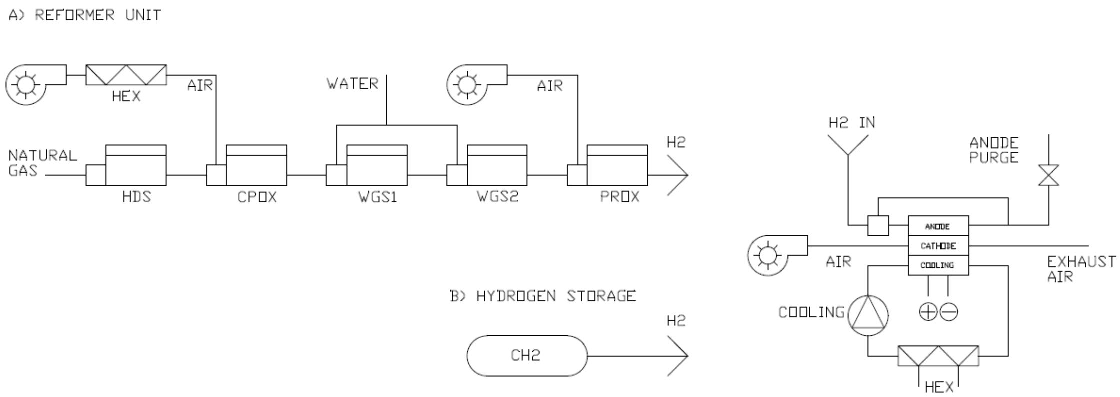

Figure 5. PEMFC system P&ID: a) Reformer unit; b) Hydrogen storage

For these reasons the definition of the fuel cell power installation is fundamental. Indeed, the IMO Maritime Safety Committee (MSC) is presently working to the definition of Part E of the IGF code [11] dedicated to the use of fuel cell systems. FCSs should reflect present and future regulations integrating all the system components in a safe and effective way in order to comply with the above-mentioned situation.

A FCS is generally composed by three main parts: the fuel processor, the fuel cell power section, the power conditioner [12]. Figure 4 shows a scheme with the fuel energy flows. Not all the system require the fuel cell processor nor the fuel processor unit is equal for any kind of fuel cells, it depends on the primary fuel and the fuel cell electrolyte. Therefore, two configuration can be derived, the first considers the use of a primary fuel that requires a fuel processor, while the second one considers the direct use of the fuel inside the fuel cell power section. The results of previous studies [6][7] brought to the choice to focus the analysis on the marine application of PEM technology. Figure 5-a shows a PEM FCS with fuel processing unit [12], in contrast with the traditional scheme of a PEM FCS directly fed with pure hydrogen (Figure 5-b). The schemes highlight the large differences between the systems. The differences are even more evident in the case of HTPEM FCS, that are able to be thermally coupled with low temperature fuel reformers as Methanol reformer [13]. The direct output of these considerations is the necessity to optimize the system design on the base of the ship requirements, fuel cell typology and energy vector storage technology.

VII. FUEL CELL SYSTEM DESIGN

Previous studies [5][6] demonstrated that there is not a unique FCS design for marine applications, in fact it depends from the primary fuel that is used and the fuel cell kind. The most general scheme that could be considered for a Marine FCS is the one published by IMO [14] (Figure 6), but it results insufficient to the purpose of ship integration. In the following a tentative architecture of the system is proposed, with the goal to outline a configuration able to ease the on-board integration and to help the definition of terminology and rules.

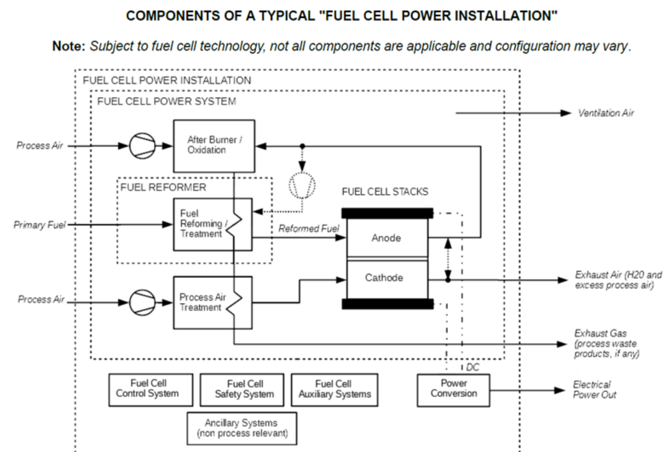

Figure 6. CCC4/WP.3 fuel cell system diagram

The former was used to design the FCS laboratory and to organize studies and analysis of the FCS. Figure 7 shows the concept scheme that should be followed in order to scale up the modular fuel cell stacks, either automotive or stationary based technology, up to marine power systems.

