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# Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives

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**Abstract:** The ambitious targets set by the International Maritime Organization for reducing greenhouse gas emissions from shipping require radical actions by all relevant stakeholders. In this context, the interest in high efficiency and low emissions (even zero in the case of hydrogen) fuel cell technology for maritime applications has been rising during the last decade, pushing the research developed by academia and industries. This paper aims to present a comparative review of the fuel cell systems suitable for the maritime field, focusing on PEMFC and SOFC technologies. This choice is due to the spread of these fuel cell types concerning the other ones in the maritime field. The following issues are analyzed in detail: (i) the main characteristics of fuel cell systems; (ii) the available technology suppliers; (iii) international policies for fuel cells onboard ships; (iv) past and ongoing projects at the international level that aim to assess fuel cell applications in the maritime industry; (v) the possibility to apply fuel cell systems on different ship types. This review aims to be a reference and a guide to state both the limitations and the developing potential of fuel cell systems for different maritime applications.

**Keywords:** emissions reduction; Hydrogen Energy; maritime transport; fuel cells; Sustainability; Alternative Marine Fuels



**Citation:** Elkafas, A.G.; Rivarolo, M.; Gadducci, E.; Magistri, L.; Massardo, A.F. Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives. *Processes* **2023**, *11*, 97. https://doi.org/10.3390/pr11010097

Academic Editor: Mohd Azlan Hussain

Received: 30 November 2022
Revised: 16 December 2022
Accepted: 22 December 2022
Published: 29 December 2022



## 1. Introduction

The growing concerns related to climate change and the average global temperature rising have pushed international organizations, groups of Countries, and national governments to adopt policies to reduce/limit GHG emissions. Among them, $CO_2$ is the most affecting, as it is produced in many anthropogenic activities, including energy generation, transport, residential and industrial sectors. Despite the energy policies adopted, $CO_2$ emissions are dramatically growing more and more at a global level. Since 2000, they increased in a continuous way year by year from 23.2 Gt up to 33.0 Gt in 2021, with slight reductions only in 2009 (due to the economic crisis) and 2020 (due to the COVID-19 pandemic) [1]. Considering IEA data [2], energy production represents the main $CO_2$ emissions sector (14.2 Gt), followed by transport (8.2 Gt). The maritime transportation sector has a significant impact accounting for 1 G-ton/year, 3% of the total. The 4th study by International Maritime Organization (IMO), published in 2020, reports an increasing trend in $CO_2$ emissions for the maritime sector, from 962 Mt in 2012 to 1056 Mt in 2018 due to the intensive use of fossil fuels for international shipping [3,4].

Today, 99% of the ships currently in operation employ fuel products derived from oil (Heavy Fuel Oil, HFO, and Marine Diesel Oil, MDO) in large Internal Combustion Engines (ICEs) for propulsion and onboard energy generation, causing high impact not only in terms of $CO_2$ but also for pollutant emissions, such as particulate matter, NOx, and SOx [5,6]. For this reason, several regulations were set up after 2000, reducing the allowed level of $SO_x$ and $NO_x$ emissions, with particular attention to navigation in Emission Control Areas (ECAs), such as coastal areas and ports.

In 2018, IMO published its initial long-term strategy to reduce GHG emissions from international shipping and to phase them out as soon as possible in this century. IMO aims to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out [7]. In 2023, IMO is going to release an updated strategy. To reach these ambitious goals, several pathways are possible, and the combinations of more solutions are under investigation: (i) use of renewable energy sources (RES), i.e., solar panels onboard [8]; (ii) waste heat recovery for cogeneration/trigeneration and reduction of primary energy/fuel consumption [9,10]; (iii) adoption of the Energy Efficiency Design Index (EEDI) for new ships to promote the use of more energy-efficient devices [11,12]; (iv) use of alternative fuels with lower GHG impact compared to HFO/MDO [13–17]. The introduction of Fuel Cell Systems (FCS) can represent a worthy solution for the maritime sector decarbonization and the IMO long-term targets' fulfillment, as they present high efficiency, also at partial load conditions and low pollutant emissions.

Several review papers in the literature studied FCS for maritime applications, exploring FCS only [18] or as a part of a hybrid system with batteries [19] or integrated with gas turbines [20]. In 2016, van Biert et al. [18] assessed various fuel cell types based on several performance criteria and provided technical guidelines for selecting the suitable fuel type for maritime fuel cell systems. In the same year, de Troya et al. [21] investigated the advantages and problems of fuel cell types, identifying the potential of emission reductions for each type and discussing the technical considerations of installing FCS onboard ships. Xing et al. [22] presented the specific layouts of fuel cell types, highlighting their characteristics for maritime applications and focusing on the development and design of hybrid marine systems based on fuel cell technology. On the same topic, techno-economic and environmental features of hybrid power marine systems based on fuel cells and batteries were investigated by Ma et al. [19] with a focus on the comparison between PEMFC and SOFC hybrid systems with batteries. Cheliotis et al. [23] investigated specific types of FCS for marine applications by presenting the advantages and drawbacks of using ammonia as the main fuel for FCS, considering its safety issues.

The present paper aims to focus on the state of the art of fuel cell systems for maritime applications highlighting the most promising types on the market, in particular, Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) by showing the recent research work in this field. As well the motivation is to conduct a comprehensive review of demonstration projects of FCS in maritime applications, present an up-to-date review of ships equipped with FCS for propulsion and/or auxiliary showing ship specification, followed by an analysis and discussion to list the most common fuel cell type and power capacity, fuel and ship type for this technology for maritime transportation. Moreover, this paper aims to address the gap in the literature on the commercialization of fuel cell systems by presenting existing products in the market and their technical specifications with a focus on appropriateness for marine applications. Furthermore, the paper presents the requirements of fuel cell systems to be suitable for maritime applications by focusing on the regulations of the classification society and the standards related to fuel cells.

## 2. Fuel Cell Systems on the Market

Studies on Fuel Cell (FC) technology began in the 20th Century, founding its most interesting use in aerospace systems during the 1960s. However, a more significant spread and investigation occurred in recent years, thanks to its characteristics that allow reaching almost zero-emission operations. Besides, the development of different types of FC allows the suitability for many applications, from residential to transportation ones.

The operation of fuel cells is based on the development of electrochemical reactions between the oxidizing side (anode) and the reducing side (cathode). An electron flow is generated and carried by an external electrical circuit to feed the load, while the ions (protons or anions, depending on the technology) are transported through an electrolyte.

The fact that electrical energy is entirely produced via electrochemical reactions has several advantages compared to traditional energy systems. First, the efficiency is high, as there is no intermediate process for mechanical work or heat production, avoiding the traditional link between efficiency and the Carnot cycle. Besides, depending on the operating conditions, such as temperature, overall efficiency can further increase by co-generation. The power produced by a single cell is low and linked to the voltage and the electrochemically active area. Nevertheless, FC-based systems are suitable for modularity: single cells are electrically connected in series to form a stack and reach the required power output by connecting multiple stacks [24]. By comparing fuel cells with other energy storage technologies, they have the ability to generate electricity continuously based on the supplement of reactants; thus, fuel cells have higher volumetric energy density than other energy storage technologies [25]. The absence of moving or rotating parts also allows for easier assembly and maintenance of the device and low noise [18,26]. Hydrogen and oxygen are usually employed as reactants at the two cell sides, respectively: in this case, no emissions are verified during the operation. However, depending on the fuel cell type, other reactants can be employed, among which ammonia, methane, and methanol are interesting options to deliver the hydrogen. In this case, the exhaust flow from the fuel cell needs to be treated.

Fuel cells can be classified depending on the operating temperature, electrolyte material, typical fuel, power range, lifetime range, and applications, as shown in Table 1, which summarizes the main FC technologies and their characteristics [27–31]. Based on the temperature range, it is possible to identify the high-temperature category (SOFC and MCFC), intermediate-temperature category (PAFC), and low-temperature category (AFC and PEMFC) [32].

Based on the literature review [33,34], there are several criteria to compare the applicability of fuel cell types for maritime applications, such as power density, emissions, safety, and efficiency.

Power density criteria are based on the mass and volume of the system; therefore, the objective is to find fuel cell types that have less mass and volume with high power. The most promising fuel cell type for maritime applications from power density criteria is PEMFC [35], while Molten Carbonate Fuel Cells (MCFC) and Phosphoric Acid Fuel Cells (PAFC) are less suitable for maritime applications due to their higher volumes and lower power density [36]. Furthermore, PEMFC has the advantage of a quick start-up that allows it to be suitable for the transportation sector [37]. On the other hand, MCFC and SOFC have a slow start-up and are less adaptable to load variations based on their high operating temperature, which leads to negative cycling effects [34]. Emission criteria are considered the cornerstone of using FCS for maritime applications, but emission criteria depend on the logistic fuel used; for example, the emission from PEMFC powered by hydrogen is only water, while SOFC, PAFC, and MCFC powered by hydrocarbon fuels (diesel or LNG) emit water and $CO_2$ [38]. Nevertheless, using hydrocarbon fuels gives the potential of flexibility onboard ship from storage, cost-effectiveness, and availability point of view [39].

The safety concept of FCS is assessed by the exhaust gas pipes, especially for MCFC and SOFC types, which must have effective insulation due to the high temperature of exhaust gases [35]. For hydrogen fuel cells, the insulation and ventilation effectiveness of the storage tanks in the transfer process between the tank and the anode side must be checked due to the explosive and volatile properties of hydrogen [40]. Therefore, low-temperature fuel cells, like PEMFC, have more potential benefits to be applied onboard ships from a safety point of view but need more regulations for hydrogen storage [41].

**Table 1.** Main fuel cell technologies and their characteristics [27–31].

| FC Type | Temperature (°C) | Electrolyte | Typical Fuel | Power Range | Electrical Efficiency | Lifetime (h) | Applications |
|---|---|---|---|---|---|---|---|
| PEMFC | 60–80 (LT-PEMFC) 110–180 (HT-PEMFC) | Water-based polymer membrane | Hydrogen | ≤1 MW (up to 200 kW per module) | 45–55% | 60,000–80,000 (stationary); >25,000 (transport) | Backup power, Portable power, Distributed generation, Transportation, Specialty vehicles |
| SOFC | 500–1000 | Porous ceramic material | $H_2$, methanol and hydrocarbons | ≤1 MW (up to 250 kW per module) | 50–60% | 20,000–80,000 | Auxiliary power, Electric utility, Distributed generation |
| MCFC | 650–800 | Molten carbonate salt | $H_2$, methanol and hydrocarbons | ≤1 MW (up to 250 kW per module) | 43–55% | 15,000–30,000 | Electric utility, Distributed generation |
| PAFC | 140–200 | Phosphoric acid | $H_2$, LNG and methanol | ≤11 MW (100–400 kW per module) | 30–42% | 40,000–60,000 | Distributed generation |
| AFC | 60–200 | Potassium hydroxide | Hydrogen | ≤500 kW (up to 100 kW per module) | 40–50% | 5000–8000 | Military, Space, Backup power, Transportation |

Based on the data reported in Table 1, the efficiency of fuel cells ranges between 50–60%, which is higher than typical values of conventional marine power plants such as ICEs fed by HFO/MDO due to the direct conversion from chemical to electrical energy in FC. Moreover, fuel cell systems have high efficiencies also at partial load, while ICEs usually present efficiency reduction when operating at low power. To increase the electrical efficiency of SOFC [42–44] and MCFC [45], their use in hybrid systems equipped with gas turbines (GT) or micro gas turbines (mGT) was investigated to take advantage of the high-temperature exhaust gases, and thus increase the overall electrical system efficiency up to 65% [21,34]. Another approach was investigated by performing an integration between SOFC and internal combustion engine (ICE) for maritime applications to explore the potential benefits of the integration from the efficiency standpoint [46]. The study showed that the integration between SOFC and ICE, when sharing power from SOFC by 67%, increases the efficiency by 8% over the conventional marine natural gas engine with a reduction of NOx emission by 60%.

