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Review

Industrial Development Status and Prospects of the Marine Fuel Cell: A Review

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Abstract: In the context of the increasingly strict pollutant emission regulations and carbon emission reduction targets proposed by the International Maritime Organization, the shipping industry is seeking new types of marine power plants with the advantages of high efficiency and low emissions. Among the possible alternatives, the fuel cell is considered to be the most practical technology, as it provides an efficient means to generate electricity with low pollutant emissions and carbon emissions. Very few comprehensive reviews focus on the maritime applications of the fuel cell. Thus, news reports and literature on the maritime applications of the fuel cell in the past sixty years were collected, and the industrial development status and prospects of the marine fuel cell were summarized as follows. Some countries in Europe, North America and Asia have invested heavily in researching and developing the marine fuel cell, and a series of research projects have achieved concrete results, such as the industrialized marine fuel cell system or practical demonstration applications. At present, the worldwide research of the marine fuel cell focuses more on the proton exchange membrane fuel cell (PEMFC). However, the power demand of the marine fuel cell in the future will show steady growth, and thus the solid oxide fuel cell (SOFC), with the advantages of higher power and fuel diversity, will be the mainstream in the next research stage. Although some challenges exist, the SOFC can certainly lead the upgrading and updating of the marine power system with the cooperative efforts of the whole world.

Keywords: fuel cell; electric propulsion; marine power; marine electrical equipment; clean energy

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1. Introduction

Climate change has become a common concern around the world, and almost all the major economies have proposed significant targets that aim to achieve carbon neutrality around the middle of the 21st century. As the second-largest economy and the largest emitter of greenhouse gases in the world, the Chinese government has proposed to reach a CO_2 emission peak before 2030 and achieve carbon neutrality before 2060 [1,2]. Furthermore, the central government and the local governments have issued a series of policy documents and action plans, from the supply side to the consumption side, to stimulate the development of clean energy [3].

The shipping industry, as one of the most economical and efficient means of commodity transportation, undertakes more than 80% of the international trade transportation, with the advantages of lower costs and greater safety and capacity, according to the United Nations Conference on Trade and Development (UNCTAD) [4]. Nevertheless, as a major consumer of fossil fuels, the greenhouse gas emissions of the shipping industry amount to more than 1.1 billion tons, which accounts for nearly 3–4% of global greenhouse gas emissions, and it is still on the rise [5,6]. According to Vessels Value Limited, the proportion of global ships under operation that conform to the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) was only 21.7% by the end of 2021 [7]. Increasingly strict emission regulations have been proposed by the International Maritime

Organization (IMO), indicating that the greenhouse gas emissions of the shipping industry should be decreased by 40% by 2030 and decreased by 50% by 2050 compared to 2008, and, finally, the carbon neutrality of the shipping industry is intended to be achieved by the end of the century, i.e., ahead of schedule [8,9]. The International Maritime Organization also imposes requirements regarding the emissions of sulfur oxides and nitrogen oxides, establishing sulfur emission control areas (SECA) and nitrogen emission control areas (NECA). Furthermore, the IMO has introduced specific guidance for the reduction of nitrogen oxide emissions; depending on the year that the ship was built, they are classified as Tier I, II, or III [10]. Thus, it is becoming increasingly important to reduce the negative impact of the shipping industry on the environment. There are two principal means. The first is the use of environmentally friendly fuels and the other is the use of high-efficiency and low-emission energy conversion devices. According to the research of the International Energy Agency (IEA), the abovementioned emission reduction targets of the International Maritime Organization cannot be achieved merely by using low-carbon fuels, and carbon-neutral fuels, such as hydrogen, should also be considered [11]. The global holding of the ship was approximately 100 thousand in 2020, and Europe, America and Asia occupy a large proportion in terms of quantity and tonnage, with values of 67% and 91%, respectively [12]. Thus, Europe, America and Asia are the primary targets for clean shipping.

In the global context of energy conservation and emission reduction, the marine industry is paying more attention to environmental protection, high energy efficiency and sustainable development, and the fuel cell has become a new alternative for the construction of an energy-saving and environmentally friendly marine power plant. With the increasingly mature techniques, the fuel cell has demonstrated its increasing potential in the emission reduction of the shipping industry.

2. Brief Introduction to the Marine Fuel Cell

Fuel cell technology is a fourth-generation electric energy generation technology, the thermal efficiency of which is not constrained by the Carnot cycle and is up to 2–3-times higher than that of the internal combustion engine during its operation under certain loads. The fuel cell can convert the chemical energy of the fuel into electric energy directly and continuously, without a combustion process or mechanical motion [13,14].

Depending on the different types of electrolytes, the fuel cell can be divided into alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC). The parameters of these five typical types of fuel cells are shown in Table 1 [15,16]. At present, the latter two types of fuel cell are the focus of marine research and have found increasingly wide and successful commercial utilization. A detailed analysis of the maritime application status of these five types of fuel cell and specific reasons are presented in Section 4.1.

Table 1. Parameters of five typical types of fuel cells [15,16].

Type	Operating Temperature	Fuel	Maximum Power Capacity	Efficiency	Life Span	Cost
AFC	50–200 °C	Hydrogen	500 kW	50–55%	3000–10,000 h	1000 $/kW
PAFC	100–200 °C	Hydrogen	400 kW	40–45%	15,000–40,000 h	200–3000 $/kW
MCFC	650–700 °C	Reformed gas Coal gas	10 MW	50–55%	10,000–20,000 h	1250 $/kW
PEMFC	25–100 °C	Hydrogen	500 kW	40–50%	5000–10,000 h	50–2000 $/kW
SOFC	600–1000 °C	Hydrogen Reformed gas Natural gas Coal gas, etc.	10 MW	50–65%	8000–100,000 h	1500 $/kW

Compared with traditional marine power, namely marine diesel engines including the main diesel engine and diesel engine generator, the fuel cell has unique advantages of high energy efficiency, low noise, no vibration, no pollution and high riding comfort, which have attracted the attention of various countries and shipping industries around the world [15–17]. Meanwhile, the disadvantages are the high costs of production, which is directly related to the small scale of production and its technical characteristics [18]. The worldwide market capacity of the marine fuel cell is approximately 160 GW by the estimation of Lloyd's Register of Shipping [19]. Moreover, according to the forecast of the China Waterborne Transport Research Institute, the numbers of converted ships and new ships using marine fuel cells will be nearly 400 and 200 by 2025, respectively, and the market size of the marine fuel cell will reach approximately 3.2 billion dollars by then [20]. Faced with the broad market prospects of the marine fuel cell, the European countries, the United States, China, Japan, South Korea and Singapore have placed the marine fuel cell on the key supported lists of their governments and have issued a series of industry planning standards to guide and support the development of the marine fuel cell in the shipping industry. Since 2000, over thirty research projects on the marine fuel cell have been set up throughout the world, and America and Europe are the leaders of the research on the marine fuel cell [13,15,16].

3. Global Industrial Development Status of the Marine Fuel Cell

3.1. The United States

The United States is the first country in the world that adopted the fuel cell as a new energy strategy [21]. The United States designed a compact submarine (Deep Submergence Rescue Vehicle, or DSRV, as shown in Figure 1 [22]) that used the AFC as its propulsion power source in the early 1970s [23]. In the early 21st century, the U.S. Navy launched a project named the Ship Service Fuel Cell (SSFC) in which the Office of Naval Research (ONR) attempted to develop a 625 kW fuel cell system combining the MCFC and PEMFC, used in the "USCGC Vindicator" owned by the United States Coast Guard [24]. It is worth noting that diesel was used as the fuel to produce the hydrogen for the reformer in the abovementioned system. The abovementioned attempts were both innovative but large-scale mature applications that were ultimately unsuccessful due to the limitations of the systems in terms of volume and complexity. In 2018, in the project "SF Breeze", a 21-meter-long passenger ship called "Water-Go-Round" equipped with a PEMFC began to be built in the San Francisco Bay Area by All American Marine (AAM), which received a grant of 3 million dollars from the California Air Resources Board (CARB) [25,26]. The visual design of the "Water-Go-Round" ship is shown in Figure 2 [25,26]. According to the design, "Water-Go-Round" has a top speed of 22 kn and the passenger capacity is 84. "Water-Go-Round" was composed of high-tensile aluminum and the hydrogen fuel was designed to be stored in hydrogen storage tanks in the top of the ship. In the latter part of 2021, the ship was built in its entirety and was named "Sea Change", with the passenger capacity of 75 eventually, as shown in Figure 3 [27,28]. The ship owner, Switch Maritime, claimed that three 360 kW PEMFCs produced by Golden Gate Zero Emission Marine (GGZEM) and Cummins Incorporated were installed flexibly in a dedicated cabin, and the hydrogen fuel was stored in hydrogen storage tanks of 264 kg capacity in total in the top of the ship. "Sea Change" has become the first commercial passenger ship that uses only PEMFCs in the world [27,28]. American fuel cell corporation Bloom Energy (BE) is approaching the field of marine SOFCs, especially when used in cruise ships. As a rough estimate, more than 100 cruise ships will be equipped with approximately 4000 MW fuel cells in total by 2027 [29]. Thus, the application of fuel cells in the international cruise market is promising. In collaboration with French shipyard Chantiers de l'Atlantique and Mediterranean Sea Cruise Group Global Limited (MSC), the Bloom Energy Corporation developed a 150 kW SOFC system using natural gas in a cruise ship named "MSC World Europa" in 2022 as an emergency auxiliary electrical power system, which aimed to identify a solution to help the Mediterranean Sea Cruise Group Global Limited to reach its 2050 net zero emissions target [30]. The cruise ship "MSC World Europa" is shown in Figure 4 [31]. At the regulation level, the American Bureau of Shipping published the "Guide for Fuel Cell Power Systems for Marine and Offshore Applications" in 2019, providing guidance for the design, construction, conversion, certification and classification of ships equipped with fuel cells [32,33]. To summarize, the marine applications for fuel cell technology in the United States started in the military field and expanded to use in the civil field, especially the large cruise ship market, in the subsequent periods.

