International Journal of Research in Advanced Engineering and Technology
www.allengineeringjournal.in
ISSN: 2455-0876
Received: 26-02-2023, Accepted: 13-03-2023, Published: 29-03-2023
Volume 9, Issue 1, 2023, Page No. 38-43

Hydrogen fuel cells for marine applications: Challenges and opportunities

Talal Elammas
Department of Computer Science, Western Illinois University, University Cir, Macomb, United State

Abstract
The marine industry is responsible for a significant portion of global greenhouse gas emissions and reducing its carbon footprint has become a pressing issue. Hydrogen fuel cells have emerged as a promising alternative to traditional marine propulsion systems, offering the potential to significantly reduce greenhouse gas emissions and increase energy efficiency. This paper provides a comprehensive analysis of the challenges and opportunities associated with the use of hydrogen fuel cells for marine applications. The environmental benefits of hydrogen fuel cells are explored, including their potential to reduce greenhouse gas emissions and improve energy efficiency. Additionally, the paper examines the potential for hydrogen to improve energy security and reduce dependence on fossil fuels, as well as the regulatory incentives driving the adoption of hydrogen fuel cell technology in the shipping industry. Safety concerns associated with the use of hydrogen fuel cells in marine applications are also addressed, including the need for safety measures to ensure safe handling, storage, and transport. Technical solutions to address these safety concerns are explored, along with the challenges associated with implementing these solutions on a large scale.

Keywords: hydrogen fuel cells, marine applications, greenhouse gas emissions, energy efficiency, energy security, regulatory incentives, safety concerns, infrastructure development, fuel cell systems, shipping industry

Introduction

The marine industry is facing increasing pressure to reduce its carbon footprint, as it is a significant contributor to global greenhouse gas emissions (Leo *et al*., 2010) [22]. According to the International Maritime Organization (IMO), the shipping industry accounts for around 2.2% of global greenhouse gas emissions, and this figure is expected to increase in the coming years (Ahmed *et al*., 2023b) [5]. Therefore, there is a need for the industry to adopt cleaner and more sustainable technologies to reduce its impact on the environment.

One technology that has emerged as a promising alternative to traditional marine propulsion systems is hydrogen fuel cells (Ahmed *et al*., 2023a). Fuel cells are electrochemical devices that convert the chemical energy of hydrogen and oxygen into electricity, heat, and water. The use of hydrogen fuel cells in marine applications has the potential to reduce greenhouse gas emissions and improve energy efficiency (van Biert *et al*., 2016) [35].

This paper will examine the challenges and opportunities associated with the use of hydrogen fuel cells for marine applications. The environmental benefits of hydrogen fuel cells will be discussed, including their potential to reduce greenhouse gas emissions and improve energy efficiency. The paper will also explore the potential for hydrogen to improve energy security and reduce dependence on fossil fuels, as well as the regulatory incentives driving the adoption of hydrogen fuel cell technology in the shipping industry (Han *et al*., 2012) [17].

In addition to the benefits of hydrogen fuel cells, the paper will also address the safety concerns associated with their use in marine applications (Ahmed *et al.*) [7]. As hydrogen is a highly flammable gas, safety measures must be implemented to ensure safe handling, storage, and transport (Ahmed & Ahmed, 2023b) [3]. The paper will also discuss the challenges associated with infrastructure development for hydrogen fuel cell technology, including the need to establish a network for hydrogen production, storage, and distribution.

Overall, this paper aims to provide a comprehensive analysis of the challenges and opportunities associated with the use of hydrogen fuel cells for marine applications. The analysis will consider the environmental, economic, and safety factors involved in the adoption of hydrogen fuel cell technology, with the goal of providing insights for stakeholders in the shipping industry and policymakers.

