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Development of a marine PEMFC system for SMVs

Electrification and Fuel Cells Development

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ABSTRACT

In comparison to large ships, small-to-medium-sized vessels (SMVs) are characterized by significant spatial constraints and exist in greater numbers. The Proton Exchange Membrane Fuel Cell (PEMFC) system is a suitable power source that aligns with these characteristics. The development of PEMFC systems for SMVs, with power outputs ranging from hundreds of kilowatts to several megawatts presents several key considerations. These include ensuring compatibility with SMV applications with space constraints, fuel efficiency, ensuring the durability and reliability of the product, compliance with safety regulations. This presentation discusses key considerations addressed by HD Hyundai Heavy Industries, including an analysis of the 350kW demonstration ship case. Additionally, the current status of the development of a 200kW PEMFC module is introduced. In the 350kW demonstration ship case analysis, the power output of both PEMFC and ESS for two different operational routes of a 40-passenger ferry was simulated. The result indicated a hydrogen consumption of 86 kg for a round-trip operation twice a day. The 200kW PEMFC system under development uses a mass-produced PEMFC stack that ensures reliability. It has been optimized for marine applications. The 200kW system is designed with a compact footprint, with space for 8 stacks in a 20ft container, including a maintenance space, to optimize space utilization in SMVs. It is being developed with the goal of achieving the world's highest volumetric energy density. This development is targeted for prototype production and performance validation by 2027.

1 INTRODUCTION

The maritime sector is experiencing escalating pressure to achieve carbon neutrality, propelling the development of technologies for ship decarbonization. Currently, GHG emission regulations such as CII and FuelEU Maritime focus on large ships over 5,000GT, but regulations for SMV may be introduced in the near future.

PEMFC is a hydrogen-based power generation device enabling carbon neutrality in ships. Its technological reliability has been proven through commercialization in various applications over the past 20 years, including stationary power generation, vehicles, and drones [1]. A typical PEMFC system operates at around 50% efficiency and maximizes the efficiency of carbon-neutral fuel utilization. Simultaneously, its rapid load fluctuation capacity of about 30%/s enables robust power distribution and flexible power generation strategies. Moreover, considering the high system energy density of 50-150kW/m^3, PEMFC is a suitable power generation device for main and auxiliary power sources in SMVs [2].

Despite these technical advantages, PEMFC integration into the maritime sector has been hindered by hydrogen fuel infrastructure issues and economies of scale [3]. This situation can be considered as an intermediate stage before PEMFC becomes a significant contributor to the 2050 net-zero greenhouse gas emissions goal for ships. The integration of the PEMFC system into ship interface must be well-prepared before infrastructure is secured and economies of scale are achieved. Moreover, targeted analysis of individual vessel cases must be conducted for the implementation of PEMFC systems.

2 KEY CONSIDERATIONS FOR MARITIME PEMFC SYSTEMS

The integration of PEMFC systems as primary or auxiliary power sources in maritime applications requires a multifaceted evaluation. Primarily, the PEMFC system's capacity to meet ship-specific GHG emission reduction targets must be assessed. Furthermore, a comprehensive analysis should encompass the durability and performance of PEMFC stacks, the reliability and availability of maintenance networks, fuel efficiency of the PEMFC system, and its spatial efficiency. These factors must be evaluated together to determine the viability and effectiveness of the implementation of PEMFC systems in SMVs.

2.1 GHG Emission Reduction

PEMFC systems provide a robust and immediate contribution to the mitigation of GHG emissions. Key indicators of ship GHG emissions, such as EEDI and EEXI, are primarily determined by main and auxiliary engine outputs. To ensure conformity with GHG regulations, calculations can be conducted to determine the percentage of electrical power that needs to be replaced with PEMFC to meet the required threshold values [4]. This approach is applicable to auxiliary engines in mechanically propelled vessels, and to both main and auxiliary engines in electrically propelled vessels. Further consideration should be given to a full lifecycle GHG emissions using the TtW methodology (CSN EN 16258:42). In a real-world case study, a 240-ton passenger vessel with full electric propulsion demonstrated approximately 25% of the TtW GHG emissions of its diesel-powered counterpart [5].

2.2 Reliability of PEMFC Stack

PEMFC stacks consist of hundreds of PEMFC cells that are stacked and electrically connected in series. Achieving reliable performance and durability for stacks in this configuration requires advanced and precise manufacturing techniques during large-scale production. Furthermore, as PEMFC technology is still in the early stages of marine application, a global maintenance network is essential for long-term operation. The defect rate during cell or stack production is a key factor influencing production costs, consequently impacting the price of cells or stacks. If defective products are not properly inspected before reaching customers, even a single faulty cell or improperly assembled component can lead to the failure of the entire stack [6, 7].

