https://doi.org/10.1051/e3sconf/202233404003

Characterization and experimental comparison of commercial PEMFC stacks for marine applications

Eleonora Gadducci*[1], *Thomas* Lamberti[2], *Loredana* Magistri[1], *Massimo* Rivarolo[1], *Andrea* Dellacasa[3], *Barbara* Campora[3], *Gerardo* Borgogna[3], *Agnese* Lancella[3], *Enrico* Speranza[3] and *Andrea* Voiello[3]

[1]Thermochemical Power Group (TPG), DIME, University of Genoa, Via Montallegro 1, 16145 Genoa, Italy
[2]BluEnergy Revolution Scarl, Viale Nazario Sauro 5/2A, 16145 Genoa, Italy
[3]Fincantieri S.p.A., via Cipro 11, 16129 Genoa, Italy

Abstract. PEM Fuel Cells are considered among the most promising technologies for hydrogen utilization in both stationary and automotive applications. The number of FC installations on board ships – alone or in hybrid configuration with batteries – is increasing significantly, although international regulations that drive their installation are still missing. In this scenario, the project TecBia aims to identify a dedicated test protocol and the best commercial PEMFC technology for marine applications, assessing the integration of a 140 kW PEMFC system on the Zero Emission Ultimate Ship (ZEUS) vessel. The system design and technology provider has been chosen after a technical comparison based on a dedicated experimental campaign. The experimental campaign had two goals: (i) analyse the performance of the different PEMFC systems to define the best characteristics for maritime applications; (ii) verify the compliance with naval requirements with reference to current and future standards. The present study shows the resulting test protocol for FC Systems (FCS) for maritime applications, defined starting from the existing international regulations on FCS installations and on naval environment requirements; the results of its application on the commercial system chosen for the installation on ZEUS are reported.

1 Introduction

The use of alternative fuels on-board ships has become crucial to decrease navigation's strong impact on the environment, as issued by the International Maritime Organization (IMO) [1,2], and to follow the recent restrictions on Green House Gases (GHG) emissions [3]. In this context, hydrogen is one of the most promising fuels for marine applications [4][5], and Polymeric Electrolyte Membrane FC (PEMFC) can be a promising technology to be employed for propulsion [6-12], also coupled with batteries, and evaluating the best hydrogen storage technology, to increase the practicable navigation distance [13-21]. In this context, many research projects have deepened the topic of experimental PEMFC systems for maritime applications [22-25], but the absence of a shared international legislation specific for fuel cells on marine vessels can create issues in the design phase of real-scale systems. Indeed, the IMO has not made available any guideline for the installation for FC Systems (FCS) on marine vessels, nor guidelines for the Type Approval Test (TA), which is the totality of the tests that an FCS should withstand in order to obtain a Type Approval Certificate (TAC). For this reason, the present work – which is part of the national research project TecBia (*Technologies at low environmental impact for energy production on ships*), financed by Fincantieri-Isotta Fraschini Motori S.p.A. and Italian Ministry of Economic Development (MISE) as part of "National Operational Programme (PON) 2014/2020 Large R&D Projects" [26] – aims to define a testing routine which can be crucial to carry out a technical comparison between different commercial PEMFC systems and to evaluate their suitability for shipping installations. Starting from the legislations available for fuel cell installations and from the aspects related to naval environment regulations, the main aspects to be checked via the testing protocols have been individuated. The previous experience of the research team in terms of experimental know-how for designing, building up and testing a FCS for maritime application in the HI-SEA UniGe-Fincantieri joint laboratory [27] has been a fundamental prerequisite to the output of the study [22-25]. This operation can lay the foundations of a future and specific international standard, defining the experimental steps necessary to assess the suitability of FC stacks for shipping requirements.

After the definition of dedicated test protocols, the different available FC technologies have been tested following the outlined procedure. This allowed to individuate the best commercially available PEMFC technology, which is going to be installed onboard the ZEUS research vessel, which is the main outcome of the TecBia project. This work presents the results of the application of the testing protocol of the chosen FCS,

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[*] Corresponding author: eleonora.gadducci@edu.unige.it

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which justify the choice for its installation onboard the ZEUS.