Under each system level a commercial example is reported. Figure 7-a shows a PEMFC stack [15]; Figure 7-b shows the only FC module specifically designed for marine applications [16]; Figure 7-c shows a FC rack derived from automotive stacks and designed for stationary applications [17]; Figure 7-d

LEVEL 1	INLET		OUTLET
Fuel cells (Level 0) Front plate End plate with manifolds H2 recirculation system Cooling regulator valves Control Voltage Monitor (CMV) Temperature transmitter Pressure transmitter	• H2 flow • AIR flow IN • Cooling IN		• DC current (unregulated) • Anode vent • AIR flow OUT • Water exit (anode/cathode) • Cooling OUT

Table 1. Level 1 components list and Level 2 concept scheme

shows a tentative design of a FC room for marine applications [18]. The concept scheme of Figure 7 has been further developed during the TESEO project at first and during the development of the HI-SEA laboratory later. The system design started from the definition of the Balance of Plant (BoP) components in order to distinguish four levels of system integration.

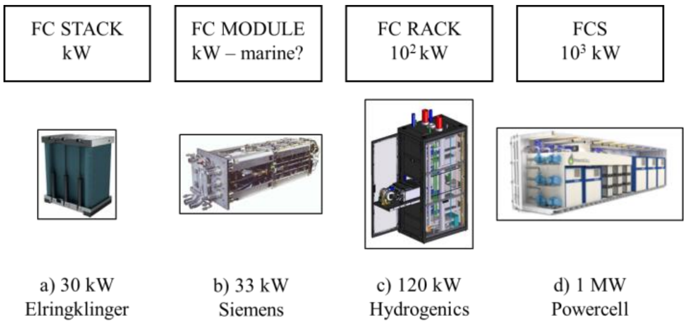

Figure 7. PEMFC scale up scheme

A. BoP components

In order to proceed with the identification of a FCS configuration able to be reproduced with any kind of PEMFC fuelled by hydrogen while complying with the present and future rules, a list of the system component should be analysed. From a market review on the PEMFC stacks available from different OEMs, the components of Table 1 have been found to be the basic supply. OEMs are able to supply also fuel cell stacks without any auxiliary system, but the majority of OEMs tend to supply a more complete product to guarantee high level of integrations and the good operation of the stack. The OEM's fuel cell supply has been identify as Level 1 (L1), as better explained later on. In order to complete a fuel cell system, other components are required.

Table 2 reports a tentative list of the main components of a PEMFC FCS. The list is divided into process lines, in particular the following lines have been considered: Anode line (Hydrogen), Cathode line (Air), Cooling line, Electric line, Control. For each line, a distinction among the components installed at the inlet and at the outlet of the fuel cell stack (L1) is made. The components on the list represent the auxiliary systems of the FCS and are generally called as Balance of Plant.

B. Level of integrations

Once the BoP is defined, the main goal of the FCS architecture design is to define a configuration scheme through which integrate the FCS on-board the ship. In order to fulfil the goal, the BoP components and related connections (pipes, wire, boxes, sensors, protection and others) have been divided into four levels of integration.

IN	OUT	OTHER
	ANODE LINE	
Anode main valve Anode humidifier Anode pressure regulator CATHODE LINE	Anode water separator Anode purge line	
	CATHODE LINE	
Air blower Air filters Cathode humidifier	Cathode water separator	
	COOLING LINE	
Cooling pump Deionizing filters	Cooling heat exchanger	Bypass
	ELECTRIC LINE	
24V aux	DC distribution board DC/DC converter DC/AC converter	Protections Diodes and switches Batteries
	CONTROL	
Sensors Valves	Sensors Valves Switches	PLC

Table 2. BoP main components

- Level 0 (L0), has been identified as the fuel cell or rather as the fuel cell stack (as defined by IEC 62282 standard). L0 is the component that is engineered and integrated by the OESs producer in their products.
- Level 1 (L1), has been defined as the fuel cell stack integrated with the gas manifolds, the Control Voltage Monitor (CVM) and all the BoP components required to control the stack. **Errore. L'origine riferimento non è stata trovata.** give a list of the BoP components considered in L1 that correspond with the basic supply of a fuel cell OEMs. Indeed, L1 components are not sufficient to control the stacks, but are considered strongly related with the stack dimension and characteristic so that are designed and produced together with it. This supply is often referred as "Stack", even if result in contrast with the IEC definition, hereafter L1 will be also indicated as stack or stack system.