Regarding the current market situation, the Fuel Cell Industry Review [47] reports a strong increase in terms of both units and installed power in the last few years. In 2021, 86,000 units of FCS were shipped, corresponding to an installed capacity of 2313 MW. It is worth noting that most of the new installations are PEMFC (64.2% in terms of the number of plants and 86.3% in terms of power), followed by SOFC technology (29.3% in terms of the number of plants and 9% in terms of power), while MCFC and AFC new installations are very limited (0.5% and 0.02% respectively in terms of installed capacity). PAFC installations (about 95 MW in 2021) are limited only to stationary and distributed generation purposes. The next sections will describe the two FC technologies that are nowadays the most employed worldwide and the most promising in the maritime field: PEMFC and SOFC.

### *2.1. Proton Exchange Membrane Fuel Cells (PEMFC)*

Proton Exchange Membrane Fuel Cells (PEMFC) are based on an aqueous electrolyte—a polymer—that transports hydrogen ions thanks to the presence of liquid water on the component itself. The main components of PEMFC are as follows [48,49]: the Membrane Electrode Assembly (MEA) which includes the Polymer Electrolyte Membrane (PEM), the catalyst layers, and gas diffusion layers. There are other components to integrate MEA into the fuel cell, such as the gaskets that give a seal around the MEA to avoid gas leakage and bipolar plates which assemble the single PEMFC into a fuel cell stack. The hydrogen enters the anode side, as shown in Figure 1, which is oxidized to produce protons and electrons; the protons diffuse through the PEM to the cathode; the electrons travel through the MEA to the cathode; the oxygen reduction reaction takes place at the cathode, where the oxygen is reduced. The unreacted oxygen and the water produced in the reaction exit [50,51].

PEMFCs are the most diffused type of fuel cell and one of the most promising technologies for decarbonizing the transportation sector, as they employ high-purity $H_2$, with only water emissions in the energy generation. They operate at low temperatures (60–85 °C), which allows fast start and stop cycles, as well as dynamic load profiles typically required by transport applications. Indeed, different kinds of vehicles can nowadays exploit PEMFC technology for propulsion or power auxiliaries; some examples are motorcycles, cars, buses, forklifts, trucks, trains, boats, and airplanes [52–60]. In 2020, more than 25,000 fuel cell vehicles were operating worldwide, which is a significant achievement [61]. However, some bottlenecks slow down the larger spread of the technology. The hydrogen infrastructure is still missing or not developed enough. Besides, despite a general decrease, FC costs are still high, especially due to the catalyst layer, as PEMFCs require a platinum-based catalyst to enhance the reactions. However, $CO/CO_2$/sulfur that can be contained in the fuel easily poisons the catalyst. Thus, PEMFC must use a pure hydrogen stream at the anode side to avoid irreversible voltage decay that may arise from platinum contamination. These problematics affect the lifetime of the fuel cells, which is eventually lower than expected for conventional ICEs.

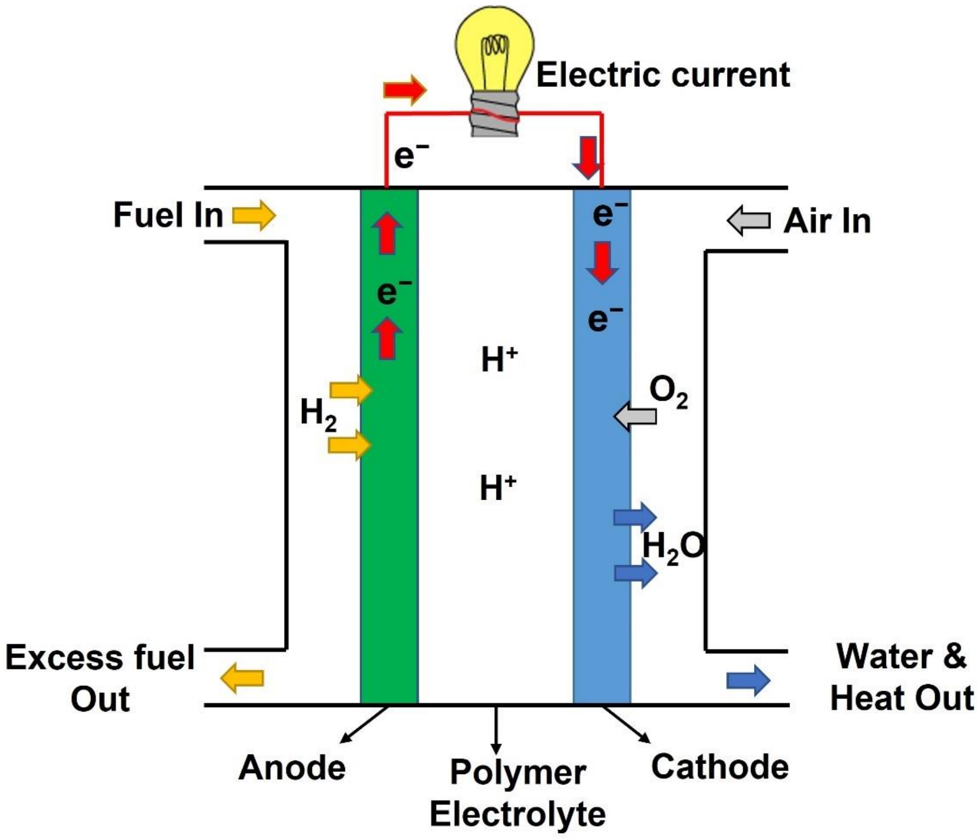



**Figure 1.** Basic schematic diagram of a PEMFC.

*2.2. Solid Oxide Fuel Cells (SOFC)*

Solid Oxide Fuel Cells (SOFC) work at very high temperatures, the highest among all the fuel cell types (around 800 °C–1000 °C). They have an efficiency of up to 55–60% when converting fuel to electrical energy; the high operating temperature gives the possibility of employing SOFC in hybrid systems with gas turbines (GT) and for Combined Heat and Power (CHP) applications [62,63]. The hybrid system can achieve very high performance at part load with low emissions compared to other systems [64]. The advantages of SOFC hybrid systems have been investigated since the end of the last century [65,66]. One of the main hybrid systems is the integration of pressurized SOFC with a micro gas turbine (mGT) [67], which leads to an increase in electrical efficiency that can be reached up to 65% [20]. Previous papers investigated the effect of using different liquid fuels in SOFC-GT hybrid systems considering various fuel-processing techniques [68–70].

SOFCs use a solid ceramic electrolyte, such as zirconium oxide stabilized with yttrium oxide, instead of a liquid (used for alkaline cells) or aqueous membrane (used for PEMFC). The main components of planar SOFC are an anode, solid ceramic electrolyte, cathode, and bipolar separator plate [71]. The molecular oxygen becomes oxide ions ($O^{2-}$) and combines with hydrogen to form water while simultaneously producing electrical energy, as shown in Figure 2 [72].

Fuel flexibility is one of the advantages of solid oxide fuel cells: thanks to their high operating temperature, the fuel can be reformed within the fuel cell itself, eliminating the need for an external reformer and allowing the units to operate with a variety of hydrocarbon fuels [73]. They are also relatively resistant to small quantities of sulfur in the fuel compared to other fuel cells. A further advantage of the high operating temperature is that the reaction kinetics are improved, removing the need for noble metal catalysts. The high temperatures and absence of a metal catalyst allow for higher tolerance to impurities in the reactants [74].

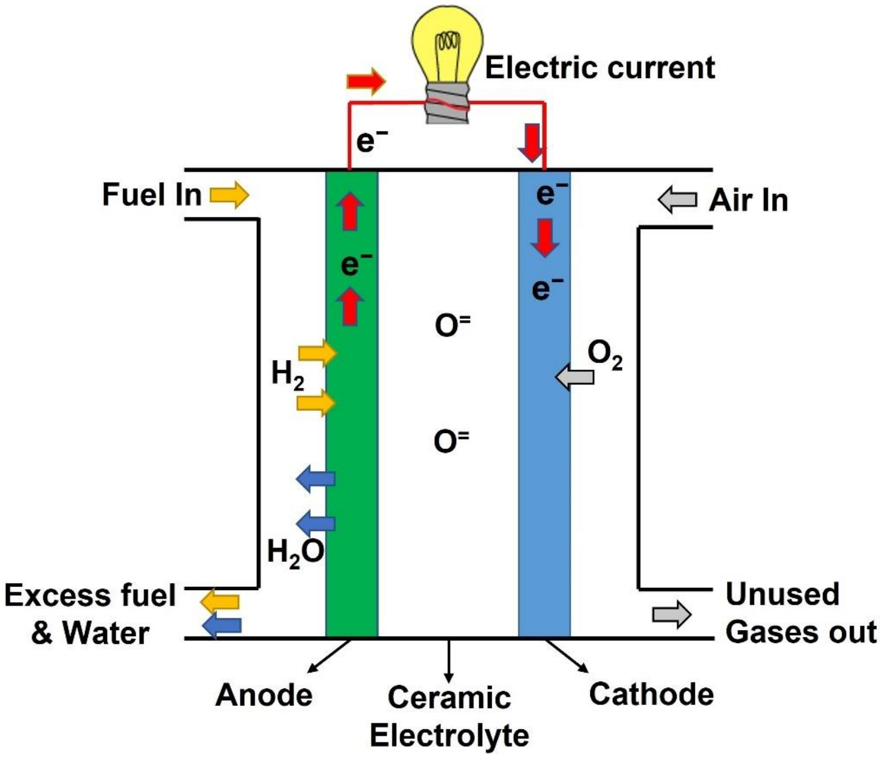



**Figure 2.** Basic schematic diagram of a SOFC.

However, high temperature leads also to some disadvantages, as the system has an intrinsically higher complexity. SOFCs must be constructed of robust, heat-resistant materials and be shielded to prevent heat loss. Besides, SOFCs take longer (up to hours) to start up and reach the operating temperature, to avoid mechanical damage to the ceramic materials of the cell. Furthermore, they should operate at constant loads during operation to avoid thermal stress. For this reason, the research is pushing to find new materials to operate the SOFC at lower temperatures (around 600 °C) [42].