1.1 Existing legislations considered

Nowadays, as a dedicated regulation does not exist, every integration process of Fuel Cell and hydrogen systems must follow the Alternative Design procedure (AD), a general procedure based on Risk Assessment (RA) that allows the introduction of limited and unregulated variants within the project if they demonstrate, through the RA, a level of security equal or higher than the one required by the regulations for traditional design. To proceed with an objective evaluation of the performance of FCS, it is therefore not possible to refer to any internationally recognized technical document. It is consequently necessary to carry out an analysis of the regulations and available standards published by Classification Societies (CS) and standardization (ISO, IEC) recognized at European (EU) and national level. Indeed, while an international legislation is expected in the next future, the CS such as the Italian Naval Register (RINA) are equipping themselves with internal rules that define the safety requirements that FC systems must comply with in order to be installed on board.

To consider in the broadest but most precise way possible both the aspects related to the naval legislation (as for the environmental conditions) and those related to the rules and standards of FC technology (as regards the operational conditions), the regulations of the CS and the standards related to fuel cells have been taken into account, in particular:

- IACS UR-E10: it defines the test specifics for the TA of electrical systems.
- RINA-FC: it is specific for FCS and gives important guidelines for their installation onboard ships, citing the IEC 62282 as a reference for the TA.
- RINA RULES, PART C: these regulations referred to all the machinery, electrical installations and the automation installed on board; it has also been used as a guideline for the design of the test stations, and it has provided multiple indications and specifications of completion to the IACS UR-E10.
- IEC 62282: it describes the TA for FCS for the installation in stationary, portable, micro and vehicles applications.

The latter has been considered also for what concerns the environmental conditions – vibrations, temperature, and wind) – which the FCS should withstand to, comparing these conditions to the ones applicable to Auxiliary Power Units (APU) on heavy-duty transport installations [28].

1.2 FCS characteristics

Table 1 reports the main technical data for the FCS investigated in this work: the data are referred to a system which can provide a maximum electrical power of 36 kW, 30 kW considering the Balance of Plant (BoP) consumption.

Table 1. FCS technical data. [29]

Parameter	**Range**
Current range [A]	50 - 500
Power range [kW]	5.1 – 36
Voltage range [V]	71 – 102
H_2 mass flow [kg/h]	0.2 – 2.3
BoP consumption [kW]	1 – 6

2 Experimental

The outcome of the study of the available legislation, as described in Section 1.1, is the definition of a test list, which can be divided into six different typologies:

- Environmental
- Operative
- Emissions
- Normal conditions
- Failure conditions
- Routine tests

The experimental test rig has been designed and built with the support of BluEnergy Revolution (BER [30]), an emerging company operating in the field of hydrogen applications on marine vessels.

To estimate the effects of static inclination on the FCS performance, BER designed a dedicated platform able to withstand 500 kg and to offer two different inclination degrees: 30 and 45°. The Table 2 summarizes the experimental tests – which were reproducible in BER's test rig – that have to be carried out on the FCS to evaluate their suitability for maritime applications:

Table 2. Experimental tests performed.

Typology	**Test description**	**Regulation**
Environmental tests	Cooling temperature: ±2°C from setpoint	RINA PartC, Vol II, Sec2
	Static inclination: startup+constant load at 30°	IACS UR E-10
Operative tests	Efficiency: calculated at 25%, 50%, 75% and 100% of nominal power	EC 62282-3-200
	Power response (electrical and thermal, time needed), minimum to nominal power and reverse	EC 62282-3-200
	Start-up/shutdown: time response of the net electrical power	EC 62282-3-200
Emissions tests	Maximum noise: during operation and in background with FCS off	EC 62282-3-200
	Maximum vibrations: during operation and background with FCS off	EC 62282-3-200
	Exhaust reaction water: quantity and quality	-
Normal conditions	Polarization curve	-

	Constant load (minimum time: 15 minutes)	-
	Typical navigation profile simulation	-
Failure conditions tests	Emergency shutdown: time needs to conclude procedure	EC 62282-3-200
Routine tests	Visual inspection (agreement with technical schemes)	IACS UR E-10
	Voltage variation measure	-
	Gas leakage assessment test (on FC stack)	-

The tests results have been the key for the evaluation of the different technologies available. In this work, the most interesting outputs of the test protocol on the FCS are reported and described in the following sections: efficiency calculation, polarization curve and operative profile.