2.3 Tradeoff in System Efficiency

Given the larger fuel tank size and higher fuel costs compared to conventional marine fuels, it is crucial to assess the operating range of the PEMFC system based on system efficiency and equipment costs. Since PEMFC efficiency is inversely proportional to its output, minimizing fuel costs necessitates increasing the number of stacks, thereby raising equipment costs [8]. For instance, generating 1MW of power could involve using ten 100kW stacks or twenty 100kW stacks each operating at 50kW. The former configuration results in higher operating costs but lower equipment costs, while the latter yields lower operating costs but higher equipment costs. In this context, PEMFC system providers need to analyze case-specific customer needs and recommend an optimal configuration accordingly.

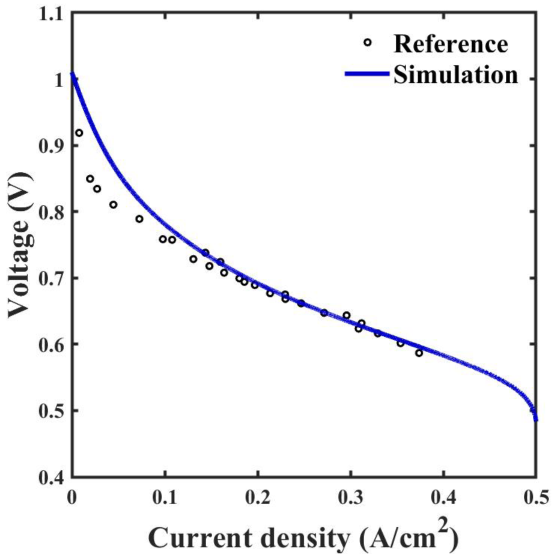

Figure 1. An example of current density–voltage characteristics of a typical PEMFC [9]

2.4 Spatial Effectiveness

The integration of PEMFC systems in maritime applications encompasses both retrofit solutions for existing vessels and installations in new vessel constructions. Maximizing volumetric energy density is crucial for efficient space utilization within a vessel's confined space. This spatial efficiency also benefits the hydrogen conversion processes for alternative fuels such as e-MeOH and e-NH_3. However, system design must balance compactness with maintenance accessibility. The internal space design must account for system maintenance. Inadequate internal design might allow most components to be serviced by opening the front of the system, but some components may still necessitate rear access for repairs. In such cases, the required installation space would increase, making high volumetric energy density impractical. While published data indicates PEMFC products generally achieve 50-200kW/m^3, marine-specific applications tend to exhibit lower densities, typically below 120kW/m^3 [10]. This reduction is partially due to maritime safety regulations.

2.5 Safety Consideration

Equipment operations on ships require stringent compliance with safety standards established by classification societies and certification authorities. The limited space of ship environments amplifies the potential severity of accidents, requiring strict safety measures. Redundancy is a primary safety requirement, demanding a minimum of two independent PEMFC systems with separate circuits. For PEMFC systems using highly flammable fuels like hydrogen, compliance with relevant gas safety standards is imperative. A key example of such a standard is the physical separation of hydrogen subsystems and stacks from other components, including air subsystems. These kinds of safety standards ultimately enhance regulations also enhance the operational reliability and completeness of the system through various margins and safety measures. Table 1 below presents a list of safety guidelines and standards that must be considered during the development and operation of marine fuel cell systems.

Table 1. Safety Guidelines related Maritime PEMFC Systems

IMO: MSC.1-Circ.1647
DNV: Handbook for Hydrogen-fuelled Ships
ISO/TC 197: Hydrogen technologies
IEC/TC105: Fuel cells
ISO/TR 15916:2004
IEC 60079-17: Explosive atmospheres; Part 17
IEC 62282-3-1: Fuel cell technologies; Part 3.1
IEC 60079-10; Part 10

3 SIMULATION-BASED DEVELOPMENT: CASE SCENARIOS

It is essential to evaluate and enhance the technical reliability of PEMFC through actual maritime demonstrations. HD Hyundai Heavy Industries is participating in a South Korean government project to demonstrate a 350kW fuel cell propulsion ship. According to the project schedule, sea trials are scheduled for completion by 2026. Prior to the actual equipment demonstration, performance analysis of the 350kW PEMFC electric propulsion system was conducted using a one-dimensional model simulation.