Basic principle of hydrogen fuel cells

The basic principle of a hydrogen fuel cell is the conversion of chemical energy stored in hydrogen fuel into electrical energy through an electrochemical process (Hacker & Mitsushima, 2018) [16]. This process involves the reaction of hydrogen fuel with oxygen from the air to produce electricity, heat, and water as the only byproduct (Mekhilef *et al*., 2012) [27]. The heart of a hydrogen fuel cell is a membrane electrode assembly (MEA), which consists of a proton exchange membrane (PEM) sandwiched between two electrodes, an anode, and a cathode. The anode is the negative electrode, where hydrogen fuel is introduced, and the cathode is the positive electrode, where oxygen is introduced (O'hayre *et al*., 2016) [30]. As hydrogen fuel is introduced to the anode, it is split into protons (H+) and electrons (e-) through a catalytic process Fig 1. The protons are then transported through the PEM to the cathode, while the electrons are forced to take an external circuit to generate an electric current. At the cathode, the protons, electrons, and oxygen from the air react to form water (H2O) and release heat (Crabtree & Dresselhaus, 2008) [13]. The overall chemical reaction in a hydrogen fuel cell can be represented as:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{electricity} + \text{heat}$$

This process is highly efficient, as it avoids the thermal inefficiencies associated with traditional combustion engines, which convert chemical energy into heat, which in turn powers a turbine to generate electricity (Revankar & Majumdar, 2014) [31]. Hydrogen fuel cells offer several advantages over traditional combustion engines, including higher efficiency, lower emissions, and quieter operation. They are also highly flexible, as they can be used in a variety of applications, from transportation to stationary power generation (Mench, 2008) [28].

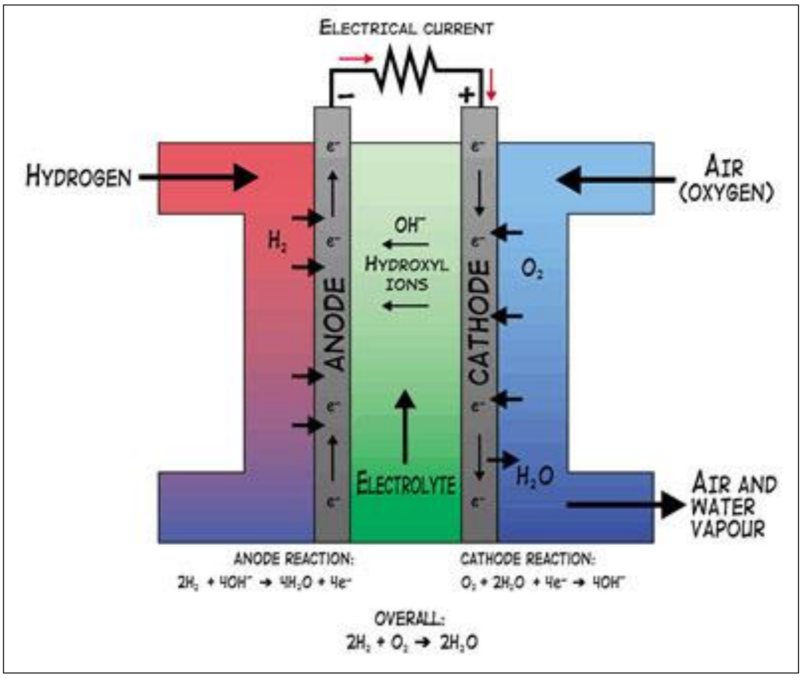

Fig 1: Basic Principle of Hydrogen Fuel Cells

Overview of the potential for hydrogen fuel cells to power marine vessels, including ships and boats:

Hydrogen fuel cells have gained attention as a promising alternative to traditional marine propulsion systems, offering the potential to significantly reduce greenhouse gas emissions and improve energy efficiency. In this paper, we examine the potential for hydrogen fuel cells to power marine vessels, including ships and boats, and the benefits and challenges associated with this technology (Han *et al*., 2012) [17]. One of the main benefits of using hydrogen fuel cells in marine applications is their environmental impact. Hydrogen fuel cells produce electricity by combining hydrogen and oxygen, with water being the only byproduct. This means that there are no greenhouse gas emissions or other harmful pollutants, which can help reduce the carbon footprint of the shipping industry(Al Hosani *et al*., 2022) [9]. This is particularly important as shipping is responsible for around 3% of global greenhouse gas emissions, making it a significant contributor to climate change (Winkler, 2009) [37]. Another benefit of hydrogen fuel cells is their energy efficiency. Fuel cells have a higher efficiency compared to traditional marine propulsion systems, which means less fuel is required to produce the same amount of power. This results in lower fuel consumption and operating costs for shipping companies, which can be significant given the high fuel consumption of marine vessels (McConnell, 2010) [26].