2.1. Test rig integration scheme

Depending on the design chosen by the supplier, each FCS can be already provided with different components and connections. In order to prepare a test rig where the technology under investigation can be easily integrated, it is necessary to define a generic integration scheme. Despite the absence of technical prescriptions for this, the authors faced the challenge thanks to the experience acquired by working on previous projects on the same topic [22,23,25].

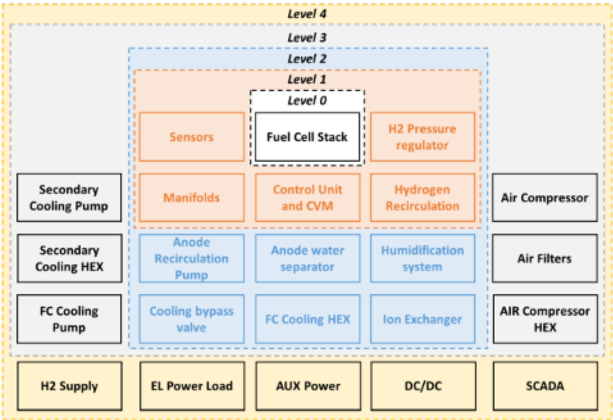

Fig. 1. Generic FCS integration scheme.

Figure 1 shows the generic integration scheme adopted to design the test rig. The scheme not only divides the integration levels but identifies the various integration modules for the various connection lines between the FCS system and the laboratory.

2.2. Comparison of tests results

To compare the performance of the different systems, it is necessary to normalize the dimensions on which carry out the comparative study. The comparative analysis mainly concerns the performance, in terms of voltage and current ranges, as well as the system efficiency. The latter is given by the difference between the net power and the gross power, thus the power absorbed by the auxiliaries. Since the power, both the nominal one and the measured one, absorbed by the BoP components has different levels of uncertainty, to make the analysis meaningful it was chosen to proceed with the comparison of the electrical performance measured with respect to the stack, excluding the consumption of the BoP.

2.2.1 Efficiency calculation

According to [31], the efficiency is calculated based on the Higher Heating Value (HHV) of hydrogen, and the calculation requires the following measures:

- Hydrogen inlet flow rate
- Heat supplied/absorbed externally
- Flow rate of the oxidant (air) entering the system
- Electrical power absorbed by auxiliaries
- Electrical power generated by the system
- The efficiency test should be conducted in accordance with the following procedure:
- Start the system and require a constant power
- Verify that the system operates in stable conditions, i.e., within the limits of variability imposed by the [31] regulation
- Measure the parameters necessary for the calculation of efficiency for no less than 1 hour.

The electrical efficiency η_{el} of the system is therefore calculated by using the following formula:

$$\eta_{el} = \frac{P_n}{P_{in}} * 100 = \frac{(P_{el,out} - P_{el,aux})}{(P_{fuel,in} + P_{air,in})} * 100 \tag{1}$$

Where P_n is the net electrical power generated by the system, and P_{in} is the total power input to the system. The thermal efficiency of the system is calculated as:

$$\eta_{th} = \frac{P_{HR}}{P_{in}} * 100 \tag{2}$$

Where P_{HR} is the recoverable thermal power output from the system, and it is obtained by the following equation:

$$P_{HR} = \dot{m}_{HR} * c_{HR} * (T_{HR1} - T_{HR2}) \tag{3}$$

knowing the mass flow $\dot{m}_{HR}$ of the cooling fluid [kg/s], its specific heat c_{HR} at given temperature and pressure [J/(kgK)], and the temperature difference $(T_{HR1} - T_{HR2})$ between entrance and exit of the system under consideration.