SOFCs find application in large and small stationary power generation (thus, where they operate at constant load). Three different geometries are possible: planar, coplanar, and micro-tubular. Planar types, for instance, find application in Bloom Energy's 100 kW off-grid power generators, and SOFCs with an output of a few kW is an option for smaller CHP applications, such as domestic: the BlueGen device developed by Solid Power is a good example of that [75]. Micro-tubular SOFCs with output in the Watt range has been developed for small portable chargers. Thanks to the advantages described earlier, such as fuel flexibility (natural gas, methane, methanol, biodiesel, and ammonia can all be employed), high resistance to poisoning compounds, and thanks to the high power that can be reached through SOFC stacks modularity, this technology is gaining attention for its potential in maritime applications. Fuel cells based on solid oxide technology offer a high operational efficiency, which can further be enhanced by utilizing the heat generated by these SOFCs while operations

### 2.3. Fuels for PEMFC and SOFC

To compare different fuels for application in fuel cells, namely in PEMFC and SOFC, two main aspects must be considered from the technical point of view: gravimetric and volumetric energy densities, reported in Figure 3 for both traditional and alternative fuels, focusing on the main devices for maritime applications, including fuel cells [76]. Red squares represent oil-derived fuels, which include the current most employed solutions for the transportation sector, including maritime, as they are liquid at ambient conditions and they present high volumetric density (about 35 MJ/l for diesel, which is, in fact, the most common solution on large size ships, in the form of MDO). Methanol is also liquid in ambient conditions, which represents an advantage: however, its energy density is less than half compared to MDO [77]. LNG has higher gravimetric and volumetric energy densities, but storage in liquid form requires cryogenic temperatures (−161 °C) [14]. Both methanol and LNG [17,78,79] can be interesting solutions to reduce SOx and NOx emissions, at the same time reducing the impact in terms of $CO_2$: however, since they still contain carbon in their molecule, they are not carbon-free, and they cannot meet the very ambitious targets set by IMO.

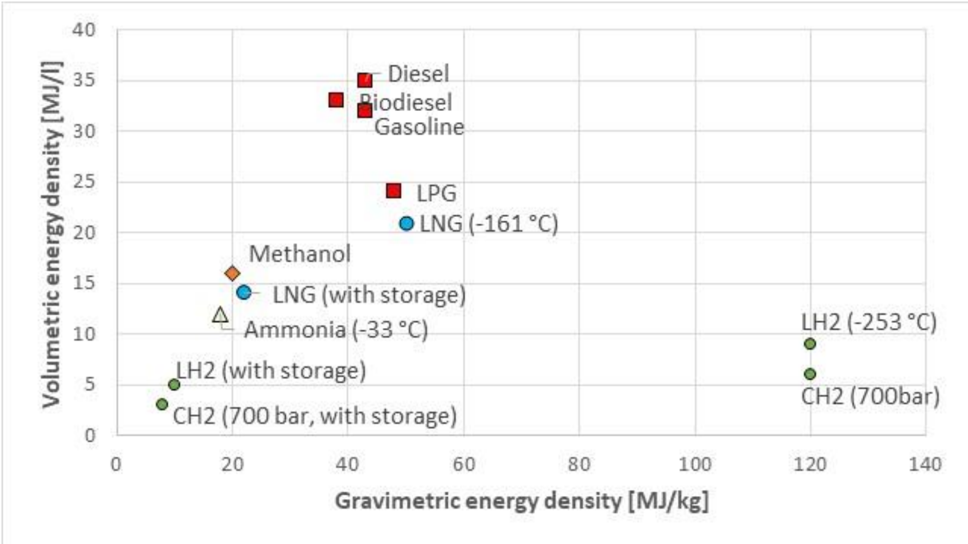



**Figure 3.** Gravimetric and volumetric energy density of different fuels.

Ammonia and hydrogen have lower energy density in volume terms, which is a drawback in terms of storage onboard; on the other hand, they have zero CO, SOx, and $CO_2$ emissions; in the case of $H_2$ utilization in PEM fuel cells, also NOx emissions are zero. Thus, several authors investigated ammonia and hydrogen potential for maritime applications in recent years [80–82].

From Figure 3, it is evident that the need for high purity Hydrogen in PEMFC presents some drawbacks in terms of volumetric energy density: thus, although PEMFC has a good power density, $H_2$ storage onboard will require larger volumes and weights. The influence of the storage system in the case of compressed/liquid hydrogen is evident. Moreover, in the case of LNG, the storage system decreases the energy density, even with a lower impact. SOFC is more flexible with fuel, as they usually operate with higher energy density fuels, commonly natural gas or liquid fuels (i.e., methanol). On the other hand, SOFC is less compact compared to PEMFC.

### *2.4. FC Systems Producers on the Market*

The fuel cell market has been growing over the last few years, as the total units shipped from all applications (transport, stationary and portable) have increased by 22% between the years 2017 and 2021, while total MWs shipped have increased by 251% in the same time frame, and it is expected to grow more and more to achieve 2030 objectives. In 2017, 658.6 MW were shipped from all fuel cell types, while in 2021, this amount grew 2.5 times to 2313.1 MW from all fuel cell types [47]. Geographically, most of the fuel cell market is in Asia, Europe, and North America; Asia held the largest share, with 56.2 million units in 2021, with 1493.2 MW shipped power [47].

2.4.1. PEMFC

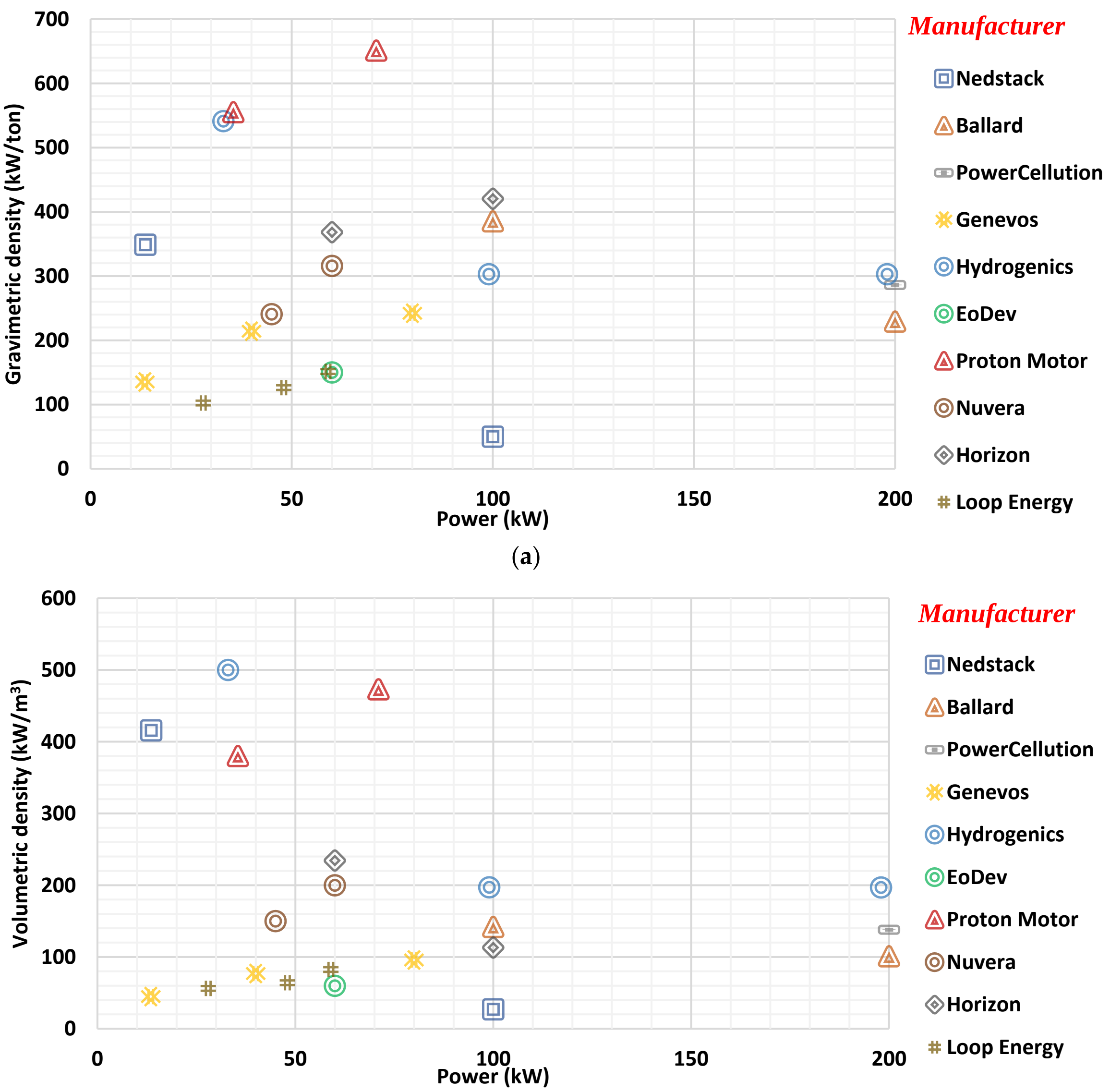
The PEMFC market has been growing over the last few years, as the total units shipments have increased from 43,700 units in 2017 to 55,200 units in 2021 (26.3% increase), while the energy size has been developed from 466.7 MW in 2017 to 1998.3 MW in 2021 [47]. The fuel cells for marine vessels market is expected to reach 390.5 million USD by 2030 [83]. From the commercialization point of view, many suppliers are carrying out production and development activities of PEMFC technology for several applications. Table 2 shows the main features of the available PEMFC products from several manufacturers such as Ballard [84], Nedstack [85], Genevos [86], Proton Motor [87], PowerCellution [88], Energy observer developments (EODev) [89], Hydrogenics [90–92], Loop Energy [93], Horizon [94] and Nuvera [95].

**Table 2.** Technical specifications of PEMFC products.

| FC Supplier | Model | Power (kW) | Efficiency (%) | Power Density (kW/ton)/(kW/m$^3$) | Voltage Range/Current Range | Lifetime (h) | Reference |
|---|---|---|---|---|---|---|---|
| Ballard | Fcmove-HD | 70 | 57 | 280/150 | 250–500/20–240 | - | [84] |
| | Fcmove-HD+ | 100 | 57 | 385/142 | 280–560/20–360 | >20,000 | [84] |
| | Fcwave | 200 | 56 | 229/101 | 350–720/0–600 | >20,000 | [84] |
| PowerCellution | PS 200 | 200 | 54 | 286/138 | 500–1000/60–450 | >10,000 | [88] |
| Genevos | HPM-15 | 13.5 | 52 | 135/54 | 48 | >20,000 | [86] |
| | HPM-40 | 40 | 54 | 214/77 | 230–800 | >20,000 | [86] |
| | HPM-80 | 80 | 55 | 242/96 | 400–800 | >20,000 | [86] |
| Nedstack | MT-FTCI-100 | 100 | 55 | 50/27.1 | 300–600/0–200 | 24,000–30,000 | [85] |
| | MT-FTCI-500 | 500 | 55 | 41.7/14.6 | 500–1000/0–1200 | 24,000–30,000 | [85] |
| Proton Motor | PM 400–120 | 35.5 | 47–67 | 555/380 | 71–137/0–500 | - | [87] |
| | PM 400–240 | 71 | 47–67 | 651/473 | 142–275/0–500 | - | [87] |
| Toyota EODev | REXH2 | 60 | 30 | 150/60 | 600 | 13,000 | [89] |
| Hydrogenics | HyPM-HD 30 | 33 | 55 | 541/500 | 60–120/0–500 | >10,000 | [90] |
| | HyPM-HD 90 | 99 | 55 | 302.8/197.2 | 180–360/0–500 | >10,000 | [91] |
| | HyPM-HD 180 | 198 | 55 | 302.8/197.2 | 360–720/0–500 | >10,000 | [92] |
| Loop Energy | S300-S | 28 | 56 | 102.2/56.3 | 370–450/0–300 | - | [93] |
| | T505-S | 48 | 55 | 126.3/64.3 | 370–450/0–300 | - | [93] |
| | T600-S | 59 | 66 | 151.3/82.6 | 370–450/0–300 | - | [93] |
| Horizon | VL II-M60 | 60 | 48 | 368.1/234.4 | 250–700/400–550 | - | [94] |
| | VLII-M100 | 100 | 48 | 420.2/113.3 | 250–700/400–550 | - | [96] |
| Nuvera | E-45-HD | 45 | 50 | 240.6/150 | 290/312.5 | - | [95] |
| | E-60-HD | 60 | 50 | 315.8/200 | 180/375 | - | [95] |

For maritime applications, Ballard holds significant shares in the PEMFC market because of its high experience in the development and production of PEMFC for transport applications [84]. Nedstack has recently developed two maritime fuel cell power systems offering compact and robust options for marine applications [85]. Hydrogenics has supplied its module HyPM HD 30 for providing fuel cell technology onboard passenger ferries (SF-BREEZE) [97]. Nuvera has developed two fuel cell power solutions that can be applied onboard ships. The Norwegian company (TECO 2030) has received approval in principle to develop and produce a 400-kW module to supply its system to Chemgas Shipping BV, which planned to install fuel cell systems onboard its fleet [47].