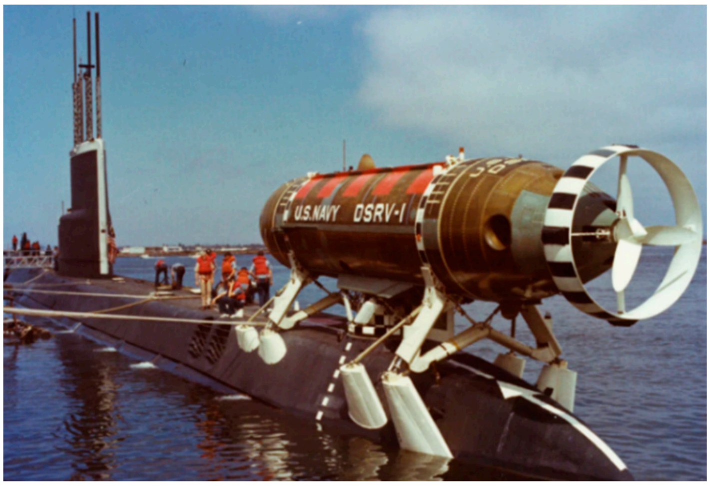

Figure 1. First-generation DSRV of the United States Navy [22].

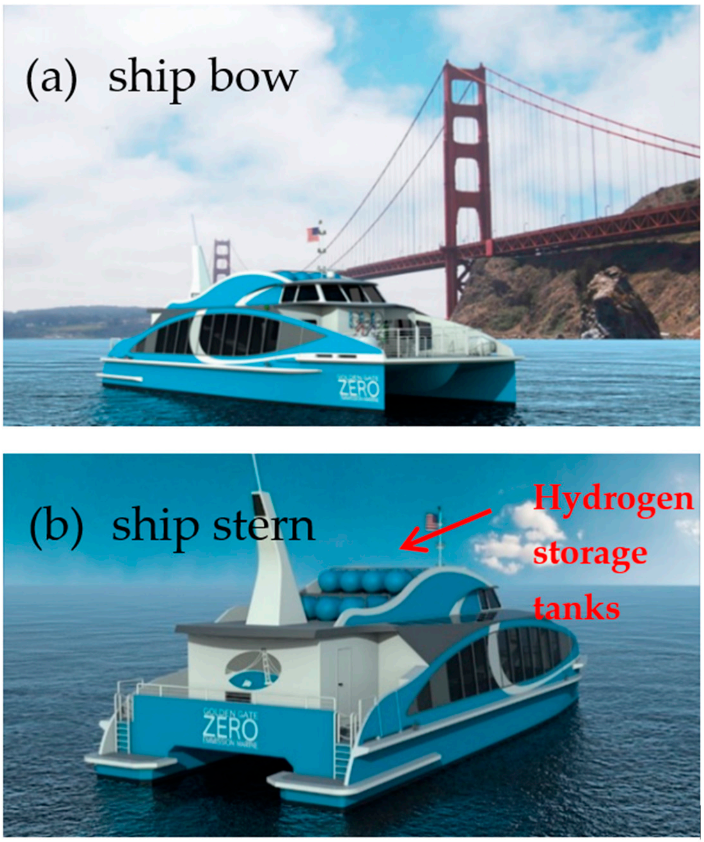

Figure 2. The conceptual design of "Water-Go-Round" [25,26].

Figure 3. The ship "Sea Change" [27,28].

Figure 4. The cruise ship "MSC World Europa" [31].

3.2. Germany

Germany is the leader in the technology of the marine fuel cell in Europe. Since the 1980s, with the advantages of low acoustic noise, low infrared radiation, air independence and high endurance, the fuel cell system was proposed to be used in a submarine in the German Navy. The AFC system was applied to the type 205 submarine (U1:6 × 16 kW) in 1988 as a groundbreaking attempt [34]. On this basis, the higher-performance PEMFC system produced by Siemens AG has been applied successively to the type 212A (U31: 9 × 34 kW, U32-U34: 2 × 120 kW, U35-U36: 9 × 34 kW), type 214, type 216 (also known as the Todaro class submarine) and type 218SG submarines at the turn of the century by Howaldtswerke Deutsche Werft AG (HDW), which is a subsidiary corporation of Thyssen Krupp Marine Systems AG (TKMS) [35–41]. This technology improved the submerged performance and concealment performance and made Germany the first country to master the technology of air-independent propulsion (AIP) using the fuel cell [34,42]. It is important to note that the hydrogen used in the abovementioned types of submarines is stored in a hydrogen storage tank (type 205, type 212A) or hydrogen storage alloy (type 214) or produced by reforming methanol (type 216, type 218SG). Moreover, oxygen is used in the fuel cell system of the abovementioned types of submarines, rather than air [35,36,42]. The abovementioned types of submarines are shown in Figure 5 [43–47].

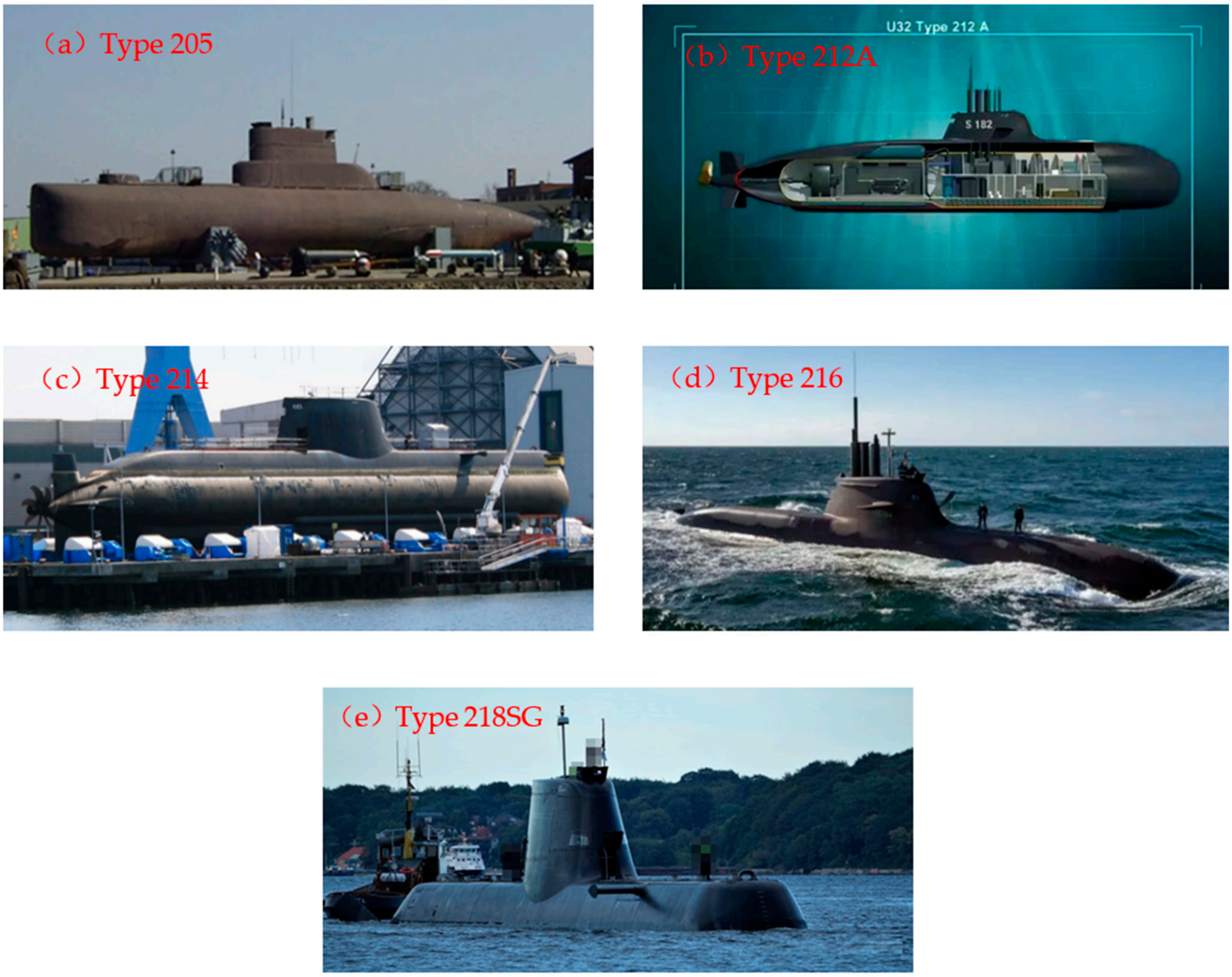

Figure 5. (**a**) Type 205 submarine [43]; (**b**) type 212A submarine [44]; (**c**) type 214 submarine [45]; (**d**) type 216 submarine [46]; (**e**) type 218SG submarine [47].

It should be noted that the main purpose of using the fuel cell system in the submarine is to reduce the acoustic noise from the diesel engines, improving the concealment performance. As for the applications of the fuel cell in cargo vessels and cruise ships, they do not require this feature but instead focus on emissions reductions and comfort improvement.