2.2.2 Polarization test

Experimentally reproducing a polarization curve implies that a FC (single cell or stack) will be subjected to the operation at subsequent current setpoints, from zero to the nominal value and back to zero. This procedure allows the operator to draw for the tested device the V-I curve, which varies slightly for FC technologies by different manufacturers. In general, the goal of measuring the polarization curve is the determination of the Membrane-Electrode Assembly (MEA) performance in terms of cell voltage and power density considering the current density as a reference. The residence time of each set-point should be long enough to ensure the stabilization of cell voltages in ±5 mV in a time range between 2 and 15 minutes, except for the Open Circuit Voltage (OCV) measure, which must not exceed 1 minute of stay. The set-points proposed by the EU Harmonised Test Protocols for PEMFC-MEA Testing in Single Cell Configuration for Automotive Applications [32] are summarized Figure 2: the y-axis represents the current density at which the FC must be tested, while the x-axis indicates the subsequent test steps. This harmonized test protocol is designed for single cell tests and for this reason the possibility to make slight changes on the protocol is allowed, in order to apply it in the best possible way to the characteristic limitations of the individual FC modules: minimum operating electrical power, longer possible operation at minimum power, etc.

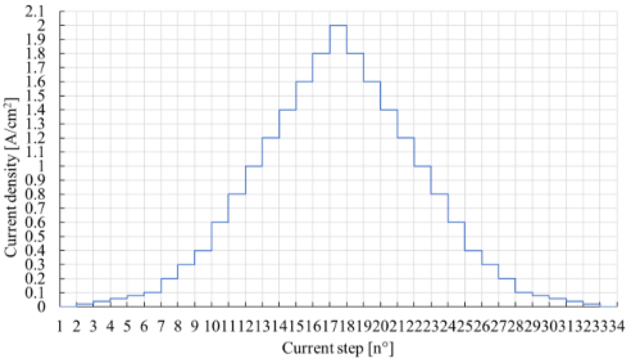

Fig. 2. Set-points for the polarization curve testing [32].

2.2.3 Operative profile test

To verify the adequacy of the performance of the FC module in a real on-board application, part of a typical naval cargo load energy demand profile – agreed with Fincantieri – is considered, which had been successfully adopted also in a previous project [25]. This profile can be divided into two parts: the first one, where first some increasing and later some decreasing load steps are present, represents the dynamic load that can be required during manoeuvring. The second one simulates navigation after manoeuvring inside the port, where the system works for a longer period at constant load and at 100% of its capabilities. It may represent the load request during navigation at constant speed for propulsion, or the case where the system is employed as an auxiliary to cover the hotel load. The profile can be obtained thanks to the implementation of the electrical control of the systems (including the FC and DC/DC module coupling).

Figure 3 shows the shipping load profile cited, to be applied to the PEM fuel cell systems under consideration for 4300 seconds.

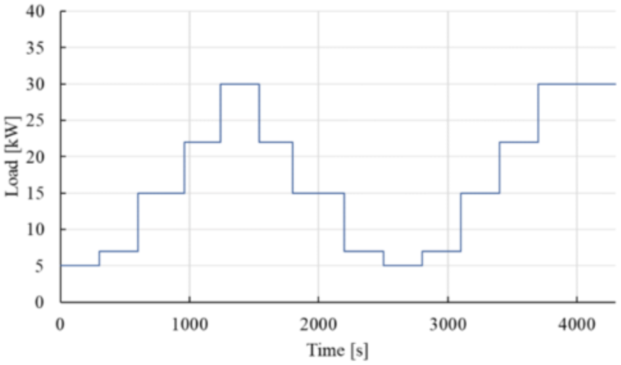

Fig. 3. Shipping load profile assumed to be tested on the FCSs.

2.2.4 Static inclination test

To assess the ability of the FCS to work while inclined, it has been installed and tested on the Test Bench developed by BER. The angle of inclination tested was 22.5°, and the load request during this part of the assessment was constant for a prolonged period (around 20 minutes), to verify the good operation of the system in this condition. The main concerns that may arise from this type of operation are linked to the efficient delivery of the reactants and cooling flows to the FCS. The results of this test are compared with the implementation of the same load profile implemented with the non-inclined stack.