The gravimetric densities of different PEMFC products available in the market are discussed in Figure 4a; the gravimetric density of PEMFC achieves the range of 100–700 W/kg while the maximum power capacity of a single stack is 200 kW. Similar observations have been applied to the volumetric power density, as shown in Figure 4b; the PEMFC systems offer a power density of 45–500 kW/m$^3$, led by Proton Motor, Horizon, and Hydrogenics (over 200 kW/m$^3$).




(**a**)



(**b**)

**Figure 4.** PEMFC products (**a**) Gravimetric power density (**b**) Volumetric power density.

Based on the literature review, capital costs for the PEMFC stack for maritime applications is ranged between 500–1200 $ USD/kW depending on its capacity and the producer [98–101], while the capital cost for the whole system (including auxiliary equipment, batteries, and propulsion motor) is estimated in literature in the range 2400–3400 $ USD/kW [102,103]. Based on ref [104], FCS capital cost decreases dramatically with increasing system size and the annual production rate. The system size increase has a greater impact on decreasing the capital cost than increasing the production rate, which is a positive point for maritime applications that often require high installed power. The study results indicated that the capital cost of a 100 kW PEMFC system equals 2278 $ USD/kW when the manufacturing rate is 100 systems/year, while the price will decrease to 1652 $ USD/kW by producing 50,000 systems/year. The O&M cost is 5% of the capital cost for the whole life of the FCS [105].

### 2.4.2. SOFC

The market size of SOFC is expected to grow from USD 1.5 billion in 2022 to USD 6.5 billion by 2027 at a Compound Annual Growth Rate (CAGR) of 33.9% during the forecast period. The market will be developed based on the increase in funding from different organizations that seek more improvement in research and development of fuel cell technology in terms of fuel flexibility, high electrical efficiency, and emissions reduction. These development points can be achieved through investing in the SOFC market, which will benefit end users and the industry sector [106].

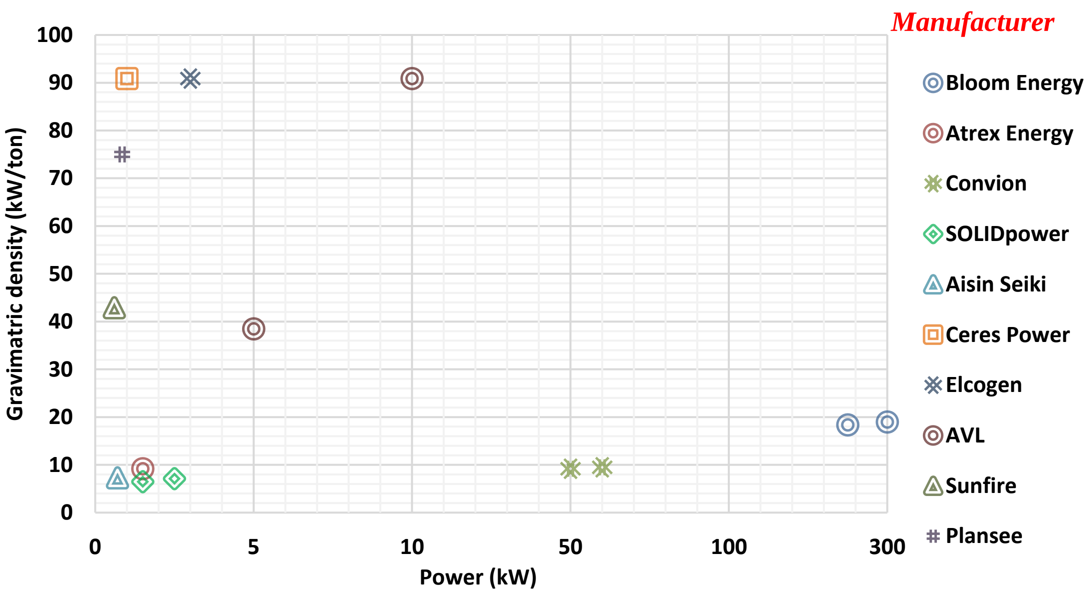
The major players in the SOFC market are Bloom Energy (US), Atrex Energy (US), Aisin Seiki (Japan), SOLIDpower (Italy), Convion ltd. (Finland), Elcogen AS (Estonia), and others. The main SOFC suppliers and products are summarized in Table 3. Bloom Energy can provide hundreds of kW solutions with an electrical peak efficiency higher than 53% [107]. Atrex Energy's tubular design can eliminate the damage caused by temperature gradients [108]. Convion is a company based in Finland and established in 2012, which continued the development of fuel cell technology based on the Wartsila fuel cell program and supplied anode-supported fuel cells fueled by natural gas or biogas [24]. Elcogen is a private company in Estonia that produces anode-supported fuel cells that can be operated at a lower temperature range of 600–700 °C [109,110]. SOLIDpower is an Italian power company specializing in producing and developing SOFC for stationary applications [109].

**Table 3.** Technical specifications of SOFC products.

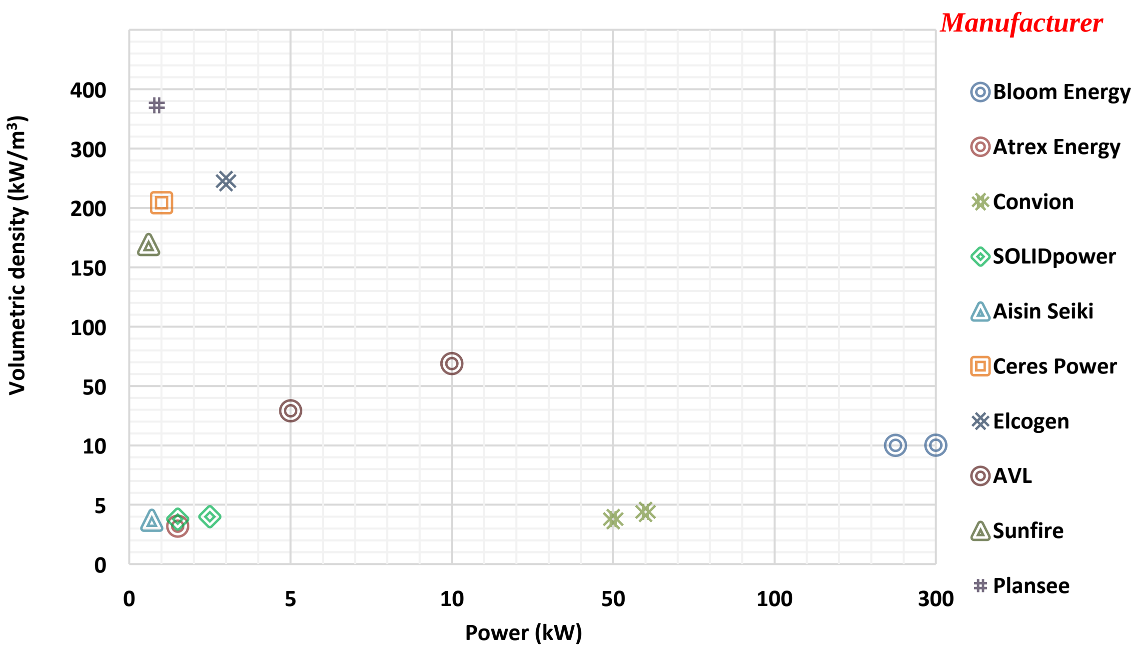
| FC Supplier | Model | Power (kW) | Efficiency (%) | Power Density (kW/ton)/(kW/m$^3$) | Voltage Range/Current Range | Lifetime (h) | Reference |
|---|---|---|---|---|---|---|---|
| Bloom Energy | ES5-EAXAAC<br>Energy server 5 | 250<br>300 | 53–65<br>53–65 | 18.4/10.1<br>19/10.2 | 480<br>480 | >5000<br>>5000 | [107]<br>[107] |
| Atrex Energy | 1.5 kW JP-8 | 1.5 | - | 9.2/3.2 | - | >10,000 | [108] |
| Convion Ltd. | Convion C50<br>Convion C60 | 50<br>60 | 53<br>60 | 9.2/3.8<br>9.5/4.4 | 400–440<br>380–500 | -<br>- | [109]<br>[109] |
| Elcogen | E3000 | 3 | 55 | 90.9/245.2 | 81–141/30–40 | >20,000 | [109,110] |
| SOLIDpower | -<br>- | 1.5<br>2.5 | 60<br>50 | 6.5/3.8<br>7.14/- | -<br>- | 8700<br>8700 | [109]<br>[109] |
| Aisin Seiki | ENE-Farm Type S | 0.7 | 46.5 | 7.3/3.7 | 100 | >20,000 | [109] |
| Ceres Power | 1 kWe Steel Cell stack | 1 | 50 | 90.9/208.8 | - | >10,000 | [111] |
| AVL | -<br>- | 5<br>10 | 35–45<br>55 | 38.5/33.3<br>90.9/69 | 85–150<br>85–150 | >20,000<br>>20,000 | [112]<br>[112] |
| Sunfire | - | 0.6 | 40–48 | 42.9/169.2 | - | >30,000 | [19,109] |
| Plansee | - | 0.85 | 47 | 75/373 | - | >20,000 | [19] |

The SOFC mass power density is generally much lower than that of the PEMFC, as shown in Figure 5a. The mass power density of SOFC stacks is usually below 90 W/kg. Large SOFC systems are mainly from US companies, particularly Bloom Energy, while SOLIDpower offers almost the least system power density (~6.5 W/kg). As far as the volumetric power density is concerned, Figure 5b highlights that SOFC technology provides lower volumetric density (in the range of 3–10 kW/m$^3$) compared to PEMFC (100–600 kW/m$^3$).

As for PEMFCs, considering that the investment cost is sensitive to the production volume, the capital cost of a 100 kW SOFC system is equal to 2242 $ USD/kW by producing 100 systems/year, while the capital cost decreases to 1816 $ USD/kW by producing 50,000 systems/year [104]. For SOFC-powered ships, it is found that FCS capital cost is about 2200 $ USD/kW [100]. SOFC maintenance and operation costs are estimated in the literature to be 5% of the capital cost [105] or 10% of the capital cost over its lifetime [100].