Germany also has made great achievements in the civil field, wherein the fuel cell has been applied to almost forty ships successively to date. In 2000, a 6.9 kW AFC produced by Electrotechnics Apparate GmbH was applied to a ferry named "Hydra" to provide propulsion power [48]. However, with the rapid development of PEMFCs, the attempt lacked guiding significance. In 2006, a project named Zero Emission Ships (or Zemships) was set up by the Free and Hanseatic City of Hamburg [49–53]. A EUR 5.5 million grant was provided to fund the research, and the first inland-river tourist ship, "FCS Alsterwasser", using only PEMFCs was launched in 2010 [51,53]. The ship builder and operator, Alster-Touristik GmbH, claimed that the ship was 25.5 m long with a top speed of 8 kn, and was equipped with two 48 kW PEMFCs, namely "PM Basic A 50 maritime", produced by Proton Motors, and twelve hydrogen storage tanks of 50 kg capacity in total were installed inside dedicated cabins [54]. The ship was certificated and inspected by Germanischer Lloyd and maintains good operation to date [54]. The inland-river tourist ship "FCS Alsterwasser" and a schematic diagram of its electric propulsion system are shown in Figure 6 [54]. Professor Gerd Holbach, working in the Technical University Berlin, has devoted himself to developing the first tugboat, "Elektra", using PEMFCs around the world since 2016, and the expenditure altogether totals EUR 13 million [55]. The shipbuilding process at Shipyard Hermann Barthel GmbH lasted two years, and the 20-meter-long ship was equipped with three 100 kW PEMFCs produced by Ballard Power Systems Incorporated and six hydrogen storage tanks of 125 kg capacity [56]. After the preliminary testing at close range, further testing for long distances will be performed in 2023 as planned [57,58]. The conceptual design of "Elektra" and the real ship are shown in Figure 7 [56,59]. Germany also conducts research on the marine fuel cell from various aspects and different points of view. German company Aida Cruises claims that luxury cruise ship "AIDAnova" will be adapted for the use of methanol PEMFCs with the support of a research project called "Pa-X-ell2" (a subproject of the "e4ships" project), making it the first cruise ship using methanol fuel cells in the world [60,61]. This PEMFC system is operated with hydrogen in essence, which is produced from methanol by means of an internal reformer. Moreover, in this project, the German fuel cell manufacturer Fischer Eco Solutions GmbH and its Danish subsidiary Serenergy A/S supplied a 30 kW high-temperature PEMFC on a cruise ship named "MS Mariella" under the guidance of the Meyer Werft shipyard, ThyssenKrupp Marine Systems GmbH and their project partners [62]. The 30 kW PEMFC can only supply partial power to marine equipment, but this attempt laid a solid foundation for the extension of the power to 120 kW. The abovementioned cruise ships "AIDAnova" and "MS Mariella" are shown in Figure 8 [63] and Figure 9 [64]. The safety issues of the hydrogen fuel used in the cruise ships "AIDAnova" and "MS Mariella" cannot be neglected because they both carry large numbers of passengers. Thus, a series of detailed safety precautions have been adopted. The fuel cell system is equipped with adequate ventilation, fire suppression, emergency shutdown, monitoring and control systems, which meet all classification requirements. The hydrogen fuel complies with the two-barrier principle for gas supply, which is either achieved by double-walled piping, ventilation ducts or gas-tight enclosures. In addition, rapid venting of leaking hydrogen fuels into the atmosphere is also ensured. ThyssenKrupp Marine Systems GmbH also cooperated with Sunfire GmbH to develop a 50 kW high-temperature SOFC system, which was operated on low-sulfur diesel rather than hydrogen or natural gas, and this SOFC system was successfully installed in a test ship named "MS Forester", provided by the Reederei Braren shipping company, and supplied a part of the electric energy needed by the ship reliably [65]. The ship "MS Forester" is shown in Figure 10 [66]. In addition, new fuels are also of relevance. Researchers at the Fraunhofer Institute for Microengineering and Microsystems IMM in Mainz are implementing a project called "Ship Fuel Cell" (ShipFC), which is sponsored by the New European Union Framework Programme for Research and Innovation, "Horizon 2020", with EUR 10 million [67]. In this project, a 2 MW direct ammonia SOFC produced by Wartsila will be applied to a 95-meter-long ocean engineering vessel named "Viking Energy", owned by Eidesvik Offshore, as shown in Figure 11 [68], which is the first attempt in the world and is expected to be finished in 2024 [68,69]. The ammonia is produced by electrolysis using renewable energy and delivered to Viking Energy in containerized form to enable easy and safe refueling. Lürssen, a German superyacht manufacturer, claims that a superyacht equipped with a PEMFC is under construction and will be delivered in 2025, and hydrogen is continuously produced by reforming methanol [70]. It is worth mentioning that the previous research project focused on the marine methanol fuel cell, called "Methapu" (validation of renewable methanol-based auxiliary power systems for commercial vessels), was funded by the European Commission with EUR 1 million in 2006, and it delivered a 20 kW SOFC system produced by Wartsila as an auxiliary electrical power system in a car carrier named "Undine", owned and operated by a Swedish corporation, Wallenius Wilhelmsen [71,72]. The hydrogen used in this SOFC system is also produced by reforming methanol. The car carrier "Undine" is shown in Figure 12 [73]. In the abovementioned examples of the marine fuel cell, the focus of fuel is methanol, because it is more suitable for storage and transport compared to gaseous fuel. The marine applications of fuel cell technology in Germany have achieved success in both the military field and civil field, and the research focus is new types of fuel at present.

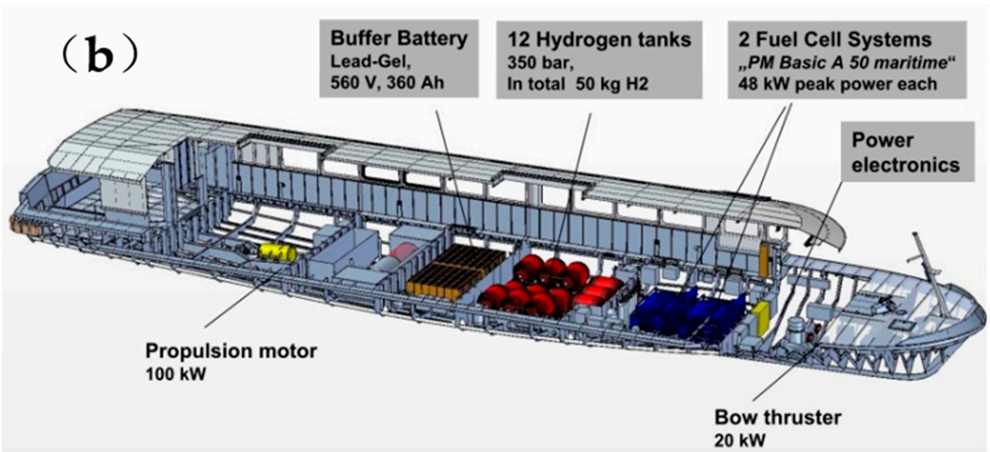

Figure 6. (**a**) The inland-river tourist ship "FCS Alsterwasser" [54]; (**b**) a schematic diagram of the electric propulsion system of "FCS Alsterwasser" [54].

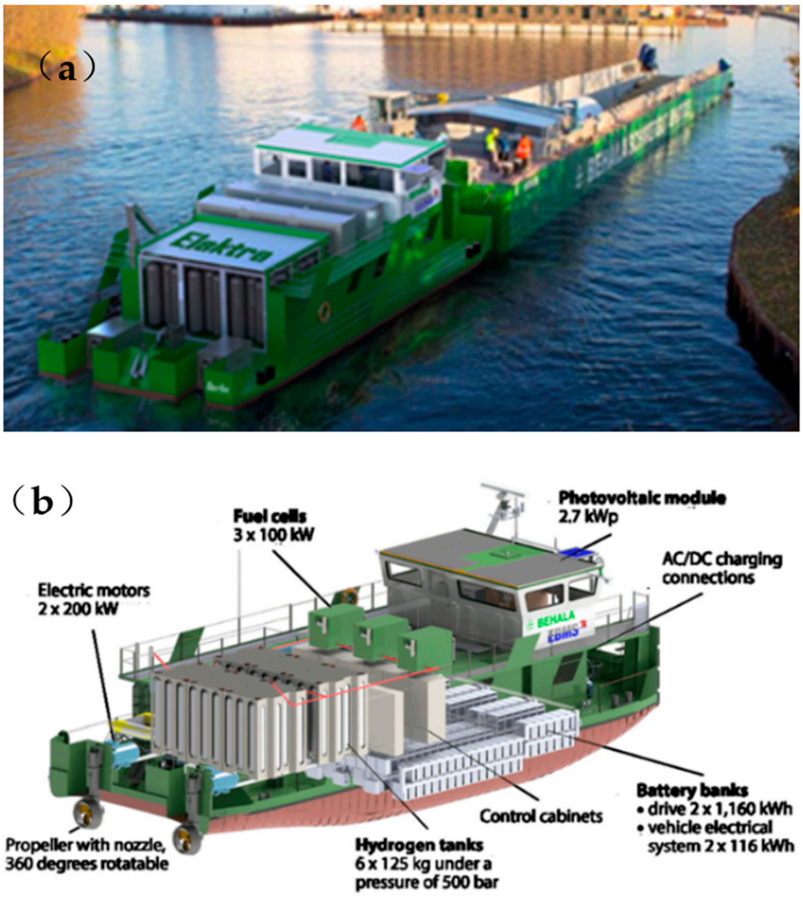

Figure 7. (**a**) The real ship "Elektra" [56]; (**b**) the conceptual design of "Elektra" [59].

Figure 8. The luxury cruise ship "AIDAnova" [63].

Figure 9. The passenger ship "MS Mariella" [64].

Figure 10. The ship "MS Forester" [66].

Figure 11. The ocean engineering vessel "Viking Energy" [68].

Figure 12. The car carrier "Undine" [73].