3 Results

Hereby are reported the results of the calculation of the FCS efficiency and the most relevant experimental results.

In order to compare the performance of FC systems, it is necessary to normalize the dimensions on which carry out the comparative study. The comparative analysis mainly concerns the performance in terms of voltage and current ranges, as well as system efficiency. The latter is given by the net system power output divided by the gross power input, that accounts for the power absorbed by auxiliaries. Since the powers absorbed by the BoP have different levels of uncertainty and changes depending on the components installed, to make the analysis meaningful it was chosen to proceed with the calculation of the electrical performance measured with respect to the stack, excluding the consumption of the BoP. Figure 4 shows the trend of η_{el} as calculated from the experimental data.

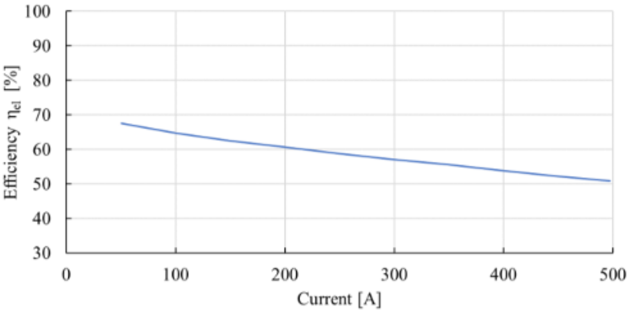

Fig. 4. η_{el} for the tested FCS.

The objective of the polarization tests is to get to the definition of the polarization curve, to have a reliable reference of the voltage as a function of current that must be verified during operation. Figure 5 shows the experimental V-I points collected during the dedicated tests (blue dots), compared with two reference curves named "FAT", which stands for Factory Tests. The yellow and orange lines represent in fact the results of the FATs that have been implemented by the FCS supplier, and which are given together with the specifics of the system. The two curves represent respectively the implementation of the first half of the current profile shown in Figure 2 (orange line), and the second descending half (yellow line). It is possible to notice from Figure 5 that FAT's results and the ones obtained inside BER's test rig are similar; the slight difference is mainly due to the lower temperature of the FCS (air, cooling fluid, components) during the test.

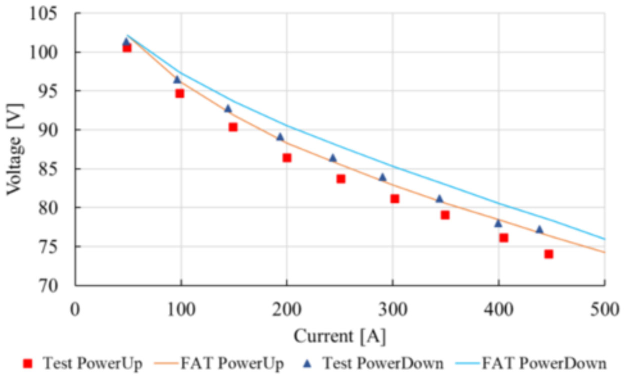

Fig. 5. Polarization test results.

The system's ability to respond to typical naval load profiles has been tested as well. The profile aims to represent the typical operating conditions that can be found on board (hotel load, manoeuvre, propulsion). Unlike tests in stationary and dynamic conditions, the operating profile represents a mix that can positively or negatively affect stack performance. The tests have been conducted in ideal conditions, with the objective of evaluating the global average performance of the FC system during the implementation of the operative profile. In Figure 6, it is reported the trend of the electrical power output – P_{el} – and of the thermal power – P_{th} – exchanged by the cooling circuit during the development of the naval profiles tested. The load request is always guaranteed, while the thermal power follows the trend of the electrical power output and is always managed correctly by the cooling loop. The FC stack voltage reaches a stable value during the implementation of each load step, despite the short time. This is especially appreciable at the end of the test, where a high and constant load is requested after the more stressing dynamic load, demonstrating that the FCS is able to withstand a similar load profile.