(**a**)




(**b**)

**Figure 5.** SOFC products (**a**) Gravimetric power density (**b**) Volumetric power density.

### *2.5. Available Legislation for the Installation of Fuel Cells for Maritime Applications*

Proton Exchange Membranes and Solid Oxide FC are largely investigated to decarbonize the maritime sector, and many international projects are evaluating the best system design and integration onboard ships of different sizes. This topic will be discussed in the next Section. Nowadays, as a dedicated regulation does not exist, the integration process of a fuel cell-based system must follow the Alternative Design procedure (AD). The latter is a general procedure based on Risk Assessment (RA), carried out by classification societies, that allows the introduction of a limited number of unregulated variants within the project if they demonstrate, through the RA, the same security level required for the traditional design. Thus, to proceed with an objective evaluation of the performance of an FCS on board, it is not possible to refer to internationally recognized technical documents. Consequently, today it is necessary to analyze the regulations and the available standards published by Classification Societies (CS), and standardization criteria (such as the ISO and/or IEC) recognized at European and national levels. Indeed, even though new international legislation is expected in the future, the CS, such as the Italian Naval Register (RINA), are developing internal rules that define the safety requirements that FCS must comply with to be installed on board.

To fill the gaps in the development of unequivocal legislation for FC installation onboard ships, different studies are under development. The project FC-PROMATE, led by BluEnergy Revolution [113], is developing testing protocols to assess the suitability of a PEMFC system for onboard installation. The tests defined which consider different typical environmental and maritime conditions—have been implemented on a 35-kW system in the EU Joint Research Centre (JRC) laboratories in Petten (NL), thanks to the EU call for open access to the JRC's hydrogen testing infrastructure. Besides, in the context of this project, the existing legislation has been revised to create a new one in collaboration with RINA, specifically dedicated to the maritime FCS topic. To consider in the broadest and most precise way 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 operating conditions), the considered regulations of the CS and the standards related to fuel cells are reported in Table 4.

**Table 4.** Baseline legislatives considered in the FC-PROMATE project to draw new specific legislation for the installation of PEMFC systems onboard ships.

| Existing Legislation | Topic |
|---|---|
| IACS UR-E10 | Defines the test specifics for the Type Approval (TA) test of electrical systems |
| IEC 62282 | Describes the TA for FC systems for the installation in stationary, portable, micro, and vehicle applications. It has also been considered for what concerns the environmental conditions—vibrations, temperature, and wind—which the FC system should withstand, comparing these conditions to the ones applicable to Auxiliary Power Units (APU) on heavy-duty transport installations. |
| RINA-FC | Specific to FC systems, it gives important guidelines for their installation onboard ships, citing the IEC 62282 as a reference for the TA. |
| RINA RULES, PART C | Regulations refer to all the machinery, electrical installations, and 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. |

## 3. Maritime Applications of Fuel Cell Systems

### *3.1. International Research Projects*

FCS has been used for maritime applications in many research projects funded by many Countries and applied to several ship types, as shown in Table 5. The list included all research projects focused on applying fuel cell technology on board ships since 2000, mentioning the logistic fuels used, the type of fuel cell, and its power size. The most recent projects are discussed in this section.

#### 3.1.1. ShipFC (2020–2024)

This project is funded by EU- Horizon 2020 and coordinated by NCE Maritime Clean-Tech [114]. The aim of the project is to deliver a safe and effective power source reaching 2 MW to an offshore vessel called Viking Energy which is owned by Eidesvik, by using a retrofitted SOFC fuelled by Ammonia and allowing the clean sailing for up to 3000 h annually. The first target of the project is to start the installation process of the retrofitted system in late 2023. The second objective is to study the possibility of transferring this kind of technology from technical and feasibility perspectives to other vessel types, such as cargo ships, bunker vessels, and offshore construction vessels, which include operational profiles reached to 20 MW.

#### 3.1.2. Maranda (2017–2022)

Maranda (Marine application of a new fuel cell powertrain validated in demanding arctic conditions) is a project that received funding from the EU under Fuel Cells and Hydrogen Joint Undertaking and has been coordinated by the VTT Technical Research Centre of Finland. The aim of the project is to develop and test a marine power plant based on hydrogen FCS. The project has succeeded in developing PEMFC fueled by hydrogen in a hybrid system for marine applications and testing it onboard a research vessel called Aranda. The fuel cell plant includes 2 × 82.5 kW modules based on PowerCell S3 commercial stacks and fueled by compressed hydrogen at 350 bars; it succeeded in covering the power requirements for electrical equipment and a dynamic positioning system. The project has alleviated the problem of hydrogen infrastructure by developing a mobile storage container for hydrogen, which can easily be refueled [115].

#### 3.1.3. Nautilus (2020–2024)

Nautilus (Nautical Integrated Hybrid Energy System for Long-haul Cruise Ships) is funded by EU-Horizon 2020 with support from nine industrial partners and six research organizations from nine EU countries coordinated by the German Aerospace Center. The aim of the project is to develop and validate a hybrid power system based on SOFC fueled by LNG, a battery system, and the existing internal combustion engine, which will be applied onboard a cruise ship. The target is to cover the electrical demand of cruise ships by using clean technology through a SOFC-battery hybrid system. The project will use a virtual demonstrator to validate the design process of the energy system under marine conditions of a size between 5 and 60 MW for two categories of cruise ships to occupy 1000 and +5000 passengers [116]. As well as a laboratory scale (30 kW SOFC + battery) and functional genset demonstrator (60 kW SOFC + battery) will be designed and implemented for energy system design validation against marine safety rules. The testing of SOFC on an inclination pod was started in June 2022 and developed by SOLIDpower to validate the safety design of the fuel cell unit [117].

#### 3.1.4. HyShip (2021–2024)

HyShip includes 14 EU partners, receives its funding from Norwegian government-owned organization Enova, and receives support from the EU Horizon 2020 program. The project aims to design and build an innovative ro-ro vessel (Topeka) powered by green liquid hydrogen through 3 MW-PEMFC integrated with a 1 MWh battery system. The green hydrogen will be provided by the RES plant at Mongstad (Norway). Topeka will be a vessel to carry cargo for customers and distribute liquid hydrogen to bunkering stations along the Norwegian coast. The project will carry out different studies for other ship types, such as bulk carrier, ferry, and tanker barge, which has an operational profile powered by 20 MW, 3 MW, and 1 MW, respectively [118].

#### 3.1.5. RiverCell (2015–2022)

RiverCell is a project funded by Germany's Federal Ministry for Digital and Transport and coordinated by Meyer Werft with support from eight other partners from the maritime industry [119]. The project aims to design and develop a hybrid propulsion system including two PEMFC modules (90 kW), three diesel generators, and two battery packs to be applied onboard an inland passenger ship in Germany. The project succeeded in setting up a ship section of an inland passenger ship at Neptun Werft in Rostock, Germany, to be a test environment for the proposed hybrid system [120]. The marine fuel cell developed by Advent Technologies, powered by methanol as a hydrogen carrier, was successfully tested in the project, as it passed the safety experiment assessment and achieved efficient performance integrated into the hybrid system [36].

#### 3.1.6. TecBIA (2018–2022)

TecBIA (Technologies at low environmental impact for energy production on ships) is a national Italian research project financed by the Italian Ministry of Economic Development (MISE) and coordinated by Fincantieri-Isotta Fraschini Motori S.p.A. The aim of the project is to reduce ship emissions, improve the eco-compatibility of ships in terms of environmental protection and passenger comfort by reducing noise and vibrations and increase safety onboard through the redundancy of generative systems. The project succeeded in developing and testing a Zero-Emission Ultimate Ship (ZEUS) powered by PEMFC and batteries. The project designed the propulsion system based on 2 $\times$ 71 kW ProtonMotor PEMFC modules fueled by hydrogen stored in 48 Metal Hydride tanks ($H_2$ capacity around 45 kg), hybridized with 150 kWh stored energy in two packs of Li-ion batteries [121]. Based on test results in the open sea, concluded in the summer of 2022, the foreseen autonomy (7 h at a cruise speed of 6 knots) has been successfully verified. The project gave an interest in the hybridization between PEMFC, battery packs, and hydrogen stored in metal hydrides [122] and represented the first Italian hydrogen vessel with FC propulsion, which received the approval certificate from RINA.

#### 3.1.7. HI-SEA (2017–2022)

The HI-SEA (Hydrogen Initiative for Sustainable Energy Applications) is funded by Fincantieri and the University of Genoa through the Thermochemical power group (TPG). The project is the fellowship of the TESEO (High-Efficiency Technologies for Energy and Environmental Sustainability On-board) project [123] for continuing the evaluation process of fuel cell systems for maritime applications [124,125]. The project contributed to building an experimental plant for fuel cell testing. The lab consisted of a 9 feet container with two branches (each one including 4 PEMFC modules) manufactured by Nuvera company and provided 240 kW. The fuel cell is fueled by compressed $H_2$, stored at 200 bar, and cooled by using two-stage cooling circuits to keep the constant temperature of seawater. Currently, the project is undergoing a new experimental campaign to analyze and compare the results with other results from the TecBIA project, previously described [126].

#### 3.1.8. HFC Marine (2018–2020)

Ballard Power Systems Europe (BPSE) manages the HFC Marine (Hydrogen fuel cell and battery hybrid technology for marine application) project, which started in 2018 and was completed in 2020. The aim of the project is to investigate the feasibility of the configuration of fuel cell technology in marine transportation, which considers the first step to the electrification of ships. These steps also included the conceptual design of a hybrid system between battery and fuel cell by taking into consideration the maritime challenges. The project contributed to building a lab environment comprised of a 200 kW fuel cell based on the Ballard-FCwave system to conduct required tests and simulations. The project includes two phases, phase 1 for designing the solution and phase 2 for full-scale implementation [127,128]. The first phase is a preparation action of the hydrogen PEMFC to operate in a hybrid system with batteries onboard ships. Then the solution is implemented in the lab environment to be tested under marine conditions. The outcome from this phase has reduced the risk, which can be accomplished in the implementation phase onboard a ferry designed by Odense Maritime Technology. The new ferry will be operated in the coastal sea of the south Funen Archipelago in Denmark [129–131].

#### 3.1.9. HySeas III (2018–2022)

HySeas III is a project funded by the EU Horizon 2020 program and connects nine European partner organizations across seven European countries related to the maritime industry, such as ship owners, port operators, fuel cell power systems suppliers, ship design offices, and research institutions. The project is a continuous work that gained its value from the previous editions that began in 2013 under the project called (HySeas I) which was supported by Scottish Enterprise and followed by the second edition in 2015 called (Hyseas II) which was also supported by Scottish Enterprise and the Canadian department of transport. The third stage of the development program (HySeas III) seeks to make significant progress in eliminating $CO_2$ emissions from marine transport to be in line with the EU's Green New Deal & Fit for 55 objectives [132]. HySeas III is looking into the construction of a zero-emission power system onboard a RoPax ferry operated in Scotland, between Kirkwall and Shapinsay in the Orkney Islands [133]. The planned passenger capacity of the ferry is 120 passengers with 20 passenger vehicles or two lorries. The ship dimensions length, beam, and depth will be 40 m, 10 m, and 4 m, respectively. The project succeeded in the full-sized string test and verification of the innovative power system, which included PEM fuel cell technology consisting of a 6 × 100 kW Ballard HD-100 fuel cell with Lithium-ion battery banks that have a capacity equal to 768 kWh. The planned prototype will be fueled by 600 kg of compressed hydrogen at 350 bars [134]. The hydrogen will be produced by electrolysis powered by wind and tidal energy generated within the research projects BIG HIT and SURF 'N' TURF on the islands of Eday and Shapinsay [135,136].