3.3. Norway

Norway is the leader in green shipping around the world and gives top priority to the development and application of the marine fuel cell. Since 2015, more than 150 million dollars have been devoted to the research of marine fuel cells. Eidesvik Offshore, an established operating corporation of ocean engineering vessels in Norway, plays an exemplary role. As early as 2003, it participated in a project named "Fellow Ship", which is managed and supported economically by Det Norske Veritas (DNV) [74]. In 2009, a 320 kW MCFC system using liquified natural gas was installed in a supply ship named "Viking Lady" to provide a part of the propulsion power [75]. The MCFC used in "Viking Lady" is certified by Det Norske Veritas, and the world's first rules and regulations for the certification and classification of the marine fuel cell were set based on this system [74,75]. The supply ship "Viking Lady" is shown in Figure 13 [76]. In 2021, three types of marine fuel cells produced by a Norwegian maritime cleantech corporation, TECO 2030 ASA, were approved in principle by Det Norske Veritas, and a total of 200 MV marine fuel cell systems ranging in size between 400 kW and 6.4 MW, singly produced by TECO 2030 ASA, will be provided to 40–60 tugboats and 120 transport barges operated by Netherlandish shipowner Chemgas Shipping BV in 2025, although the exact number remains to be decided [77,78]. TECO 2030 ASA are offering a specifically designed modular fuel cell system for heavy-duty marine applications and a series of products are shown in Figure 14 [78]. Based on its experience with the certification and classification of the marine fuel cell, Det Norske Veritas has set a series of technical specifications and standards with the support and assistance of the government, the industrial community and research institutions at home and abroad, such as the Norway Maritime Administration (NMA), Norwegian Defence Materiel Agency (NDMA), Norwegian Public Roads Administration (NPRA), Standards Council of Canada (SCC), Equinor, Royal Dutch Shell, Air Liquide, Linde AG, Ballard Power Systems, Kawasaki Heavy Industries, Fincantieri, Feadship, Commins, Hexagon Purus, Corvus Energy, Umoe Advanced Composites (UAC), the Memorial University of Newfoundland (MUN), etc. [79]. The most representative project led by Det Norske Veritas is a joint development project called "MarHySafe", which provided a series of technical guidance for the marine hydrogen fuel cell, especially the PEMFC [80,81]. Norway is the most active country in terms of researching and developing the marine fuel cell around the world. Table 2 presents the other representative projects involving marine fuel cells led or participated in mainly by Norway, which were funded by the European Union, organizations or large enterprises.

Figure 13. The supply ship "Viking Lady" [76].

Figure 14. Series of marine fuel cells produced by TECO 2030 [78].

Table 2. Other representative projects involving the marine fuel cell led or participated in mainly by Norway.

Project	Project Supervisor	Major Participants	Expected Achievements
FreeCO2ast [82]	Research Council of Norway, Innovation Norway, Enova Systems Incorporated	Havila Kystruten, Havyard Group ASA, Sintef Ocean ASA, Proto Technologies Incorporated, etc.	Produce a 3.2 MW hydrogen fuel cell system used in a 120-meter-long passenger ship before 2023
Zero-Emission Fast Ferry [83] (ZEFF)	European Union	Norway Hyon AS, Wärtsilä, etc.	Produce hydrogen fuel cell system used in high-speed passenger ships in 2022
SeaShuttle [84]	Enova Systems Incorporated	Norway Hyon AS, Samskip Norway AS, etc.	Produce hydrogen fuel cell system used in short-distance container ships in 2025
HySeas III [85]	European Union	University of St. Andrews, Orkney Islands Council, Norway Kongsberg Maritime AS, Ballard Power Systems Incorporated, etc.	Develop a ferry using hydrogen fuel cell system in Scotland
HyShip [86]	European Union	Norway Wilhelmsen AS, Norway Equinor AS, Norwegian Center of Expertise, Norway Maritime Clean Tech AS, Norway Det Norske Veritas, Norway Kongsberg Maritime AS, Norway LMG Marin AS, University of Strathclyde, etc.	Develop a 3 MW PEMFC in a roll-on-roll-off ship named "Topeka" in 2024, a 0.5 MW PEMFC in a small oil barge, a 3 MW PEMFC in a high-speed passenger ship, a 20 MW PEMFC in a Capesize bulk carrier
MF Vågen [87]	Australian Renewable Energy Agency	Norway Common Mode Rejection Prototech AS	Develop a 12 kW high-temperature modularized PEMFC system for a river cruise vessel in Norway

3.4. France

In France, the corporation Energy Observer Developments (EODev) developed a PEMFC system that has been certified and classified by Bureau Veritas (BV) with the latest published rules and regulations for the design, construction and installation of the marine fuel cell, named "NR 542", in 2017 [88]. This 22 kW PEMFC system has been installed in a 30-meter-long yacht named "Energy Observer", as shown in Figure 15 [89], which is sailing around the world at present [88,89]. It is worth mentioning that the hydrogen used in this PEMFC system is produced by the electrolysis of water using renewable energy on the sea, such as solar energy and wind energy. In addition, French corporation Hydrogene De France SA cooperated with the Swiss corporation ABB Limited and Canadian corporation Ballard Power Systems to develop a high-power PEMFC installed in ocean-going vessels in 2020, and a 3 kW PEMFC system was approved in principle by Det Norske Veritas in 2022 [90]. Besides this, the FC-RACK^{TM} Marine PEMFC developed by Helion Hydrogen Power, a subsidiary corporation of Alstom Limited, gained approval in principle from Bureau Veritas [91]. This type of PEMFC is based on a modular design and thus the power can be extended from 100 kW to several megawatts, with a 25,000 h service life [92]. Recently, the 200 kW FC-RACK^{TM} Marine PEMFC, shown in Figure 16 [93], has been applied to a dredger named "HyDrOMer", as shown in Figure 17 [92,93], which was designed by LMG Marin AS and built by the Piriou shipyard and will be fully operational by the end of 2023.

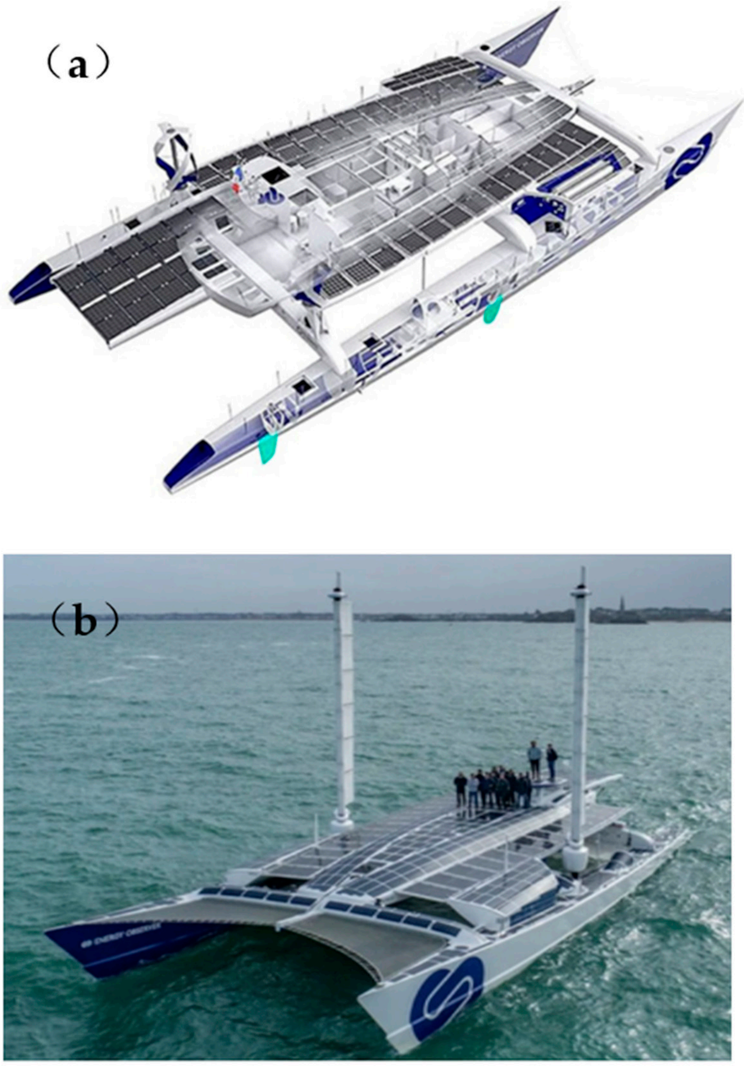

Figure 15. (**a**) The conceptual design of “Energy Observer” [89]; (**b**) the real ship “Energy Observer” [89].

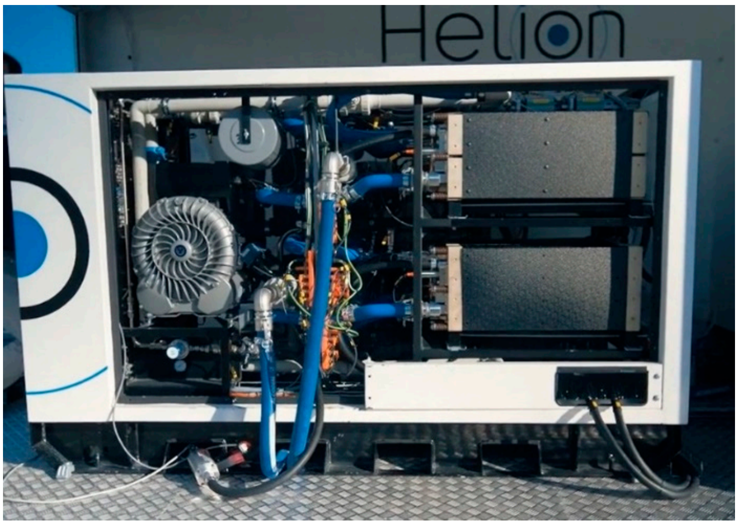

Figure 16. The 200 kW FC-RACK^{TM} Marine PEMFC [93].

Figure 17. The dredger "HyDrOMer" [92,93].

3.5. Canada

As for Canada, two corporations, Corvus Energy and Ballard Power Systems, have been approved in principle by Det Norske Veritas for the first time within the European Union in 2022. The former developed a PEMFC system supported by a project called "H2NOR" [94,95]. The latter provided two 200 kW PEMFCs named "FCwave" with the lifespan of 30,000 h in a 120-meter-long ferry named "MF Hydra" [96]. The ferry is owned and operated by Torghatten Nord and was designed and constructed by the Norwegian Ship Design Corporation and Westcon Yards Shipyard, respectively. The PEMFC "FCwave" and the ferry "MF Hydra" are shown in Figure 18 [97] Figure 19 [98], respectively. It is noteworthy that a European innovation program, "Flagships", sponsored by "Horizon 2020" with EUR 5 million, funded the latter and also provided financial support to the corporation Compagnie Fluvial de Transport (CFT, owned by Sogestran Shipping) to develop, construct and operate the first river cargo ship equipped with PEMFCs in the world, named "Zulu" [99,100]. At the beginning of 2021, Ballard Power Systems claimed that it would cooperate with the Australian corporation Global Energy Ventures Limited (GEV) to develop a hydrogen carrier named C-H2, which will be equipped with a PEMFC system [101,102]. The marine applications for fuel cell technology in Canada indicate that Canada only develops fuel cell systems, and the actual ship experiments are performed with the assistance of other powerful nations in the field of shipbuilding in Europe.