In addition to environmental and economic benefits, the use of hydrogen fuel cells can also improve energy security and reduce dependence on fossil fuels. Fossil fuels are subject to price volatility and supply chain disruptions, which can have significant economic and logistical implications for the shipping industry. By using hydrogen as a fuel source, the industry can reduce its dependence on fossil fuels and improve energy security. However, there are also significant challenges associated with the adoption of hydrogen fuel cells for marine applications (Ahmed & Miller, 2022) [1]. One of the main challenges is the technical and logistical aspects of hydrogen production, storage, and distribution. Hydrogen is a highly flammable gas, which requires specialized handling and storage facilities. The development of a network for hydrogen production, storage, and distribution, including the infrastructure required to transport and store hydrogen on ships, is a significant challenge that requires significant investment and technological advancements (Vogler & Würsig, 2011) [36]. Another challenge is the safety concerns associated with the use of hydrogen fuel cells in marine applications. Hydrogen is a highly flammable gas and requires special safety measures to ensure safe handling, storage, and transport. This includes the development of safety protocols and standards, as well as specialized training for personnel who will be working with hydrogen fuel cells (Ahmed, 2022) [8]. Despite these challenges, there have been several successful demonstrations of hydrogen fuel cell technology in marine applications (Ahmed & Ahmed, 2023a) [2]. For example, in 2018, a fuel cell-powered passenger ferry was launched in Norway, which was the first of its kind in the world. The ferry, named the MF Hydra, has a capacity of 80 passengers and can travel at speeds of up to 10 knots.

Another successful demonstration of hydrogen fuel cell technology in marine applications is the Energy Observer, a catamaran that is powered by hydrogen fuel cells and solar panels. The vessel is on a round-the-world trip, which started in 2017, and aims to demonstrate the potential of hydrogen fuel cell technology for the maritime industry. The Advantage of using the Hydrogen Fuel Cells in Marine Applications can be summarized in Table 1.

Table 1: Advantage of using the Hydrogen Fuel Cells in Marine Applications

Advantage	
Environmental Benefits	One of the primary benefits of hydrogen fuel cells is their potential to reduce greenhouse gas emissions. Unlike traditional marine propulsion systems that rely on fossil fuels, fuel cells produce only water and heat as byproducts, significantly reducing the emission of harmful pollutants and greenhouse gases. The reduction in emissions can help the shipping industry comply with regulatory requirements, such as the International Maritime Organization's (IMO) greenhouse gas reduction targets (Sürer & Arat, 2022) [32]. Furthermore, hydrogen is a renewable energy source that can be produced from a variety of sources, including renewable electricity, natural gas, and biomass. This means that the use of hydrogen fuel cells in marine applications can help reduce the industry's dependence on fossil fuels and contribute to a more sustainable energy future (van Biert *et al*., 2016) [35].
Energy Security	Another advantage of hydrogen fuel cells is their potential to improve energy security. Unlike oil and gas, which are often sourced from politically unstable regions, hydrogen can be produced domestically, reducing dependence on foreign energy sources. This can help mitigate the impact of energy price volatility and geopolitical tensions on the shipping industry (de-Troya *et al*., 2016) [15].
Efficiency	Fuel cells can be more efficient than traditional engines, resulting in lower fuel consumption and operating costs. This is because fuel cells convert the chemical energy of hydrogen into electricity with a high degree of efficiency, compared to traditional engines that convert chemical energy into mechanical energy, which is then converted into electricity. As a result, fuel cells can provide a more energy-efficient and cost-effective alternative to traditional marine propulsion systems (Tse *et al*., 2011) [34].
Improved safety	Hydrogen fuel cells are a safer option for marine applications as they do not require the storage of flammable fuels on board. This eliminates the risks associated with fuel spills, leaks, and explosions that are commonly associated with traditional fossil fuel-based engines. Additionally, hydrogen fuel cells are not prone to the ignition hazards that arise from the accumulation of combustible gases in confined spaces, making them a safer alternative for marine vessels. Overall, hydrogen fuel cells offer a safer, more sustainable, and efficient energy source for the marine industry, helping to reduce the environmental impact of marine transport while improving the safety of the crew and the vessel (Luckose *et al*., 2009) [24].
Reduced weight and space requirements	Hydrogen fuel cells are lighter and take up less space than traditional diesel engines, making them an attractive option for smaller vessels or those with limited space for energy storage (Cullen *et al*., 2021) [14].
Improved reliability	Hydrogen fuel cells are highly reliable and have a longer lifespan than traditional engines. This means that they require less maintenance and have a lower risk of breakdowns, reducing downtime and increasing vessel uptime (Jafarzadeh & Schjølberg, 2017) [20].
Regulatory Incentives	Governments around the world are implementing policies and incentives to support the adoption of hydrogen fuel cell technology. This includes tax credits, grants, and subsidies for research and development, as well as regulatory measures to reduce greenhouse gas emissions from the shipping industry. For example, the IMO has set a target to reduce greenhouse gas emissions from the shipping industry by at least 50% by 2050, compared to 2008 levels (He & Angenent, 2006) [18].
Supporting sustainable development	The use of hydrogen fuel cells in marine applications supports the development of sustainable technologies and reduces the reliance on fossil fuels. This is particularly important in the marine industry, which has traditionally been heavily reliant on fossil fuels (Inal & Deniz, 2020) [19].
Safety Concerns	Despite the potential benefits of hydrogen fuel cells, there are also safety concerns associated with their use in marine applications. Hydrogen is a highly flammable gas and requires careful handling and storage to prevent accidents. There is also a risk of hydrogen leaks, which can result in explosions or fires. Safety measures must be implemented to ensure that hydrogen is stored and transported safely (Baccioli *et al*., 2021) [10].