#### 3.1.10. Pa-X-ell 2 (2019–2022)

Pa-X-ell 2 is the second phase following the results of the PaXell project; it is a part of the National Hydrogen and Fuel Cell Technology Innovation Program, funded by the German Federal Ministry of Transport and Digital Infrastructure and managed by Meyer shipyard cooperative with eight other partners. The aim of the project is to develop, conceptualize and test new fuel cell technology in a hybrid system onboard a seagoing ship following the results from the PaXell project. The target fuel is the hydrogen reformed from methanol using an internal reformer inside the PEMFC system [137]. In the project, a fuel cell system is being tested on a cruise ship called AIDAnova, which will be powered by 2 MW so that the new system allows for sailing with minimal noise, vibration, and emissions. The test of a new fuel cell from the manufacturer Freudenberg [138] proved the durability of the system with 35,000 operating hours [139].

#### 3.1.11. SHIPPINGLAB (2020–2024)

ShippingLab is a project based in Denmark between many partners from different stakeholders, including ship owners, universities, research organizations, maritime authorities, shipyards, and clean energy solutions companies. The project includes four work packages with a common goal of creating the first autonomous and environmentally friendly ship in Denmark. The project aims to design and demonstrate a zero-emission power solution for a dredger in Hvide Sande Port based on the hydrogen fuel cell system hybridized with batteries. The fuel cell system is based on LT-PEMFC fueled by compressed hydrogen, which is produced by electrolysis powered by the wind energy from three wind turbines, 3MW, which is also part of the project. Ballard Power Systems Europe will develop the fuel cell system as a partner in the project [140].

#### 3.1.12. HIMET (2021–2022)

HIMET (Hydrogen in an Integrated Maritime Energy Transition) is a project funded by the Department for Transport's Clean Maritime Demonstration Competition & Innovate UK and led by European Marine Energy Centre (EMEC) Hydrogen in Orkney, including ten other partners. The aim of the project is to find solutions to be implemented onboard ships operated in Orkney to decarbonize it by using a hydrogen fuel cell as an auxiliary power system and a containerized hydrogen storage onboard the RoRo ferry (MV Shapinsay). Another objective of the project is to test the conventional ICE when fueled with pure hydrogen at the experimental lab in Shoreham. The project will explore hydrogen engine and microgrid solutions to power ferry terminal facilities. The hybrid system between hydrogen engine and solar PV will be demonstrated at Hatston Pier in Orkney to provide the required power for facilities of crew welfare at the terminal. The project chose Genevos, one of the fuel cell suppliers, to supply PEM fuel cells to be installed onboard MV Shapinsay as an auxiliary power system [141].

#### 3.1.13. FLAGSHIPS (2019–2023)

The FLAGSHIPS is a project funded by the European Union project called Clean Hydrogen Partnership (previously Fuel Cells and Hydrogen Joint Undertaking) through 11 partners with ship owners that have many experiences in the shipping industry, fuel cell technology, and electrical power systems. The aim of the project is to implement two zero-emission vessels powered by hydrogen fuel cell technology in France and the Netherlands to increase the alacrity of this technology in the shipping industry. The first ship operated on the Seine River in Paris, France (ZULU) is a self-propelled barge powered by a 2 × 200 kW PEM fuel cell system with a 350 kg hydrogen produced from electrolysis stored at a 300 bar compressed tank. ZULU will carry the cargo in the shape of containers and pallets [142]. The other ship operated on the river Rhine between Rotterdam in Netherlands and Duisburg in Germany (FPS Waal—Formerly named Fenny 1) is a 200 TEU container cargo ship powered by a hybrid system including PEM fuel cell system, battery, and electric motor. The integrated power to propel FPS Waal is around 1200 kW. Currently, FPS Waal is under retrofit operation and scheduled to be in operation by summer 2023 [143].

#### 3.1.14. H2PORTS (2019–2023)

H2PORTS is a project funded by the EU cooperation between nine partners, which have received funding from Clean Hydrogen Partnership (previously Fuel Cells and Hydrogen Joint Undertaking). The aim of the project is to enhance the industry of marine ports by using fuel cell technologies to improve energy efficiency, achieve sustainable development goals and increase durability and safety in different terminals [144]. The project was established at Valencia Port in Spain through a demonstration of Reach Stacker and Yard Tractor to be operated in the MSC terminal and Valencia Terminal Europa, respectively [145]. The two solutions will be used for real port activities every day for two years and will analyze the different options to improve the performance, energy efficiency, and safety of operations. The yard tractor is powered by the hybrid system using a battery system (60 kWh) and a fuel cell system from Ballard (e-HD), with 70 kW-installed power, fueled by hydrogen [146]. Thus, the project aims to install a hydrogen refueling station in Valencia port to facilitate the work of fuel cell technology.

### *3.2. Ships Operated by Fuel Cell Systems*

The wide variety of power range of fuel cell types makes them reasonable for different maritime applications, as Table 1 shows. The most common type for installation in maritime applications is PEMFC fueled by hydrogen for application onboard ships operating near the shore and the hydrogen refueling stations like tourist boats, canal boats, and passenger/car ferries. Based on SOFC research projects in Table 5, this technology has been installed onboard different vessels, such as cruise ships, car carriers, general cargo ships, and offshore vessels. Table 6 shows the application of fuel cell systems as a power source in the maritime industry and discusses the features of ships equipped with FCS.

Based on the data, SOFC has been demonstrated onboard two ships in a capacity of 20–50 kW, while PEMFC has been demonstrated onboard 23 ships in a capacity of 5–3200 kW. Most of the demonstration projects onboard ships have employed PEM fuel cell technology combined with a battery storage system due to easy configuration and development of dynamic performance. However, SOFC technology has more potential in hybridization based on its possibility of heat and power co-generation and high efficiency, but it is limited in maritime applications due to its lower gravimetric and volumetric power densities.

**Table 5.** Overview of international research projects for fuel cell systems in maritime applications.

| Project | Time Period | Country | Fuel Cell Power | Fuel Cell Type | Logistic Fuel | Application | Ship Name | Ref |
|---|---|---|---|---|---|---|---|---|
| FLAGSHIPS | 2019–2023 | The Netherlands/France/ Norway | 1200 kW/ 400 kW/ 600 kW | PEMFC | Hydrogen | Container cargo ship/self-propelled barge/Passenger and car ferry | FPS Waal/Zulu/MF Hidle | [142,143] |
| H2PORTS | 2019–2023 | Spain, Valencia | 70 kW | PEMFC | Hydrogen | Reach Stacker and Yard Tractor | - | [144–146] |
| HFC MARINE | 2018–2020 | Denmark | 200 kW | PEMFC | Hydrogen | Ferry | - | [127–131] |
| SHIPPINGLAB | 2020–2024 | Denmark | N/A | PEMFC | Hydrogen | Dredger | - | [140] |
| HYSEAS III | 2018–2022 | Scotland | 600 kW | PEMFC | Hydrogen | RoPax ferry | - | [132–136] |
| FellowSHIP | 2003–2018 | Norway and Germany | 320 kW | MCFC | LNG | Offshore supply | Viking Lady | [36,147,148] |
| SchIBZ | 2009–2018 | Germany | 100 kW | SOFC | Diesel | General cargo ship, yachts | MS Forester | [149–152] |
| PaXell | 2009–2016 | Germany | 60 kW | PEMFC | MeOH | Cruise ship | MS Mariella | [153] |
| ZEMSHIP | 2007–2014 | Germany | 96 kW | PEMFC | Hydrogen | Inland passenger ship | FCS Alsterwasser | [40,154] |
| Nemo H2 | 2008-present | Netherlands | 65 kW | PEMFC | Hydrogen | Passenger boat | Nemo H2 | [155,156] |
| PaXell 2 | 2019–2022 | Germany | N/A | PEMFC | MeOH | Cruise ship | AIDAnova | [137,139] |
| RiverCell | 2015–2022 | Germany | 90 kW | PEMFC | MeOH | Inland passenger ship | - | [120] |
| ELEKTRA | 2017–2019 | Germany | 300 kW | PEMFC | Hydrogen | Canal tug | Elektra | [36] |
| MC-WAP | 2005–2010 | Italy | 150 kW | MCFC | Diesel | RoPax, RoRo/cruise vessels | - | [157,158] |
| US SSFC | 2000–2011 | US | 625 kW/500 kW | MCFC/PEMFC | Diesel | Naval ships | - | [36] |
| METHAPU | 2006–2010 | European Union | 20 kW 250 kW | SOFC | MeOH | Car carrier | MV Undine | [159–161] |
| FCSHIP | 2002–2004 | European Union | - | MCFC | Diesel | RoPax vessel and harbour commuting ferry. | - | [162] |
| FELICITAS | 2005–2008 | European Union | 250 kW | SOFC—PEMFC | LNG, LPG, CNG | Mega yacht | - | [43] |
| DESIRE | 2001–2004 | Germany—The Netherlands, UK and Turkey | 25 kW | PEMFC | Diesel | Naval ship | - | [163] |
| TecBIA | 2018–2022 | Italy | 140 kW | PEMFC | Hydrogen | Research vessel | ZEUS | [121,122] |

**Table 5.** *Cont.*

| Project | Time Period | Country | Fuel Cell Power | Fuel Cell Type | Logistic Fuel | Application | Ship Name | Ref |
|---|---|---|---|---|---|---|---|---|
| TESEO | 2012–2015 | Italy | 50 kW | PEMFC | Hydrogen | Yachts and sailing boats | - | [123,124,164] |
| HI-SEA | 2017–2022 | Italy | 250 kW | PEMFC | Hydrogen | Experimental plant | - | [126] |
| HIMET | 2021–2022 | United Kingdom | 500 kW | PEMFC | Hydrogen | Ferries | MV Shapinsay | [141] |
| ShipFC | 2020–2024 | Norway | 2 MW | SOFC | Ammonia | Offshore vessel | Viking Energy | [165] |
| Nautilus | 2020–2024 | European Union | 60 kW | SOFC | LNG | Cruise ship | - | [116] |
| Maranda | 2017–2022 | European Union | 165 kW | PEMFC | Hydrogen | Arctic research ship | Aranda | [115] |
| Energy Observer | 2017–present | France | 60 kW | PEMFC | Hydrogen | Experimental vessel | Energy observer | [166] |
| MF Hydra | 2020-present | Norway | 400 kW | PEMFC | Hydrogen | Ro-Pax ferry | MF Hydra | [167] |
| HyShip | 2021–2024 | Norway | 3 MW | PEMFC | Hydrogen | Coastal goods-carrying RoRo | Topeka | [118] |
| NAVIBUS | 2018–2019 | France | 10 kW | PEMFC | Hydrogen | River boat | Jules Verne 2 | [168] |
| FC-PROMATE | 2019–2022 | Italy & Netherlands | 35 kW | PEMFC | Hydrogen | Protocols for testing PEMFC for maritime applications | - | [113] |
| Sea Change | 2016–2022 | USA | 360 kW | PEMFC | Hydrogen | Passenger ferry | Sea Change | [47,169] |
| Hydrogenia | 2019–2021 | South Korea | 100 kW | PEMFC | Hydrogen | Small boat | Hydrogenia | [47,170] |