Figure 18. The PEMFC "FCwave" [97].

Figure 19. The ferry "MF Hydra" [98].

3.6. Netherlands

In the Netherlands, as early as 2009, the Dutch corporation Boat Amsterdam operated a canal cruise ship named "Nemo H2", equipped with a 70 kW PEMFC system and six hydrogen storage tanks of 24 kg capacity [103]. It has a lifetime of 9 h under the speed of 7 kn and the passenger capacity is 87, as shown in Figure 20 [104]. The Dutch corporation Nedstack Fuel Cell Technology BV, a leading player and manufacturer in the PEMFC industry, designed a coastal ship using a 2 kW PEMFC system with the cooperation of a Norwegian corporation, Ulstein Group ASA, in 2019 [105]. The ship is named "Ulstein SX190 Zero Emission DP2" and the test work will be executed in 2022 [106]. The hydrogen used in this PEMFC system is from a containerized pressure vessel, which is a well-proven and readily available technology. These hydrogen storage containers can be loaded and unloaded via normal container handling operations and equipment, which can eliminate the need for expensive bunkering infrastructure and provide worldwide operational flexibility [105,106]. The conceptual design of "Ulstein SX190 Zero Emission DP2" is shown in Figure 21 [107]. The Dutch Nedstack Fuel Cell Technology BV also collaborated with the Power Conversion Department of the General Electric Company (GE) to develop PEMFC systems to power zero-emissions cruise vessels [108]. They envisaged using this technology on passenger ships, replacing traditional diesel engines with fuel cells, and heavy fuel oil (HFO) with hydrogen, and the result would be highly efficient fuel cell solutions that enable a zero-emissions cruise industry [109]. Thus far, they have designed the concept for a 2 kW PEMFC power plant on an expedition vessel and delivered a 100 kW maritime PEMFC system to an international client [110]. Figure 22 [111,112] shows part of the maritime PEMFC produced by Nedstack Fuel Cell Technology BV. In 2022, the Dutch corporation C-Job Naval Architects launched a concept design of a 144-meter-long hydrogen carrier equipped with a PEMFC system, which was planned to be operated in 2027, and it also proposed in 2020 that ammonia is a promising fuel to be used in the shipping industry in the future, especially in the marine SOFC [113,114]. However, at present, it has the disadvantages of low power density and poor responsiveness. The concept design of the abovementioned 144-meter-long hydrogen carrier is shown in Figure 23 [113]. It is worth mentioning that the conceptual design of a super-premium yacht named "Aqua", shown in Figure 24 [115], was published in 2019 at the Monaco Yacht Show. This 112.3-meter-long yacht was designed by well-known Dutch design company Sinot Yacht Architecture and Design, and a 4 MW PEMFC system is intended to be installed [116].

Figure 20. The canal cruise ship “Nemo H2” [104].

Figure 21. The conceptual design of “Ulstein SX190 Zero Emission DP2” [107].

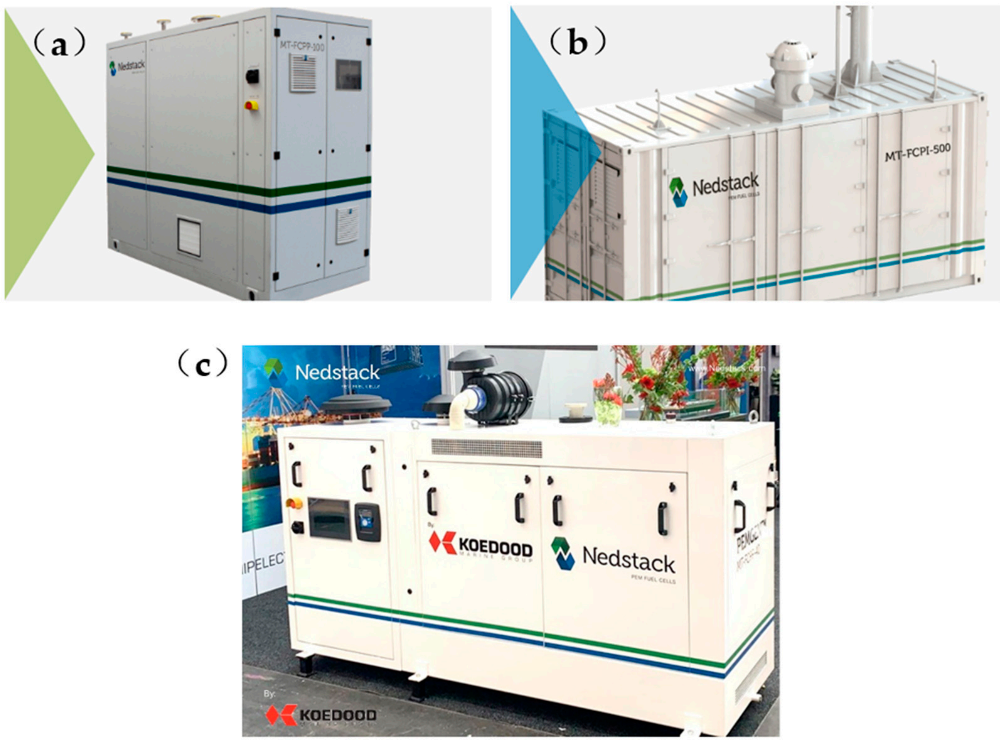

Figure 22. (a) Images of 100 kW PemGen MT-FCPI-100 [111]; (b) PemGen 500 kW MT-FCPI-500 [111]; (c) Nedstack extended long-life (XXL) PEMFC stacks [112].

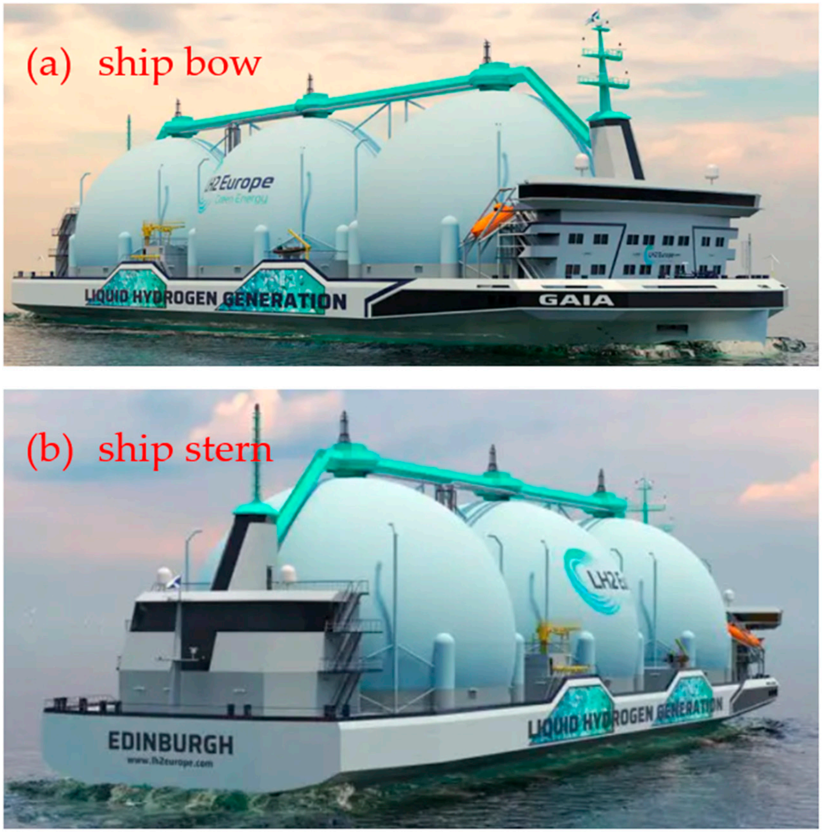

Figure 23. The conceptual design of the hydrogen carrier of C-Job Naval Architects [113].

Figure 24. The conceptual design of a super-premium yacht, "Aqua" [115].

The marine applications for fuel cell technology in the civil field in the Netherlands have shown great success. Several types of fuel cells have been successfully applied to various types of ships, which makes the Netherlands another leader in green shipping, besides Norway.