Discussion of the challenges to deploying hydrogen fuel cells for marine applications, including safety, infrastructure, and regulatory barriers

Hydrogen fuel cells have the potential to revolutionize the marine industry by offering a clean, efficient, and renewable alternative to traditional fossil fuels. However, the deployment of hydrogen fuel cells for marine applications faces a number of challenges that must be addressed before it can become a viable and widespread solution Table 2.

Table 2: Dis-advantage of using the Hydrogen Fuel Cells in Marine Applications

Dis-advantages	
lack of infrastructure	One of the biggest challenges facing the deployment of hydrogen fuel cells for marine applications is the lack of infrastructure. While there are already some hydrogens fueling stations in place for vehicles, the same cannot be said for marine vessels. Building a hydrogen refueling infrastructure for marine vessels would require significant investment in infrastructure and logistics, as well as a coordinated effort between industry stakeholders, government agencies, and communities to support its implementation (Sürer & Arat, 2022) [32].
Cost	Another challenge to the deployment of hydrogen fuel cells for marine applications is the cost. Currently, the cost of producing and deploying hydrogen fuel cells for marine applications is prohibitively high. The cost of the technology itself is high, but there are also additional costs associated with building and operating the necessary infrastructure, such as refueling stations, storage facilities, and safety systems. Additionally, the cost of producing hydrogen fuel is also higher than traditional fossil fuels, making it difficult to compete on price alone (Han *et al*., 2012) [17].
Safety	Safety is another concern when it comes to hydrogen fuel cells for marine applications. Hydrogen is a highly flammable gas, and any leaks or malfunctions in the fuel cell system could lead to catastrophic accidents. Therefore, it is essential to have robust safety measures in place, such as automatic shutoff valves, leak detection systems, and emergency response protocols. Ensuring the safety of crew, passengers, and the environment is of utmost importance and should be a top priority when considering the deployment of hydrogen fuel cells for marine applications (Luckose