**Table 6.** Overview of maritime applications powered by fuel cell systems.

| Ship Name | Ship Type | Fuel Cell Type | Specification | Power System | Power Output | Fuel | Ref |
|---|---|---|---|---|---|---|---|
| German-based MTU Friedrichshafen | Yacht | PEMFC | 12-m-long—range 225 km at a speed of 8 knots | 4 × 1.2 kW + 9 lead-gel batteries | 20 kW | Hydrogen | [171] |
| Ross Barlow | Canal boat | PEMFC | - | 5 kW PEMFC module + lead-acid battery | 5 kW | Hydrogen | [155,172] |
| Hydrogenesis | Small boat | PEMFC | Max operating time 10 h at max speed of 7 knots | 12 kW PEMFC module | 12 kW | Hydrogen | [173,174] |

**Table 6.** *Cont.*

| Ship Name | Ship Type | Fuel Cell Type | Specification | Power System | Power Output | Fuel | Ref |
|---|---|---|---|---|---|---|---|
| FCS Alsterwasser | Passenger ship | PEMFC | 25 m long—100 passengers—maximum speed of 8 knots. | 2 × 48 kW PEMFC, 7 lead-gel battery packs 234 kWh, 100 kW propulsion electric motor and a 20-kW bow thruster | 96 kW | Hydrogen | [175] |
| Nemo H2 | Passenger ship | PEMFC | 22 m long—88 passengers—maximum speed of 8.6 knots | 2 × 30 kW PEMFC, 55 lead-acid battery packs 70 kWh, a 75-kW propulsion electric motor and 11-kW bow thruster | 60 kW PEMFC with 30–50 kW battery | Hydrogen | [156] |
| SF-BREEZE | Passenger ferry | PEMFC | 150 passengers—maximum speed of 35 knots | 41 × 120 kW PEMFC, each rack 4 × 30 kW PEMFC stacks. | 120 kW | Hydrogen | [35,176] |
| Cobalt 233 Zet | Tourist Boat | PEMFC | 20-m-long, light weight of 20 tons—50 passengers | 2 × 28 kW PEMFC, 3 × 15.7 kWh Li-ion battery packs | 50 kW | Hydrogen | [177] |
| MS Mariella | Passenger ship | PEMFC | 2500 Pax | 2 × 30 kW PEMFC, each comprised 6 × 5 kW modules. | 60 kW | Methanol | [153] |
| MF Vågen | Small passenger ship | PEMFC | - | - | 12 kW | Hydrogen | [178] |
| Viking Lady | Offshore supply vessel | MCFC | Length 92.2—breadth 21 m-draft 7.6 m-deadweight 5900 ton | 320 kW MCFC as APU, internal reforming unit and WHR system | 320 kW | LNG | [148] |
| MV Undine | Car carrier | SOFC | - | 20 kW SOFC | 20 kW | Methanol | [159–161] |
| MS Forester | General cargo ship | SOFC | - | 50 kW SOFC with Li-ion battery packs developed for APU | 50 kW | Low-sulphur diesel | [149–152] |
| Hornblower Hybrid | Passenger ferry | PEMFC | Length × Breadth: 20 × 10 m | Hybrid ferry with diesel generator, batteries, PV, wind and fuel cell | 32 kW | Hydrogen + Diesel | [36] |
| Class 212A/ 214 Submarines | Submarines | PEMFC | - | Hybrid propulsion using a fuel cell and diesel ICE | 306 kW | Hydrogen | [36] |
| ZEUS | Experimental research vessel | PEMFC | Length = 25.6 m Tonnage = 100 ton autonomy of approx. 8 h at 7.5 knots | 2 × 150 kW diesel generators and 2 electric propulsion motors- 2 × 70 kW Fuel Cell plant and Battery | 130 kW (FC) and 160 kWh (Battery) | Hydrogen | [121] |

**Table 6.** *Cont.*

| Ship Name | Ship Type | Fuel Cell Type | Specification | Power System | Power Output | Fuel | Ref |
|---|---|---|---|---|---|---|---|
| MF Hydra | Ro-Pax ferry | PEMFC | Length 82.4 m, 292 passengers and up to 80 cars—speed of 9 knots | 2 × 200 kW PEMFC and 1.36 MWh Batteries and 2 × 440 kW diesel generators. | 400 kW (FC), 880 kW (ICE), 1.36 MWh (Batteries) | Hydrogen + Diesel | [167] |
| Jules Verne 2 | River boat | PEMFC | 12 passengers and 6 bicycles | 2 × 5 kW PEMFC + Batteries | 10 kW | Hydrogen | [179] |
| FJORDS | Cruise ship | PEMFC | - | 3.2 MW fuel cell + battery | 3.2 MW | Hydrogen | [180] |
| MV Shapinsay | Ro-Ro Ferry | PEMFC | Length 26.6 m, Beam 8.8 m, Draft 1.45 m, Capacity 91 passengers + 12 cars | Hydrogen fuel cell for auxiliary power system | - | - | [141] |
| S80 class | Submarines | PEMFC | 80.8m long | 300 kW FC stacks | - | Hydrogen | [181] |
| MF Hidle | Passenger and car ferry | PEMFC | 199 passengers, 60 cars & 6 trucks.—Daily operation: 260 km, 19 h | 3 × 200 kW PEMFC modules—Battery capacity 500 kWh—Biodiesel generator back-up power | 600 kW | Hydrogen | [182] |
| Topeka | Coastal goods-carrying RoRo | PEMFC | - | 3 MW PEMFC + 1 MWh batteries | 3 MW | Hydrogen | [118] |
| Hynova | Yacht | PEMFC | Autonomy 8 h | 80 kW FC + 2 battery stacks + 2 electric motor of 300 kW | 80 kW | Hydrogen | [183] |
| FPS Maas | Inland container vessel | PEMFC | Length × breadth = 110 × 11.45 m | 825 kW PEMFC + 504 kWh lithium-ion battery pack | 825 kW | Hydrogen | [184] |
| Ulstein SX190 | Offshore construction vessel | PEMFC | Length × breadth × Draught = 99 × 23.4 × 6 m | 2 MW PEMFC | 2 MW | Hydrogen | [185] |
| Zero-V | Coastal research vessel | PEMFC | Trimaran Hull, Length × breadth × Draught = 52 × 17 × 3,7 m, Range: 2400 nm, Cruise Speed: 10 knots, | 10 × 180 kW PEMFC racks | 1.8 MW | Hydrogen | [186] |
| Sea Change | Passenger ferry | PEMFC | Length × breadth = 22 × 7.5 m, 78 passengers, Max speed = 20 knots | 3 × 120 Kw PEMFC + 2 × 50 Kw battery + 2 × 300 kW electric motor | 360 kW | Hydrogen | [47,169] |

**Table 6.** *Cont.*

| Ship Name | Ship Type | Fuel Cell Type | Specification | Power System | Power Output | Fuel | Ref |
|---|---|---|---|---|---|---|---|
| EX38A | Experimental boat | PEMFC | Length × breadth = 12.4 × 3.4 m, Navigation speed = 22 knots, capacity = 10 passengers | 2 × 92 kW PEMFC + 32 kWh battery + propulsion motor 250 kW | 184 kW | Hydrogen | [187] |
| Xianhu 1 | passenger cruise ship | PEMFC | Length × breadth =12 × 4 m, Navigation speed = 22 knots, capacity = 20–30 passengers | 30 kW PEMFC + Battery | 30 kW | Hydrogen | [47] |

### 3.3. Analysis of Past and Present Maritime Applications

In the past 22 years, a significant increase in the number of maritime fuel cell projects occurred. Since 2000, more than 30 relevant funded projects for FCS application onboard ships have been developed on the authors' knowledge, as discussed in Table 5, investigating various fuel cell solutions. The power range of these projects is between 25 kW and 3 MW, incorporating different technologies, such as PEMFC, SOFC, and MCFC. As shown in Figure 6, PEMFC is the most tested technology; it is worth noting (Figure 7) that hydrogen is the most used fuel, as PEMFCs are very sensitive to fuel impurities and must use hydrogen as primary fuel [18]. However, it is worth noting that three projects combined PEMFC with diesel and methanol by using reforming technology in order to avoid the limitations related to $H_2$ storage at high pressure or cryogenic temperature on board, with the related safety and regulatory issues. There are five projects based on SOFC and utilized LNG, Diesel, MeOH, and ammonia as the logistic fuels, on account of the advantage of SOFC technology in high fuel flexibility.

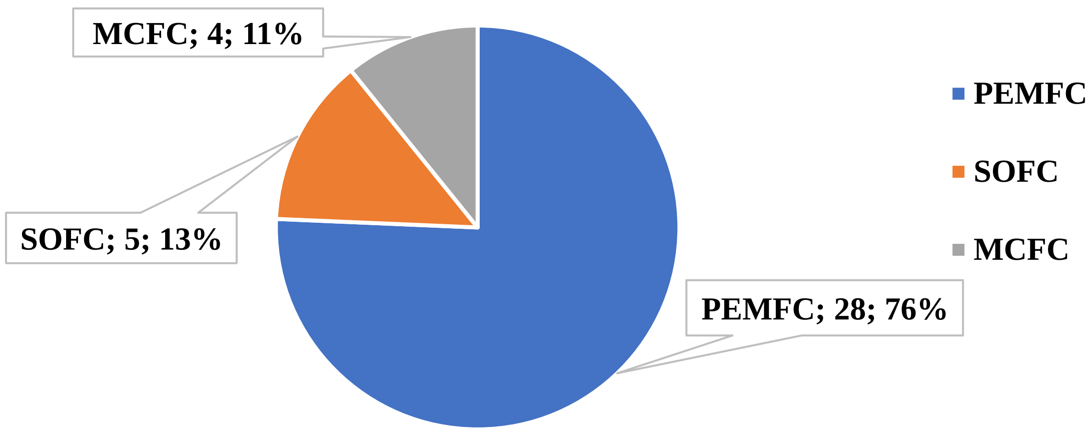



**Figure 6.** Number of research projects applied in the maritime industry by using different fuel cells (Data callout: Fuel cell type; number of projects, percentage).

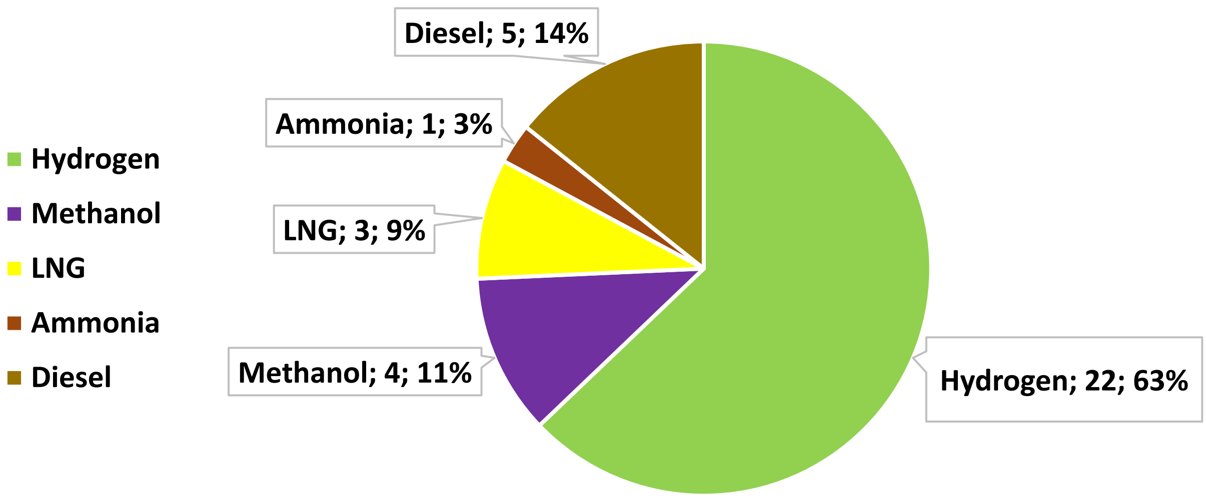



**Figure 7.** Number of research projects applied in the maritime industry by using different fuel types (Data callout: Fuel type; number of projects, percentage).