3.7. Japan

The technology source of the fuel cell in Japan is derived from Ballard Power Systems Incorporated. Over time, Japan has formed its own industry system [117]. Japan remains the leader in terms of fuel cells used in automobiles, but lags in the field of marine fuel cells [118]. In 2009, the Japanese government proposed that the fuel cell can be used as a marine power source to reduce emissions in the shipping industry [119]. Japan attempted to install a PEMFC in a fishing vessel in 2015 as an initial attempt, where the fishing vessel had a maximum speed of 20 kn [120]. The first commercial development project of the marine fuel cell in Japan was launched in 2020, which planned to develop a 150-ton ferry equipped with a 500 kW PEMFC system [121]. The project was approved by Japan's New Energy and Industrial Technology Development Organization (NEDO). Nippon Yusen Kabushiki Kaisha undertook the overall responsibility, and the Toshiba Energy Systems and Solutions Corporation (Toshiba ESS), Kawasaki Heavy Industries, the ENEOS Corporation and Nippon Kaiji Kentei Kyokai (class NK) worked together on this project [122]. The construction and production are planned for 2023, with pilot operation expected in 2024 [123]. Significantly, the Toshiba Energy Systems and Solutions Corporation will design and produce a 200 kW marine hydrogen fuel cell named "H2Rex^{TM}-Mov" based on its successful experience of developing a more compact and flexible 30 kW mobile marine fuel cell in 2019 [124]. The ferry was planned to be designed in 2021 and be constructed in 2023, and the demonstration operation and the test work of the ferry will be executed in 2024, intending to provide trial data for the further application of the marine fuel cell in 2030 [124,125]. The marine hydrogen fuel cell "H2Rex^{TM}-Mov" is shown in Figure 25 [126]. Furthermore, a 3.5 kW hydrogen fuel cell produced by the Toshiba Energy Systems and Solutions Corporation has also been used in an experimental ship named "Raicho N", owned by Tokyo University of Marine Science and Technology (TUMSAT), as Figure 26 [127] shows. The more mature technology of the fuel cell of the Toshiba Energy Systems and Solutions Corporation also attracts foreign corporate clients. In 2022, Swedish corporation Echandia Marine Leclanche AP, a leading developer and global pioneer of energy solutions for maritime electrification, entered into an agreement to deepen its strategic partnership with the Toshiba Energy Systems and Solutions Corporation to develop marine fuel cells for heavy-duty applications [128,129]. Besides the Toshiba Energy Systems and Solutions Corporation, the Yanmar Engine Corporation Limited and Toyota Motor Corporation Limited also made several attempts in the field of marine fuel cells. In 2018, the Yanmar Engine Corporation Limited installed a 60 kW hydrogen fuel cell in a 16.5-meter-long ship named "Shimpo", owned by the Toyota Motor Corporation Limited, as Figure 27 [130,131] shows. In 2019, the Yanmar Engine Corporation Limited participated in a project that intended to install a PEMFC system, "MIRAI", produced by the Toyota Motor Corporation Limited, in ships as the practical basis for further research. In 2021, a 12.5-meter-long yacht named "EX38A", with the 250 kW PEMFC system "MIRAI", was successfully converted, which led the Yanmar Engine Corporation Limited to achieve the commercial application of its 300 kW marine fuel cell in 2023 and its successful practical application is expected in 2025 [132]. The yacht "EX38A", equipped with 250 kW PEMFC system "MIRAI", is shown in Figure 28 [133]. Meanwhile, the Toyota Motor Corporation Limited is actively seeking international cooperation to export its mature technology. In 2021, a joint development program involving the Toyota Motor Corporation Limited and Canadian corporation Corvus Energy was launched, which plans to deliver a marine fuel cell system successfully by 2024 [134]. In short, the development of the marine fuel cell in Japan maintains good momentum. According to the preliminary estimates, if the coastal ships with a tonnage of 500 and below in Japan are all converted into hydrogen fuel cell systems, the carbon dioxide emission reduction is expected to reach 5 million tons per year [135].

Figure 25. The marine hydrogen fuel cell "H2Rex™-Mov" [126].

Figure 26. The experimental ship "Raicho N" [127].

Figure 27. The ship "Shimpo" [130,131].

Figure 28. The yacht "EX38A" [133].

The marine applications for fuel cell technology in the civil field in Japan show the main characteristic in which the development of the marine fuel cell is based on the proven technique of the fuel cell vehicle, and thus the automobile enterprises in Japan are the main force in the development the marine fuel cell in the present and future.

3.8. South Korea

The technology source of the fuel cell in South Korea is derived from Ballard Power Systems Incorporated, but South Korea still needs to import some components of the technology [136]. South Korea is a powerful nation in the field of shipbuilding. In 2010, the South Korean government proposed that the fuel cell could be applied in the shipping industry [137]. In 2013, a project focusing on designing and developing the first ship equipped with a 100 kW hydrogen fuel cell in Korea was launched. The ship was named "Pyeongchang 2018" but the project has yielded no results so far [138]. In 2015, 16 million dollars were provided by the government to launch an independent research and development project for the marine fuel cell, which was led by the Korea Register of Shipping (KR) and involved the participation of the Daewoo Shipbuilding and Marine Engineering Corporation Limited (DSME), Pohang Iron and Steel Corporation Limited (POSCO), Samsung Heavy Industries Corporation Limited (SHI) and System Technology Excellence Corporation Limited (STX) [119]. As the industry leader, the Korea Shipbuilding and Offshore Engineering Corporation Limited (KSOE), owned by Hyundai Heavy Industries Corporation Limited (HHI), the world's largest shipbuilding enterprise, planned the industry development of the marine fuel cell. In the past two years, the Korea Shipbuilding and Offshore Engineering Corporation Limited has signed several agreements with the Doosan Fuel Cell Corporation Limited and plans to develop marine fuel cell systems, especially SOFC systems. In this project, a 600 kW SOFC system will be installed as the auxiliary electrical power system in a ship, and a one-year operation will be carried out to provide trial data for the system's optimization and improvement [139]. The Doosan Fuel Cell Corporation Limited claimed that the marine SOFC system will be developed and certified successfully in 2024 and launched on the market in 2025 according to the project aims, and the first client is most likely to be Norwegian company Navig8 Chemical Tankers [140]. In 2021, another two subsidiaries of the Hyundai Heavy Industries Corporation Limited, Hyundai Motor Group Tech (HMG) and Hyundai Global Service Corporation Limited (for short HGS), also started developing marine PEMFC fuel cells in partnership with the Korea Register of Shipping, and intended to achieve commercial application in recent years [141]. In 2022, the Korea Register of Shipping also signed a memorandum of understanding with the System Technology Excellence Corporation Limited and Daewoo Shipbuilding and Marine Engineering Corporation Limited to develop a marine SOFC system jointly [142]. The Ulsan government constructed two small ships equipped with hydrogen fuel cells under the support of the Ministry for Small and Medium Enterprises of Korea (SMEs), and in 2021, the experimental operation was completed, providing data support for the formulation of safety standards [143,144]. Samsung Heavy Industries Corporation Limited entered a joint development project with Bloom Energy (BE) to design and develop ships equipped with SOFC fuel cells in 2020, and the market demand is expected to be 300 MW after being approved in principle by Det Norske Veritas in 2021, realizing commercial application successfully in an engine-less liquefied natural gas carrier in 2022 [145–148]. According to the estimations, if the coastal ships of South Korea are all converted into hydrogen fuel cell systems, the carbon dioxide emission reduction is expected to reach 11.43 million tons [138]. The marine applications for fuel cell technology in Korea are clearly thriving and it is guaranteed to make remarkable achievements in the foreseeable future.

3.9. China

The first publicly reported ship equipped with a fuel cell in China was "Fu Yuan 1" in 2002, which used a 0.4 kW hydrogen fuel cell produced by the Beijing Century Fuyuan Fuel Cell Corporation Limited [149]. The first ship equipped with a fuel cell and recognized by the Chinese government was “Tian Xiang 1” [150]. This yacht was developed by Shanghai Maritime University (SMU) in 2005 and the electrical power output was only 2 kW, as Figure 29 [151] shows. The above two bold attempts did not receive significant attention in China, and China has failed to keep up with the worldwide trend of developing the marine fuel cell at the turn of the century. Though it started late, the development of the marine fuel cell in China in recent years shows good momentum and is catching up with and surpassing the advanced level of other nations around the world. The guidelines on the energy conservation and emission reduction of the Chinese shipping industry consider clean energy as the core and the new propulsion technology and high-energy-efficiency technology as supplementary measures [119,151]. The “Made in China 2025” strategy also placed the highly technical ship among the top ten fields in science and technology [152]. By early 2021, the TWZFCSZ marine PEMFC had been designed, researched, developed and produced completely independently by Wuhan Troowin Power System Technology Corporation Limited and gained the approval of the China Classification Society [153]. The real products and detailed parameters of the TWZFCSZ marine PEMFC system are shown Figure 30 [154] and Table 3 [154]. In collaboration with Guangdong Zhongjiang Boat Technology Corporation Limited, this type of marine PEMFC system will be applied to a 20-meter-long sightseeing boat with the passenger capacity of 50 in Foshan city [153]. Moreover, a 12-meter-long cruise ship named “Xian Hu 1”, as shown in Figure 31 [155], with the passenger capacity of 30, using a 30 kW PEMFC system as the propulsion power source, was also launched in Foshan city in 2021 [155]. Additionally, at the beginning of 2021, the China Lihu Corporation Limited developed and launched a 13.9-meter-long sightseeing boat named “Li Hu”, equipped with a 70 kW PEMFC system, in partnership with Dalian Maritime University (DMU), and the trial voyage was successfully performed, as shown in Figure 32 [156]. It is worth mentioning that the PEMFC system used in this ship was developed by the Dalian Institute of Chemical Physics (DICP), Chinese Academy of Sciences (CAS), which also independently developed a high-temperature methanol fuel cell and applied it to a demonstration cruise ship named “Jia Hong 01”, as Figure 33 [157] shows, in Foshan city in November 2021 [157,158]. Large state-owned enterprises also venture into marine fuel cells and the related industrial chain, among which the most representative enterprise is the Wuhan Institute of Marine Electric Propulsion, China State Shipbuilding Corporation Limited. A test vessel equipped with their 70 kW PEMFC system with independent intellectual property rights performed a mooring test successfully in the Yangtze River in 2021 [159]. The 70 kW PEMFC system is shown in Figure 34 [159]. The Wuhan Institute of Marine Electric Propulsion has devoted efforts to developing marine fuel cells since the 1960s, and their 500 kW marine fuel cell system has gained approval in principle from the China Classification Society [160]. Besides this, the Guangzhou Ship and Ocean Engineering Design and Research Institute, China State Shipbuilding Corporation Limited, leads the major scientific and technological project “Green Pearl River”, in which the design scheme of a 70.5-meter-long 2100-ton inland-water self-discharging ship equipped with four 125 kW PEMFCs gained approval in principle from the China Classification Society at the end of 2019 [161,162]. In the middle of 2022, the FCPS-S120 120 kW marine PEMFC developed by the State Power Investment Group Hydrogen Energy Technology Development Corporation Limited gained approval in principle from the China Classification Society, and this type of marine PEMFC is especially designed for kiloton inland-water ships [163]. The FCPS-S120 120 kW marine PEMFC is shown in Figure 35 [163,164]. At present, the most striking ship under construction is the 49.9-meter-long “San Xia Qing Zhou 1”, funded by the China Yangtze Power Corporation Limited (CYPC), designed by the Wuhan Changjiang Ship Design Institute Corporation Limited (CSDI; owned by the China Yangtze River Shipping Group Corporation Limited, a secondary subsidiary company of the China Merchants Group) and built by the Jianglong Shipbuilding Corporation Limited, and the abovementioned 500 kW marine fuel cell system developed by the Wuhan Institute of Marine Electric Propulsion will be installed in the ship [165]. “San Xia Qing Zhou 1”, shown in Figure 36 [165,166], is the first ship with independent intellectual property rights to be classified by the China Classification Society that is equipped with hydrogen fuel cells. This ship is an important breakthrough in the shipping industry, which can provide an important theoretical foundation and data support for the promotion of ships equipped with hydrogen fuel cells in the future [165]. Furthermore, “San Xia Qing Zhou 1” will be an important test platform for ships using hydrogen fuel cells, which indicates that the application level of key technologies of hydrogen fuel cells used in ships in China has reached a new level [151,165]. Based on the abovementioned examples, it is undeniable that the research on marine fuel cells in China focuses more on the PEMFC rather than other types of fuel cell, and the actual ship applications are concentrated more on inland water. The practice and trials in these relatively simple application scenarios can lay a solid foundation for further application in more complex navigation zones.