	et al., 2009) [24].
Technical challenges	One of the main technical challenges is the limited range and storage capacity of hydrogen fuel cells. Marine vessels require a lot of energy to operate, and the current technology does not provide enough energy density to support long-distance or long-duration trips. Moreover, hydrogen storage is a significant challenge as hydrogen has a low energy density and needs to be compressed or liquefied, which requires significant energy input (de-Troya *et al*., 2016) [15].
limited availability of suitable fuel cell systems	Another technical challenge is the limited availability of suitable fuel cell systems for marine applications. While there are already some commercially available fuel cell systems for land vehicles, these are not necessarily suitable for marine applications due to differences in operating conditions, power requirements, and safety regulations. Therefore, specialized fuel cell systems need to be developed specifically for marine applications (van Biert *et al*., 2016) [35].
Environmental impact	Another challenge is the environmental impact of hydrogen fuel cells. While hydrogen fuel cells produce zero emissions during operation, the production of hydrogen fuel itself can be environmentally damaging if not produced sustainably. Most of the world's hydrogen is currently produced from fossil fuels, which release greenhouse gases and contribute to climate change. Therefore, it is important to ensure that the production of hydrogen fuel is sustainable and environmentally friendly (Tse *et al*., 2011) [34].
Regulatory and policy challenges	Regulatory and policy challenges also need to be addressed to facilitate the deployment of hydrogen fuel cells for marine applications. Regulations and policies governing marine transportation are complex and vary by country, making it difficult to develop and implement a unified regulatory framework for hydrogen fuel cell technology. Furthermore, policymakers must establish clear standards and regulations for the production, storage, and transport of hydrogen fuel to ensure safety and environmental sustainability (Markowski & Pielecha, 2019) [25].
Public perception and acceptance	public perception and acceptance of hydrogen fuel cell technology also pose a challenge. Many people are unfamiliar with the technology and may view it as unsafe or unproven. Therefore, it is crucial to raise public awareness and promote education about the benefits and safety of hydrogen fuel cell technology to gain wider acceptance and support (He & Angenent, 2006) [18].
Infrastructure Development	Another challenge associated with the use of hydrogen fuel cells in marine applications is infrastructure development. The development of infrastructure for hydrogen production, storage, and distribution is still in its early stages, and it requires significant investment. For example, the infrastructure for hydrogen production and distribution is not yet as widespread as the infrastructure for traditional marine fuels such as diesel and gasoline. This means that significant investment is required to build a network of hydrogen (Lovley, 2006) [23].

Comparison of the performance of hydrogen fuel cells with other potential marine technologies

Hydrogen fuel cells, batteries, and biofuels are three potential aviation technologies that have been explored as alternatives to traditional fossil fuels. When comparing their performance, it is important to consider factors such as energy density, power output, and environmental impact (Contestabile *et al*., 2011) [12]. Hydrogen fuel cells have the highest energy density and can provide a longer range than batteries or biofuels. However, the infrastructure for producing and distributing hydrogen fuel is not yet widely available. Batteries have lower energy density but are more widely used in aviation and can provide quick bursts of power (Ahmed *et al*., 2023a) [4]. Biofuels have lower emissions than traditional fossil fuels, but their energy density is also lower, and they require significant land use for production (Thomas, 2009) [33]. Ultimately, the choice of technology will depend on the specific needs of the aviation industry, balancing factors such as cost, environmental impact, and energy efficiency. Fuel cell technologies exhibit unique advantages and challenges that set them apart from one another (Ahmed & Ahmed, 2023c) [6]. we can review a comparative analysis of different fuel cell technologies to see how they stack up against each other.

Table 3: performance of hydrogen fuel cells with other potential marine technologies.

Fuel Cell Types	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency (LHV)	Applications
Polymer electrolyte membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW–100 kW	60% direct H2; 40% reformem fuel	Backup power Portable power Distributed generation Transportation Specialty vehicles
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1–100 kW	60%	Military Space Backup power Transportation
Phosphoric acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150°–200°C	5–400 kW, 100 kW module (liquid PAFC) <10 kW (polymer membrane)	40%	Distributed generation
Molten carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600°–700°C	300 kW–3 MW, 300 kW module	50%	Electric utility Distributed generation
Solid oxide (SOFC)	Yttria stabilized zirconia	500°–1,000°C	1 kW–2 MW	60%	Auxiliary power Electric utility Distributed generation

Case studies of successful deployments of hydrogen fuel cells for marine applications

There have been several successful deployments of hydrogen fuel cells for marine applications, including:

- ABB's fuel cell system for ferries: The fuel cell system installed on the MS Viking Grace consists of two 125 kW fuel cells and a 220 kWh battery pack. The system provides clean power to the vessel's electrical grid, which powers the propulsion system, lighting, air conditioning, and other onboard systems. The system also includes a hydrogen storage and refueling system that allows the vessel to be refueled quickly and safely (Yartys *et al*., 2021) [38].
- San Francisco Bay Area Water Emergency Transportation Authority's (WETA) fuel cell ferry: The Hydrus is a 84-passenger ferry that uses a 100 kW hydrogen fuel cell system to generate electricity. The system is supplemented by a 100 kWh battery pack and a 70 kg hydrogen storage system. The vessel was designed to be fully zero-emissions and is expected to reduce greenhouse gas emissions by over 800 tons per year (NO, 2014) [29].
- Toyota's fuel cell system for a cargo vessel: Toyota's fuel cell system uses a proton exchange membrane fuel cell that converts hydrogen into electricity. The system is capable of producing up to 2,000 kW of electricity, which is used to power the vessel's electric motors. The system also includes a large hydrogen storage system that allows the vessel to operate for several days without refueling (Sürer & Arat, 2022) [32].
- Norway's zero-emissions passenger vessel: The MS Bard is a 80-passenger vessel that uses a 200 kW hydrogen fuel cell system to generate electricity. The system is supplemented by a 1 MWh battery pack and a 700 kg hydrogen storage system. The vessel was designed to be fully zero-emissions and is expected to reduce greenhouse gas emissions by over 640 tons per year (Johansen, 2021) [21].
- China's hydrogen fuel cell-powered ship: The Feihong 98 is a 70-meter-long cargo vessel that uses a 2 MW hydrogen fuel cell system to generate electricity. The system is supplemented by a 1.5 MWh battery pack and a 35-ton hydrogen storage system. The vessel was designed to be fully zero-emissions and is expected to reduce greenhouse gas emissions by over 2,000 tons per year (Chen & Guan, 2021) [11].

These successful deployments of hydrogen fuel cells for marine applications demonstrate the potential of this technology to provide a sustainable and efficient alternative to traditional fossil fuel-powered vessels.

References

1. Ahmed H. Human Systems Integration Of Agricultural Machinery In Developing Economy Countries: SUDAN AS A CASE STUDY Colorado State University], 2022.
2. Ahmed H, Adebayo P, Ahmed M, Arbab AI. Hydrogen Fuel Cell Technology: Benefits, Challenges, and Future Potential, 2023a.
3. Ahmed H, Adebayo P, Ahmed M, Arbab AI. Life Cycle Assessment of Hydrogen Fuel Cells: Environmental Impact and Sustainability. Life, 2023b, 13(1).
4. Ahmed H, Ahmed M. Facts, Myths, and Evolving Research Agenda on the Mechanization of the African Agricultural Sector, 2023a.
5. Ahmed H, Ahmed M. Human Systems Integration: A Review of Concepts, Applications, Challenges, and Benefits, 2023b.
6. Ahmed H, Ahmed M. Influencing Factors on Adoption of Modern Agricultural Technology in Developing Economy Countries, 2023c.
7. Ahmed H, Edzie EAS, Ahmed M. Investigating the effect of local activated carbon in the treatment of some heavy metals in spent synthetic based mud.
8. Ahmed H, Miller EE. Human ‐ Systems Integration of Agricultural Machinery in Developing Economy Countries: Perceptions of Adoption. INCOSE International Symposium, 2022.
9. Al Hosani N, Fathelrahman E, Ahmed H, Rikab E. Moving Bed Biofilm Reactor (MBBR) for decentralized grey water treatment: Technical, ecological and cost efficiency comparison for domestic applications. Emirates Journal of Food and Agriculture, 2022.
10. Baccioli A, Liponi A, Milewski J, Szczęśniak A, Desideri U. Hybridization of an internal combustion engine with a molten carbonate fuel cell for marine applications. Applied Energy,2021:298:117-192.
11. Chen L, Guan W. Safety design and engineering solution of fuel cell powered ship in inland waterway of China. World Electric Vehicle Journal,2021:12(4):202.
12. Contestabile M, Offer G, Slade R, Jaeger F, Thoennes M. Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner? Energy & Environmental Science,2011:4(10):3754-3772.
13. Crabtree GW, Dresselhaus MS. The hydrogen fuel alternative. Mrs Bulletin,2008:33(4):421-428.
14. Cullen DA, Neyerlin K, Ahluwalia RK, Mukundan R, More KL, Borup RL,*et al*. New roads and challenges for fuel cells in heavy-duty transportation. Nature energ,20216(5):462-474.
15. de-Troya JJ, Alvarez C, Fernández-Garrido C, Carral L. Analysing the possibilities of using fuel cells in ships. International journal of hydrogen energy,2016:41(4):2853-2866.
16. Hacker V, Mitsushima S. Fuel cells and hydrogen: from fundamentals to applied research. Elsevier, 2018.
17. Han J, Charpentier JF, Tang T. State of the art of fuel cells for ship applications. 2012 IEEE international symposium on industrial electronics, 2012.
18. He Z, Angenent LT. Application of bacterial biocathodes in microbial fuel cells. Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis,2006:18(19 ‐ 20):2009-2015.
19. Inal OB, Deniz C. Assessment of fuel cell types for ships: Based on multi-criteria decision analysis. Journal of Cleaner Production,2020:265:121734.
20. Jafarzadeh S, Schjølberg I. Emission reduction in shipping using hydrogen and fuel cells. International Conference on Offshore Mechanics and Arctic Engineering, 2017.
21. Johansen BH. Establishing A Basis For Decision Support Modelling Of Future Zero Emissions Sea Based Tourism Mobility In The Geiranger Fjord Area. ECMS, 2021.