From the experience maturated during the development of the HI-SEA laboratory conducted with Fincantieri, it has been found that L1 could not be considered as a standard basic system able to be integrated on-board the ship. The reason relay mainly on the absence of a supply homogeneity among the fuel cell OEMs products available on the market and the lack of basic marine requirements. At the present, there are no product specifically designed for marine applications (excluding small Direct Methanol Fuel Cell (DMFC) – Efoy [19] or the BM Siemens H2-O2 FCMs). Depending on the supplier, some automotive and stationary/based products results to be too bare or too specific. Some shipbuilder will try to develop their own technology and probably the first fuel cell marine applications will make use of highly customized systems. But for future large applications of fuel cells, it is believed that a fixed level of integration have to be established. The proposed configuration takes into account the last draft of Part E of the IGF code [11] (actually under development) together with the IEC standards [20] dedicated to fuel cells systems and ships electrical installations.

Figure 8 resume the hierarchy of the integration levels that have been designed. The core level of FCS integration has been defined as the "Fuel Cell Module". Due to the characteristic of modularity, the higher level considers the integration of more modules and has been called "Fuel Cell Power System" or "Fuel Cell Rack", while the last level of integration has been called "Fuel Cell Power Installation". In the following a detailed explanations of these levels is reported.

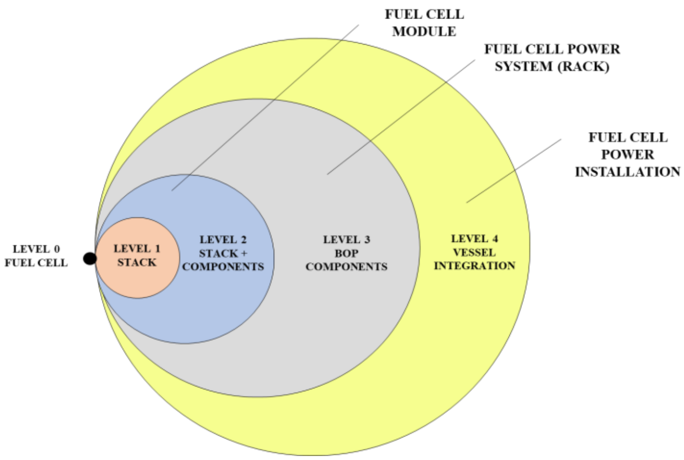

Figure 8. FCS levels hierarchy

- Level 2 (L2). After the definition of L1 and the decision to not consider it as the basic element of the FCS, the "Fuel Cell Module" was defined as L2. The most peculiar characteristic of L2 is the integration of L1 and all the BoP required to control the fuel cell stack inside a closed box provided with the fluid and electric connection. The Figure in Table 1 shows a scheme of the fuel cell module with a brief list of BoP components integrated inside the module, the inlet and outlet connections. The ship builders can consider the module as a black box, it means that the ship builder should not concern about anode recirculation system, the fuel cell humidification, the voltage cell monitoring and alarms, the basic stack control more in general. Moreover, from the rule maker point of view, L2 could represent a standard power generator module just like Internal Combustion Engines (ICEs) or batteries, indeed modular like batteries but provided with fuel and air like ICEs. The market analysis showed that fuel cell modules are available with one or more stacks integrated inside, for this reason it has been left the possibility to have more stacks inside the modules (like having more cylinders in an ICE). The module should be designed to fulfil marine requirements (to be defined) like high level of inclinations, vibrations, and shock from an environmental point of view. Dimensions, weight, form and connections should be so as to permit the installation inside the ship and easy removal in case of maintenance. The module should be certifiable from classification societies, meaning that safety level should comply with IMO SOLAS. For this reason, the module should be provided with sensors (voltage, hydrogen leak), alarms and integrated Emergency Shot Down procedures. In order to have a higher level of safety, the L2 box could be designed to be gas tight or not. Since a proper guide rule for the installation of fuel cell on board ships is not available yet, the "gas tight" requirement for fuel cell module could be too stringent but it can also ease a lot the L2 integration within the higher integration level. From the analysis of stationary and marine standards, the use of gas inside close spaces require the avoidance of explosive atmosphere through the use of ventilation or by the use of gas tight enclosure with overpressure of inert gas (nitrogen) [11]. In the first case the avoidance of the explosive atmosphere is provided by mechanical ventilation at higher integration level or at the fuel cell space level. In the second case, the mechanical ventilation of the fuel cell space could be reduced or activated only in emergency case, highly reducing the BoP energy consumption. The L2 configuration with gas tight enclosure can be indicated as "gas safe".
- Level 3 (L3). From the market analysis the standard L1 power size of 30 kW has been found, together with higher power L1 module made of single or more stacks up to 200 kW power. As average, L2 fuel cell module could be considered between 30 to 100 kW power range. In order to reach MW power ranges required by ships, many modules should be connected together. Following the "modularity" property of the fuel cells and considering the "redundancy" principle of marine systems, an intermediate integration level between the fuel cell module and the fuel cell installation has been created. L3 was defined as "Fuel Cell Power System" or "Fuel Cell Rack". Due to the compact dimensions of L2 modules, the same philosophy of large battery systems has been followed and racks with the dimension of power electronic shelf has been considered as external case for the assembly of L2 modules inside the L3 fuel cell power system. Indeed L3 has been thought to be designed such as to be an independent power system, able to provide conditioned air flow, fuel, cooling, auxiliary electrical power to the fuel cell module as well as to collect the module exhausts (air, condensed water and anode purges). Depending on the L2 module power, the L3 fuel cell rack could range between 100 to 400 kW power. Figure 9 shows a scheme of integration with the distribution of the BoP components among the integration levels. The external case of L3 could represent an element of discussion for the rule makers. The same argument addressed to L2 module is faced for L3, either to have a "gas safe" L3 enclosure or not. The fuel cell rack represents the last level of fuel cell