The results obtained from research projects and ships using fuel cells were collected as mentioned in Tables 5 and 6 and have been analyzed to obtain Figure 8, which shows the distribution of marine applications of the fuel cell in terms of ship type. Passenger ferries and RO-RO ships are the most common types of vessels using fuel cells, as shown in Figure 8, with the PEMFC type integrated into a hybrid system with batteries. Yachts and research vessels had been used as case studies for the fuel cell system 5 and 6 times, respectively. Moreover, cruise ships and offshore support vessels are potentially good candidates to be powered by fuel cell technology. On the other hand, tug and dredgers are the lesser types of ships that have used fuel cell systems on board based on past and present research projects.

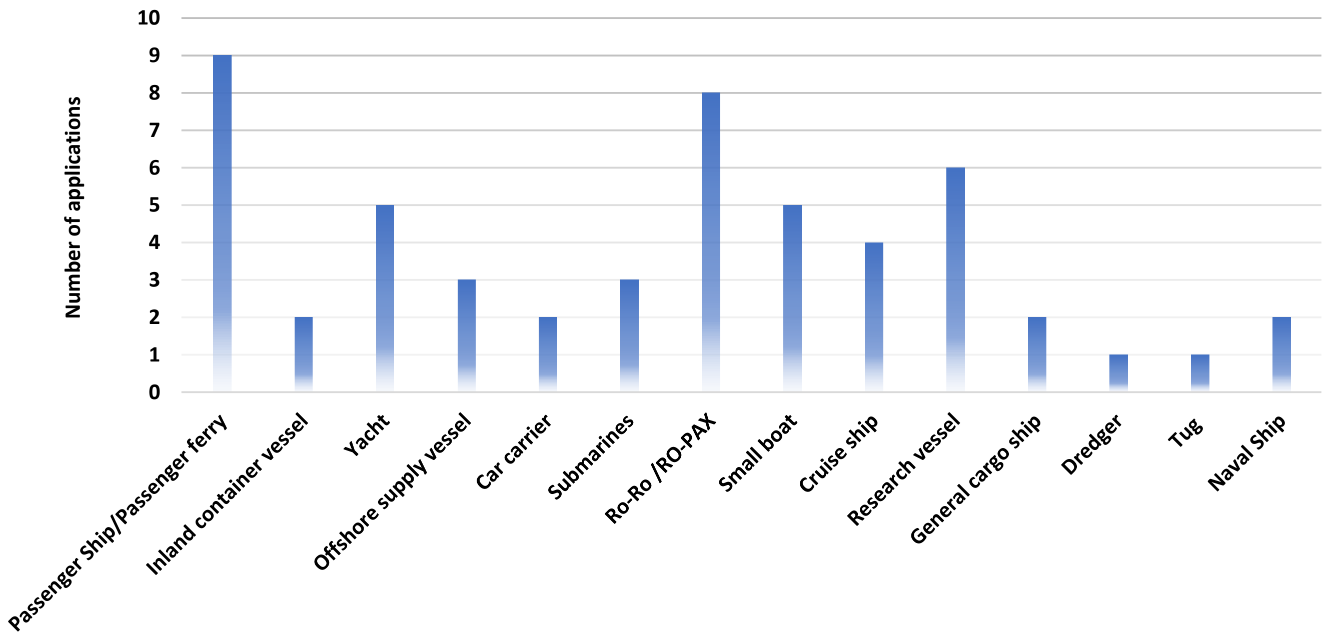



**Figure 8.** Number of applications for different ship types operated by fuel cell systems.

### 3.4. Expectations for the Future of FC Ships

Based on the environmental benefits of using FCS onboard ships, it is important to widespread this kind of technology, as it is the most promising system for zero-emission shipping, in particular in the case of hydrogen utilization as fuel. Therefore, the future of fuel cells for maritime applications can be developed and expected by considering many factors such as power capacity, size, safety, costs, durability, and reliability.

The power capacity is one of the limitations of FCS as the power capacity of fuel cells ranges between tens of kW to a few MW, as discussed in Section 3.3; therefore, applications are limited to short-sea shipping and inland waterways. The power capacity of FCS could be extended to fit deep-sea shipping by integrating batteries as an energy storage source or with ICE/GT in hybrid propulsion systems. Optimizing the power distribution of a hybrid system based on FC and ICE/GT is the proper concept to increase the output power; on the other hand, optimizing the energy management system is a key point for hybrid systems based on FC and batteries.

The second factor that controls the future of FC for maritime applications is power density from volume and weight standpoints. In order to facilitate the commercialization step of fuel cells for ships, size standardization will need to be developed; there are ongoing projects tackling this issue, such as STASHH (Standard Sized FC module for Heavy Duty applications) [188], which will develop an open size standard for fuel cell modules which can be extended to be integrated into maritime applications. This project includes eight FC suppliers, which help in the development process of FC size and drive the prices down. Through the development of FC size, the system will become a competitive alternative to other power systems like engines and batteries.

Safety assessment of fuel cell power systems is important for maritime applications, but it is affected mostly by the fuel stored onboard than by the FCS itself. Although there are regulations and rules for using gases or low flash point fuels onboard ships (i.e., the

IGF code), there are shortcomings in the integration of FCS onboard. Therefore, including fuel cell systems in international maritime regulations and rules from a safety perspective is mandatory for their future application in the maritime sector.

The demonstration of FCS onboard ships started a quarter of a century ago, but high capital and operating costs are the limiting factors to the wide spread of this technology in the shipping industry. FCS' capital costs can be reduced by increasing the maritime market demand due to the economics of scale; also, the use of less expensive materials in the production stage can reduce investment costs, as reported in recent studies [189,190]. Moreover, the investment cost of the FCS can be reduced by developing fuel-reforming technologies to enable the use of various hydrocarbon fuels, as reported in recent studies [191,192] that develop different fuel cell types fuelled by syngas or hydrocarbon fuels. On the other hand, variable costs strongly depend on the fuel price, thus on the facilities' investment and market supply chain. Therefore, infrastructure development for renewable fuels (i.e., green hydrogen) is a key point for the future of FCS.

As far as durability is concerned, the degradation of electrolyte, electrode, and bipolar plates has a significant impact on the lifetime of a fuel cell stack in terms of catalyst performance loss, decreased electrolyte conductivity, cracking, and corrosion [193–195]. Therefore, sustaining performance throughout the operating life or reducing degradation rates to a reasonable level are important priorities for large-scale commercialization and future development of fuel cells. To boost performance, new materials and technologies must be implemented based on the causes of a fuel cell stack's degradation. Furthermore, to ensure longer durability, FCS must operate in steady-state conditions as much as possible, with the help of an adequate system design and an optimum control strategy that considers all components of the power system. Moreover, based on the seawater nature that contains mist that can reduce the efficiency of fuel cells [196], care must be taken to prevent its entry into the cathode air.

For the fuel cell reliability challenge, the availability of fuel infrastructure and green fuel bunkering stations are one of the main obstacles to low-carbon shipping and the development of fuel cells for maritime applications. Consequently, it is important to adopt legislative structures and policy strategies to increase fuel infrastructure at international, national, and local levels. This perspective is expected to expand over the next few years based on the IMO's vision of achieving carbon-free shipping. On the other hand, the cycling effects and load variation challenges have a significant impact on the reliability of fuel cells, especially for fuel cell types operating at high temperatures. Accordingly, the integration of fuel cells with batteries is a practical solution to dampen fuel cell load variations and increase the reliability of marine power systems. Additionally, effective control procedures are essential to guarantee the dependability of that kind of hybrid system.

## 4. Conclusions

Fuel cell systems can be a key technology in decarbonizing the maritime sector, which is a crucial step towards accomplishing carbon neutrality targets set at the international level for the next years. In this context, the present work has reviewed the two technologies that emerged as the most promising in the field: proton exchange membrane and solid oxide fuel cells. The PEMFC and SOFC technology suppliers on the market for maritime transport have been individuated and classified, focusing attention on the systems 'characteristics in terms of size, efficiency, power density, voltage, current ranges, and expected lifetime. The gravimetric and volumetric density of the available systems on the market have been compared, as this is an important feature for an efficient installation design for transport applications: the analysis of the commercial products underlines the advantages of PEMFC systems as a preferred solution from both the weight and volume standpoints. In the second part of the paper, the most relevant international projects for innovative FCS installation onboard ships have been presented to draw conclusions on the preferred FC type, size, and type of ship for the application. More than 30 projects and related ship applications have been investigated, with a particular focus on the case studies developed in the last ten years. The analysis confirmed that PEMFC and SOFC had gained a special interest in maritime applications. PEMFC is the most common solution (73% of total projects), in most cases directly fed by pure hydrogen (61% of total projects). SOFC are investigated for different kinds of fuels, while MCFC was investigated mainly in the past (2000–2010 years). PEMFC use for propulsion has been tested recently for propulsion as well, in hybrid systems with batteries, while SOFC is employed for hoteling or as APU. As far as the application is concerned, the review highlighted that FCS are employed mostly for passenger ferries, Ro-pax, research vessels, or yachts. For large-size ships, the use of fuel cells is limited to hoteling service only. Last, the existing maritime applications powered by fuel cell systems have been analyzed and compared to analyze the current trends and future perspectives.

**Author Contributions:** Conceptualization, A.G.E. and M.R.; methodology, M.R.; formal analysis, E.G.; investigation, A.G.E. and E.G.; data curation, A.G.E.; writing—original draft preparation, A.G.E.; writing—review and editing, M.R. and L.M.; visualization, A.F.M.; supervision, A.F.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

| | |
|---|---|
| AD | Alternative Design |
| AFC | Alkaline Fuel Cell |
| APU | Auxiliary Power Unit |
| CHP | Combined Heat and Power |
| CS | Classification Societies |
| ECA | Emission Control Area |
| EEDI | Energy Efficiency Design Index |
| EU | European Union |
| FC | Fuel cell |
| FCS | Fuel Cell Systems |
| GHG | Green House Gases |
| GT | Gas Turbine |
| HFO | Heavy Fuel Oil |
| HT | High Temperature |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| IGF | International Code of Safety for Ships using Gases/other Low-flashpoint Fuels |
| IMO | International Maritime Organization |
| LNG | Liquefied Natural Gas |
| MCFC | Molten Carbonate Fuel Cell |
| MDO | Marine Diesel Oil |
| MEA | Membrane Electrode Assembly |
| mGT | micro–Gas Turbine |
| MH | Metal Hydrides |
| PAFC | Phosphoric Acid Fuel Cell |
| PEM | Polymer Electrolyte Membrane |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| RA | Risk Assessment |
| RES | Renewable Energy Source |
| SOFC | Solid Oxide Fuel Cell |
| TPG | Thermochemical Power Group |
| ZEUS | Zero Emission Ultimate Ship |

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