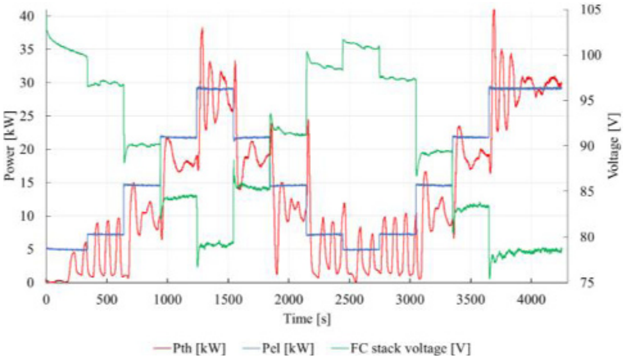

Fig. 6. Operative profile test results.

The FCS has eventually been tested under static conditions (stable load levels) for prolonged periods of time, on a 22.5° inclined plane, to evaluate the proper functioning of the system at all current densities. During these tests, the specific consumption, the efficiencies of the system, the analysis of the purges, the temperatures and operating pressures of the FC system, the temperatures and flow rates of the cooling output to the FC system, the measurement of water produced at the cathode, and the measurement of the water purged at the anode have been defined. No abnormal operating conditions have been encountered, confirming the good setting and operation of the stack control system which automatically manages the cooling, the air flow rates and the current supply ramp. Figure 7 shows the test results. The constant load has been maintained for a long time without major fluctuations but, most important, no difference in the stack voltages has been measured, proving that the humidity management of the system is optimal.

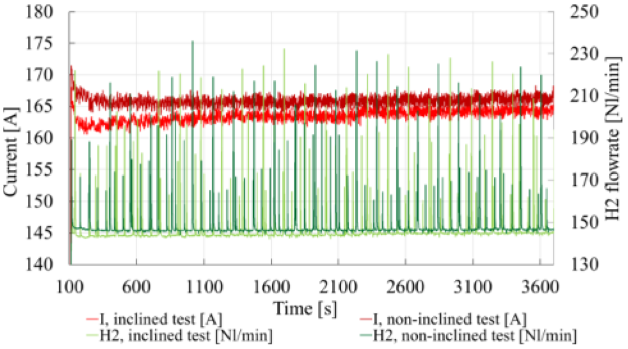

Fig. 7. Static inclination test results : current and H_2 flowrate.

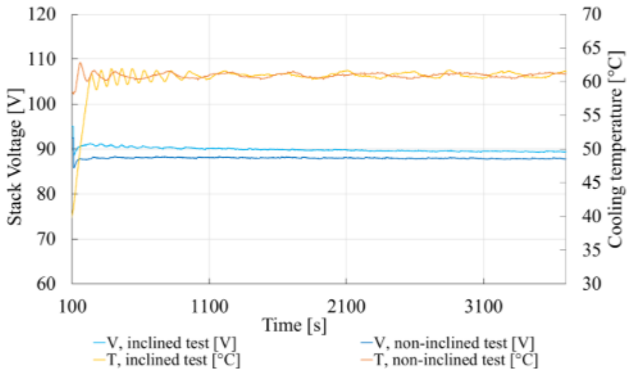

Fig. 8. Static inclination test results : cooling temperature and stack voltage.

4 Conclusions

The activities carried out for the TecBIA project, and described in this work, show the results of the definition of a test protocol for FCS installation in a ship environment – starting from the available international regulations – and its application to the system chosen for the installation onboard the ZEUS vessel. The test protocol can hint technical differences between FCS designed by different suppliers which make one technology more suitable than another; it will provide a guidance to integrators and to ranking institutes for the evaluation of the performance of PEMFC systems for marine application.

A dedicated Test Bench was developed, specifically designed to check and test FC systems, allowing the operator to test them even in static inclinations. The test protocol developed has been therefore applied to the commercial FCS chosen for the application on ZEUS, and the main outputs of the experimental campaigns are reported. From an environmental point of view, the tests conducted during the TecBIA project certify that the PEM technology can operate in naval use conditions without problems. In particular, it is confirmed that the system chosen for the installation onboard the ZEUS vessel is able to operate in the entire operative range maintaining a good performance, as well as it can withstand an operative profile comparable to the ones required to shipping power systems.