integration that permit the restriction of possible gas losses caused by malfunctions of ruptures inside a well defined border, the rack enclosure. The mechanical ventilation of the whole fuel cell space represents the obliged mean of protection from the formation of explosive atmosphere. The ventilation energy consumption increase with the increasing volume of the ventilated space. Moreover, a small well designed box would be ventilated in a more efficient way than a larger room. Again, to indicate the capability of L3 box to hold possible gas leakage, the "gas safe" label can be used.

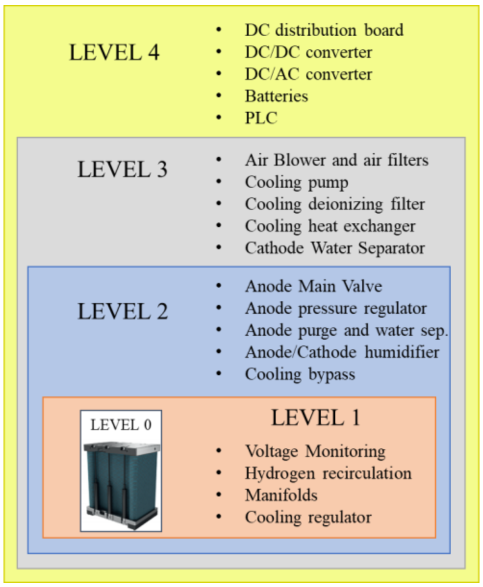

Figure 9. FCS level of integration BoP description

- Level 4 (L4). The last integration level is the "Fuel Cell Power Installation". The term has already been used by various classification societies inside their own fuel cell guidelines as well as by the IMO. The same is also present inside the draft of Part E of the IGF code to define the fuel cell power plant able to supply electrical power to the ship. Some classification societies provide a difference between system dedicated to the furniture of electrical power to auxiliary systems only and systems used to power the ship propulsion, as the "FC Power" and "FC Safety" notation of the DNV-GL rules [21], or the FC-SHIP "Essential" or "Non-Essential" notation of the RINA rules [22]. This distinction was not considered since SOLAS already give different prescription for generators dedicated to power auxiliary systems and generators dedicated to propulsion. L4 consider all the BoP components excluded by the previous level since are not considered peculiar of the fuel cell power system but are considered as auxiliaries required to the integration on-board the ship. Among the components of L4 there are all the electric power conditioner required. Depending on the ship electric distribution characteristic, a traditional DC/AC converter could be considered in conjunction with the DC/DC converter as well as the unique presence of the DC/DC, in the case of a modern DC distribution system. The L3 cooling system require dedicated deionized and glycol and is supposed to exchange heat inside a heat exchanger connected to a secondary cooling loop that could use see water. On the base of the ship power operational profile, batteries will be required to manage pick power control. Finally, the Programmable Logic Controller is required to control the system. The fuel cell power installation should be provided with active and passive safety system to reduce the explosion and fire risks.

VIII. Conclusions

Recent announcements from different ship owners, the strong commitment by IMO in the development of FCs and alternative fuels codes combined with the increasing public pressure on global warming and environmental issues represent the signal that the momentum for the introduction of FCS on board ships is growing. Past projects experiences, marine, mechanical and electric engineering competences are merging in the industrial and academic fields all around Europe, from Norway to Italy. The HI-SEA laboratory represents an important step by private and public entities towards the development of the knowledge required for the design, test and installations of the marine FCSs of the future, starting from PEMFC systems. The paper shows the path that was followed to develop the laboratory, with a focus on the FCS architecture, a fundamental study necessary for the understanding of the system. Moreover a resume of experiences is reported together with a list of studies that the authors consider important for the development of marine FCS.

Acknowledgment

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