Figure 29. The yacht “Tian Xiang 1” [151].

Figure 30. Type TWZFCSZ marine fuel cell system [154].

Table 3. The detailed parameters of the TWZFCSZ marine fuel cell system [154].

Parameter	Type	
	TWZFCSZ-80	TWZFCSZ-60
Rated power (kW)	80	60
Size (length × width × height, mm)	1600 × 827 × 1235	1600 × 827 × 1235
Weight (kg)	350	338
Operating ambient temperature (°C)	−40–60	−40–60
Cold boot temperature (°C)	−20	−20
System efficiency (%)	>50	>50

Figure 31. The cruise ship "Xian Hu 1" [155].

Figure 32. The yacht "Li Hu" [156].

Figure 33. The demonstration cruise ship "Jia Hong 01" [157].

Figure 34. The 70 kW marine PEMFC developed by Wuhan Institute of Marine Electric Propulsion [159].

Figure 35. (**a**) Visual design of the FCPS-S120 120 kW marine PEMFC [163]; (**b**) real FCPS-S120 120 kW marine PEMFC [164].

Figure 36. The ship “San Xia Qing Zhou 1” [165,166].

3.10. Other Countries and Regions

Other countries and regions, such as Sweden, Denmark, Spain, Austria, Italy, Switzerland, Britain, Singapore, Turkey, India and the Taiwan region of China have also made progress or executed research projects in the field of the marine fuel cell. The details are as follows.

In Northern Europe, the Swedish corporation PowerCell AB launched a 200 kW fuel cell system named the “Power Cellution Marine System 200”, as shown in Figure 37 [167], in 2021 and received several major orders in succession [167]. The Swedish corporation Alfa Laval AB and the Technical University of Denmark took the lead on a program named “SOFC4 Maritime”, funded by a grant from the Danish “Energy Technology Development and Demonstration Programme” (EUDP), which aims to accelerate the application of SOFCs in order to reduce carbon emissions from shipping [168–170]. The Danish corporation Det Forenede Dampskibs Selskab (DFDS) intends to develop a ferry named “EuropaSeaways”, equipped with a 23 MW fuel cell system, as Figure 38 [171] shows, which will be launched in 2027 and can eliminate 64,000 tons of carbon dioxide emissions per year [171,172]. The hydrogen used in this fuel cell system is produced by the electrolysis of water using wind energy on the sea [171]. Danish towage and marine solutions corporation Svitzer A/S, owned by the A.P. Moller Maersk Group, claimed that it will construct a type of transverse tugboat equipped with a methanol fuel cell system with the cooperation of Canadian ship design corporation Robert Allan Corporation Limited (RAL) and Turkish shipyard Sanmar Shipping Corporation Limited (SSL) [173]. According to the design of this new type of tugboat, the power of the methanol fuel cell system is slightly more than 4000 kW, which is expected to be challenging. This new type of tugboat, shown in Figure 39 [174], will be delivered in 2023 as one of the methods that can be used to achieve carbon neutrality, as stated by the A.P. Moller Maersk Group, by 2040 [173,174]. Regarding other European countries, a PEMFC system produced by the Spanish corporation Abengoa SA has been applied successively to the type S80-Plus submarine, as shown in Figure 40 [175], and the hydrogen used in this type of submarine is produced by decomposing bioethanol [176]. Austrian corporation Automatic Vehicle Location List GmbH is also working with Norwegian TECO 2030 ASA and the Korea Shipbuilding and Offshore Engineering Corporation Limited to develop a marine hydrogen fuel cell system, which is planned to be developed successfully by 2025 [177,178]. In Italy, the project "Molten-Carbonate Fuel Cells for Waterborne Applications" (MC-WAP) aimed at the study of the application of the MCFC technology on-board large vessels was led by the Italian Cetena S.P.A. during 2005 to 2008, and a 250 kW MCFC system was developed successfully as an auxiliary power supply system [179–181]. In Switzerland, the Swiss corporation Brunnert-Grimm AG worked with German fuel cell technology company Zebotec GmbH to construct and sell zero-emission fuel cell runabout motor boats [182]. In Britain, a fuel cell ferryboat named "Hydrogenesis", which was the first fuel cell ship in Britain, had been due on the water in 2012 [183–185]. The fuel cell ferryboat "Hydrogenesis" is shown in Figure 41 [186]. In addition, the British motor corporation Rolls-Royce Group PLC also ventured into marine fuel cells such as SOFCs and PEMFCs used in luxury yachts, especially in the project "Felicitas" [187,188]. Engineers at the Rolls-Royce Group PLC are also considering the use of hydrogen fuel cells, in which the hydrogen is produced from methanol [189]. Figure 42 [189] shows a propulsion system with fuel cells and batteries for tugboats, which was designed by the Rolls-Royce Group PLC.

Figure 37. The 200 kW fuel cell system "Power Cellution Marine System 200" [167].

Figure 38. The ferry "EuropaSeaways" [171].

Figure 39. The new type of tugboat proposed by the A.P. Moller Maersk Group [174].

Figure 40. The type S80-Plus submarine [175].

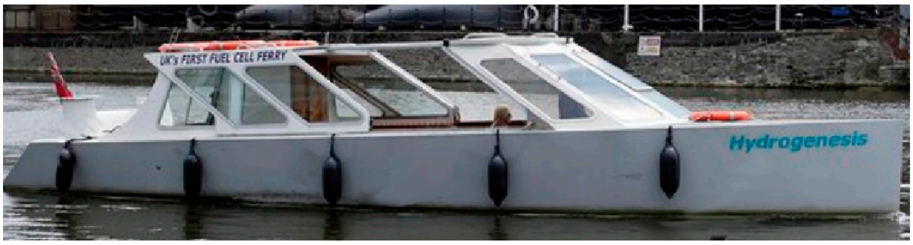

Figure 41. The fuel cell ferryboat "Hydrogenesis" [186].

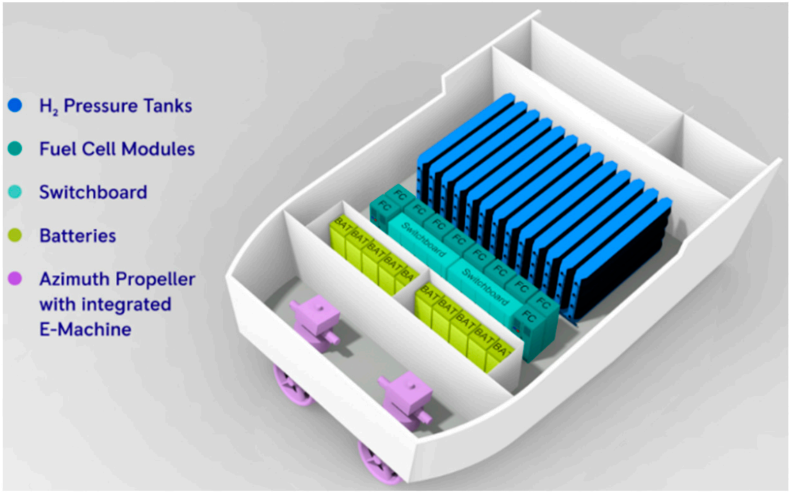

Figure 42. A propulsion system with fuel cells and batteries for tugboats, which was designed by Rolls-Royce Group PLC [189].

In Asia, Penguin International Limited, a Singaporean shipyard corporation, claimed in 2021 that it will install a PEMFC system as an auxiliary electrical power system in a converted roll-on-roll-off ship with the cooperation of the Royal Dutch Shell and LMG Marin [190,191]. In 2022, the Indian government claimed that the Indian Cochin Shipyard Corporation Limited (CSL) intends to develop and construct the first low-temperature PEMFC ship with independent intellectual property rights for India and formulate the relevant technical specifications with cooperation and support from the Indian register of shipping and KPIT Cummins Infomation Systems Company Limited [192–195]. In Turkey, Istanbul Technical University (ITU) unveiled a hydrogen fuel cell ship named "Marti" (or "seagull") in 2012, developed over four years with funding from several organizations, including the Istanbul Metropolitan Municipality (IMM) and the United Nations Industrial Development Organization (UNIDO) [196,197]. The ship "Marti" is shown in Figure 43 [198]. In the Taiwan region of China, three passenger ships named "Star of Hope", "Naruwa" and "Mu Yang" were launched in the 2010s [199,200]. The PEMFC system installed in these three passenger ships is produced by YC Synergy Corporation Limited and the abovementioned passenger ships are shown in Figure 44 [201,202].

Figure 43. The Turkish fuel cell ship "Marti" [198].

Figure 44. (**a**) The passenger ship "Star of Hope" [201,202]; (**b**) the passenger ship "Naruwa" [201,202]; (**c**) the passenger ship "Mu Yang" [201,202].