22. Leo T, Durango J, Navarro E. Exergy analysis of PEM fuel cells for marine applications. Energy,2010:35(2):1164-1171.
23. Lovley DR. Microbial fuel cells: novel microbial physiologies and engineering approaches. Current opinion in biotechnology,2006:17(3):327-332.
24. Luckose L, Hess H, Johnson B. Fuel cell propulsion system for marine applications. 2009 IEEE Electric Ship Technologies Symposium, 2009.
25. Markowski J, Pielecha I. The potential of fuel cells as a drive source of maritime transport. IOP Conference Series: Earth and Environmental Science, 2019.
26. McConnell VP. Now, voyager? The increasing marine use of fuel cells. Fuel cells bulletin,2010:(5):12-17.
27. Mekhilef S, Saidur R, Safari A. Comparative study of different fuel cell technologies. Renewable and Sustainable Energy Reviews,2012:16(1):981-989.
28. Mench MM. Fuel cell engines. John Wiley & Sons, 2008.
29. No A. San francisco bay area water emergency transportation authority, 2014.
30. O'hayre R, Cha SW, Colella W, Prinz FB. Fuel cell fundamentals. John Wiley & Sons, 2016.
31. Revankar ST, Majumdar P. Fuel cells: principles, design, and analysis. CRC press, 2014.
32. Sürer MG, Arat HT. Advancements and current technologies on hydrogen fuel cell applications for marine vehicles. International journal of hydrogen energy,2022:47(45):19865-19875.
33. Thomas CS. Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles. International journal of hydrogen energy,2009:34(23)-9279-9296.
34. Tse LKC, Wilkins S, McGlashan N, Urban B, Martinez-Botas R. Solid oxide fuel cell/gas turbine trigeneration system for marine applications. Journal of Power Sources,2011:196(6):3149-3162.
35. van Biert L, Godjevac M, Visser K, Aravind P. A review of fuel cell systems for maritime applications. Journal of Power Sources,2016:327:345-364.
36. Vogler F, Würsig G. Fuel Cell in Maritime Applications Challenges, Chances and Experiences, 2011.
37. Winkler W. Ships: fuel cells. Encyclopedia of Electrochemical Power Sources,2009:1:338-358.
38. Yartys VA, Lototskyy MV, Linkov V, Pasupathi S, Davids MW, Tolj I,*et al*. Hydride4mobility: an EU Horizon 2020 project on hydrogen powered fuel cell utility vehicles using metal hydrides in hydrogen storage and refuelling systems. International journal of hydrogen energy,2021:46(72):35896-35909.