References

1. International Maritime Organization (IMO). Third greenhouse gas study. 2015.
2. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx, International Maritime Organization (IMO) official website, last access 22/01/2021
3. https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1599
4. K. Kołwzan, M. Narewski, Latv J Chem; **51** ; 398-406 (2013)
5. Veldhuis IJS, Richardson RN, Stone HBJ. Int J Hydrogen Energy; **32 ;** 2553-66 (2007)
6. T. Tronstad, H. Astrand, G. Haugom, L. Langfeldt; www.emsa.europa.eu (2017)
7. M. Rivarolo, D. Rattazzi, L. Magistri, A.F. Massardo, En. Conv. And Management, 244, 114506 (2021)
8. M. Rivarolo, D. Rattazzi, T. Lamberti, L. Magistri. Int J Hydrogen Energy;**45** ;25747-57 (2020)
9. O.B. Inal, C. Deniz; J Clean Prod;**265**:121734 (2020)
10. Y. Bicer, I. Dincer, C. Zam, G. Vezina, F. Raso ; **135** ; 1379-1395 (2016)
11. H. Nazir, N. Muthuswamy, C. Louis, S. Jose, J. Prakash, M.E.M. Buan, et al., Int J Hydrogen Energy; **45** ; 28217-39 (2020)
12. A. Pfeifer, P. Prebeg, N. Duic ; E Transportation; **3 ;** 100048 (2020)
13. C. Nuchturee, T. Li, H. Xia ; Renew Sustain Energy Rev; **134** ; 110145 (2020)
14. S.E. Hosseini ; *Reference Module in Earth Systems and Environmental Sciences*, Elsevier (2020)
15. P. Wu, R. Bucknall ; Int J Hydrogen Energy; **45** ; 3193-208 (2020)
16. M. Cavo, E. Gadducci, D. Rattazzi, M. Rivarolo, L. Magistri ; Int H Hydrogen Energy, 46, 32630-32644 (2021)
17. A. Bouakkaz, A.J.G. Mena, S. Haddad, M.L. Ferrari ; Journal of Energy Storage, **33**, 101887_1-13 (2021)
18. A.L. Dicks ; *Reference Module in Earth Systems and Environmental Sciences*, Elsevier (2020)
19. J.J. De-Troya, C. Alvarez, C. Fernandez-Garrido, L. Carral ; Int J Hydrogen Energy; **41 ;** 2853-66 (2016)
20. M. Rivarolo, D. Rattazzi, T. Lamberti, L. Magistri ; Int J Hydrogen Energy; **45 ;** 25747-57 (2020)
21. C.H. Choi, S. Yu, I.S. Han, B.K. Kho, D.G. Kang, H.Y Lee, et al. ; Int J Hydrogen Energy; **41**;3591-9 (2016)
22. G. Borgogna, E. Speranza, T. Lamberti, A.N. Traverso, L. Magistri, E. Gadducci, et al. ; E3S Web Conf.;**113**:1-8 (2019)
23. E. Gadducci, T.Lamberti, D. Bellotti, L. Magistri, A.F Massardo ; Int J Hydrogen Energy ;**46 ;** 24305-17 (2021)
24. TESEO project (2012-2015) PON02_00153_2939517, http://www.ponrec.it
25. Gadducci, T. Lamberti, L. Magistri ; *Proceedings of EFC2019,* 235-236 (2020)
26. www.fincantieri.com, last access 12 September 2021
27. http://www.tpg.unige.it/TPG/
28. IEC 62282-4-101:2016 https://webstore.iec.ch/ (TRUCK&APU) (2016)
29. https://www.proton-motor.de/
30. https://bluenergyrevolution.com/
31. IEC 62282-3-200:2016 https://webstore.iec.ch/ (paragraph 9.2.6) (2016)

32. G. De Marco, T. Malkow, G. Tsotridis, A. Pilenga ; https://ec.europa.eu/jrc (2015)