4. Prospects, Challenges and Suggestions

4.1. Prospects

Throughout the research progress of the marine fuel cell, the early studies before 2010 involved AFCs and MCFCs, but the PEMFC and the SOFC have been the mainstream in the past fifteen years, especially the former. The PAFC is not used as a marine fuel cell due to the low output power, low durability and requirement for expensive platinum catalysts. The PEMFC has attracted extensive attention due to its advantages of a short start-up time, good dynamic response, low-temperature operation characteristics and high power density. The numerical simulations and experiments showed that the dynamic response performance of the PEMFC is much better than that of other types of fuel cell [203,204]. However, the optimum output power of the PEMFC is below 300 kW, and the expensive platinum catalyst is indispensable. Thus, when the power demand is higher, the SOFC, with the advantages of high output power and no expensive catalyst required, is a better choice. Furthermore, the SOFC can be used in conjunction with the solid oxide electrolysis cell (SOEC) to set up large ship power stations. As for the AFC, the disadvantages of a relatively low output power, relatively low lifespan, high requirements for pure hydrogen and oxygen and expensive platinum catalysts all limit its further maritime application. The power of the MCFC is also high, but the disadvantages of the oversized volume, relatively low lifespan and the existence of liquid molten carbonate restrict its maritime application. Moreover, the results of the numerical simulations and experiments suggested that the dynamic response performance of the MCFC is also not sufficient under some maritime working conditions [205]. The same problem also exists during the application of the SOFC, but it can be solved reliably by combining the SOFC with an energy storage device, such as a battery and a super-capacitor.

Based on the current situation, the development trends in the application of the marine fuel cell range from small boats to large ocean-going vessels; from auxiliary power sources to propulsion power sources; and from navigation zones with low environmental complexity, such as coastal waters and inland waters, to the ocean, with complex navigation conditions. There is a direct correlation between the abovementioned three development trends and the power of the marine fuel cell. Specifically, the types of ships equipped with marine fuel cells are various, and the marine fuel cell should be applied to specific ships with suitable technical characteristics. In a ship with small tonnage whose power demand is not large, such as a sightseeing boat, yacht, patrol boat or passenger ship, etc., the PEMFC and the SOFC are both applicable as propulsion power sources and auxiliary power sources. However, when the power demand is large, such as in a cargo ship with large tonnage, the PEMFC cannot satisfy the power demand due to its low optimum output power, while the SOFC is still competent, especially as a propulsion power source. Moreover, the power demand of the ship when sailing in the ocean, with complex navigation conditions, is much high than that in a navigation zone with low environmental complexity, which can also demonstrate the advantages of the SOFC. To summarize, the marine fuel cell in the future needs to be more powerful, and thus the SOFC will play an increasingly important role, with the advantage of high output power, from this perspective.

Furthermore, excluding the difference in power, there are also two nonnegligible differences between the PEMFC and the SOFC from the business perspective. The fuel type of the SOFC is more flexible, including hydrogen, reformed gas, natural gas, coal gas and ammonia gas, while the PEMFC can only use pure hydrogen and the water produced needs to be managed [206]. The price of pure hydrogen is much higher than that of other gaseous fuels, and the fuel diversity of the SOFC can be better adapted to the reality of fuel production and consumption in different regions. Recently, the "World Energy Outlook 2022" published by the International Energy Agency (IEA) stated that ammonia will satisfy 45% of the fuel demand of the shipping industry by 2050 [207]. The existing research has also provided evidence that ammonia is the most suitable zero-carbon fuel for the application of the marine fuel cell, with the advantages of higher safety, lower costs, lower storage issues and higher sustainability [208]. The objective of establishing a sustainable and reliable shipping industry would benefit from the use of ammonia, which also provides new development opportunities regarding the SOFC. Numerical research showed that the SOFC using liquefied natural gas (LNG) is the most economical solution in reducing the emissions of greenhouse gases, which was claimed to be up to 34% [209]. Based on numerical simulation, if the SOFC can be combined with a gas turbine (for short GT) and other thermal equipment, such as an absorption heat pump (AHP), the energy efficiency will increase by 47% relative to the traditional system [210]. The numerical research also suggested that the combination of an SOFC and a battery can smooth the electric output and improve the lifespan [211]. Moreover, the service life of the SOFC can reach 100,000 h, which exceeds that of other types of fuel cell and the service life of the ship greatly. Consequently, the SOFC is more suitable for commercial application and will become more popular than the PEMFC in the shipping industry market in the future, from the perspective of the fuel and the service life. The maritime application status of the main types of fuel cell and their challenges are summarized in Table 4 [13,15,16,71,146,211].

Table 4. Maritime application status of the main types of fuel cell and their challenges [13,15,16,71,146,211].

Type	Maritime Application Status	Main Challenges
AFC	Very few applications	Relatively low output power High requirements for pure hydrogen and oxygen Relatively low lifespan Single fuel type Requirement for expensive platinum catalyst
PAFC	No application	Low output power Low durability Requirement for expensive platinum catalyst
PEMFC	Wider applications	Relatively low output power High requirements for pure hydrogen Complex system for water management Relatively low lifespan Single fuel type Requirement for expensive platinum catalyst
MCFC	Fewer applications	Relatively high cost Oversized volume Relatively low lifespan Existence of liquid molten carbonate Slow dynamic response
SOFC	Increasing applications	Relatively high cost Slow dynamic response

4.2. Industry Challenges and Suggestions

Several challenges must be addressed before applying the fuel cell in ships on a large scale. At present, there is a lack of infrastructure for the storage and supply of gaseous fuels, especially hydrogen, in the ship and the port [212]. Some scholars suggest that the hydrogen in the ship can be produced by the electrolysis of water, but this technology still requires the coordination of wind energy and solar energy [213]. Moreover, the cost of the fuel cell system is too high. For example, the costs of the PEMFC system and the PEMFC stack in China were 4400 Yuan per kilowatt and 2600 Yuan per kilowatt by the end of 2021, and, according to estimations, it will reach 3100 Yuan per kilowatt and 1800 Yuan per kilowatt by the end of 2022 [214]. Thus, the operating costs of the fuel cell ship are much higher in the initial operational stage, which means that the ship owner and ship management company may be unwilling to consider it [215]. To solve this problem, a practical solution is that the fuel cell used in the vehicle and the ship could undergo mutual development and share the infrastructure, which can lower the cost of the fuel cell system and the infrastructure [216]. In addition, the successful application of the fuel cell system in a ship requires the coordination of several sets of systems, but the related technology is still not mature due to some specific factors of the working conditions of the ship, such as high salt spray, high humidity, high oil spray, swing and vibration, which can cause low reliability, low stability and a low useful service life of the fuel cell. Thus, some equipment must to be improved to accommodate the working conditions on the sea [217,218]. For example, the air filter should have a unique design to protect the fuel cell against salt corrosion by the sea air. Lastly, the relevant laws and standards of shipbuilding, safety management, maritime control, infrastructure construction and seamen training are inadequate. At present, only an interim procedure intended to provide guidance for the arrangement and installation of the marine fuel cell became effective from May 2022, which was set and approved in Maritime Safety Committee Meeting 105 (MSC 105) [219]. The World Maritime Organization and national governments are advised to accelerate the legislative process, providing targeted policy guidance and support for industrial development, shipbuilding, safety management, maritime control, infrastructure construction and seamen training related to the marine fuel cell.

5. Conclusions

This review summarized the publicly reported maritime applications for the fuel cell worldwide, and the industrial development status and prospects of the marine fuel cell are obtained. However, this review did not focus on the areas of the technology and the economic analysis of the marine fuel cell, which are the main limitations. These issues will be fully addressed in our next study. The main achievements of this work are as follows.

(1) A thorough review of the maritime applications of the fuel cell worldwide in the past sixty years was performed, which can provide a convenient resource for the subsequent investigation and study of other researchers who are interested in this field.
(2) The industrial characteristics of the marine fuel cells of different countries were summarized.
(3) Detailed comparisons between different types of marine fuel cell were conducted, and a new viewpoint was proposed whereby the SOFC has greater prospects in maritime application given the increasing power demand of the marine fuel cell.

A series of research projects on the marine fuel cell have achieved a great deal of effective and fruitful work, laying a solid foundation for the further application of the marine fuel cell in the future. However, it cannot be ignored that the successful application of the marine fuel cell on a large scale cannot be completed in one step, and it needs constant efforts in the future. Some possible future studies are as follows.

(1) Increase the power of the marine fuel cell, especially the SOFC. In the long term, the power demand of the marine fuel cell will be increased steadily to achieve the ultimate objective in which the fuel cell can supply total power to a ship with large tonnage sailing in the ocean, such as ships of medium and high deadweight (50,000 tons and more), which provide intercontinental transportation. The SOFC has significant potential to satisfy the demand and will be the mainstream in the next research stage.
(2) Reduce the composite cost and shorten the payback time. At present, the composite cost of the marine fuel cell is much higher than that of the marine diesel engine with the same power. The higher composite cost and long payback time hamper the further application of the marine fuel cell in the shipping industry, which places great stress on the economic benefits. Thus, reducing the composite cost and shortening the payback time of the marine fuel cell are crucial directions to consider.
(3) New legislation on the marine fuel cell. The marine fuel cell system involves the complex integration of multiple types of equipment, components and subsystems, which involves numerous upstream and downstream industries and can lead the rapid development of related manufacturing industries. Furthermore, the additional installation of fuel cell elements on sea vessels should be agreed with the ship register.

The abovementioned cases both need to be regularized by the relevant laws and standards of the marine fuel cell. Thus, studies of the legislation on the marine fuel cell need to be strengthened.

Although some challenges exist, with the rising global fossil fuel prices and increasingly stringent environmental protection requirements, applying the fuel cell, especially the SOFC, to ships on a large scale, which will lead the upgrading and updating of the marine power system, can be expected in the near future with a global, concerted effort. Our future study will pay attention to the latest achievements in the industrial development of the marine fuel cell.

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