3.1 Ship Overview

The 350kW PEMFC electric propulsion ship is designed as a 40-passenger vessel for domestic routes. The main propulsion power is supplied by four 100kW PEMFC systems. To ensure redundancy, the PEMFC, ESS, and motors are configured in a dual arrangement. For safety reasons, hydrogen tanks are positioned on the upper deck of the ship.

Table 2. Specifications of the 350kW PEMFC ship

Specifications	Value	Unit
Ship dimension (L×W×H)	20×9×2	m
Gross tonnage	50	GT
Ship velocity	Max. 14	knots
Fuel cell capacity	400	kW
Sailing distance	21	km/trip
Passenger capacity	40	-

Figure 2. 3D rendering of the 350kW PEMFC ship

3.2 Performance of Propulsion System Model

An electric propulsion system model was developed in AMESim software for simulating the demonstration ship. This comprehensive model includes all major media flows and power connections of the electric propulsion ship including the ship model (based on towing tank test data) and the seawater cooling system.

The 100kW PEMFC system, as illustrated in Figure 3, was validated with a relative voltage error of 1.2% against actual operational data, confirming its accuracy for integration into the propulsion system model. Primary errors were observed near the activation overpotential region immediately after start up and near maximum load, areas typically outside normal operating ranges.

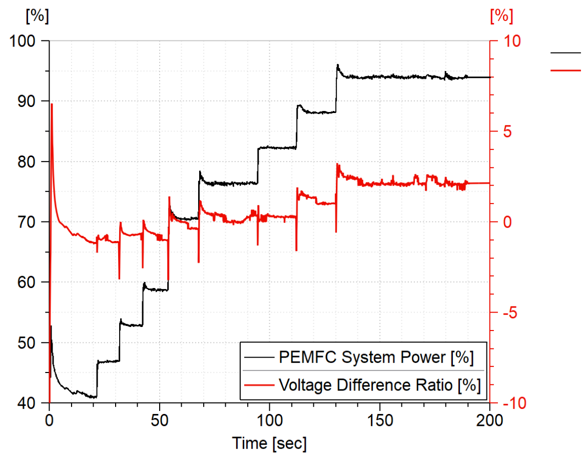

Figure 3. Voltage relative error by PEMFC system power

To investigate the dynamic performance of the PEMFC propulsion system model, a simulation was conducted using a short-term load variation scenario. This simulation aimed to verify the PEMFC's performance in tracking the ship's electric motor load, given its rapid load variation characteristics. In a scenario where the load reaches maximum within about 6 seconds and then drops back to minimum load within 6 seconds, Figure 4 shows that the power generated by the PEMFC system lagged behind the required load increase and decrease. The output delay of several seconds was compensated for peak shaving from the ESS, effectively balancing insufficient or excessive output.

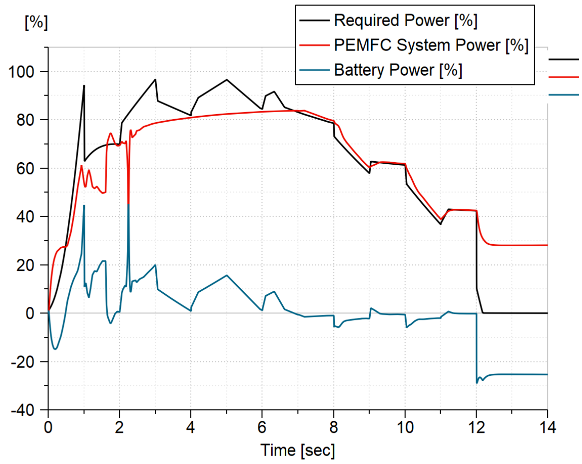

Figure 4. PEMFC system and ESS output due to propulsion motor power variation

3.3 Ship Operation Scenario Simulation

The 350kW demonstration ship is scheduled for sea trials and commercial operations along the path shown in Figure 5. The route consists of two segments: the segment between Port A and Port B, and the segment between Port B and Port C.

Table 3. Sailing route layout

Route	Distance [km]	Travel/day
A ↔ B	9.5	2
B ↔ C	11.5	2

Figure 5. 350kW fuel cell ship sailing route

Route A to B and Route B to C will operate at a speed of 5 knots during departure and arrival phases, with main operational speeds of 10 knots and 12 knots, respectively. Simulations were conducted to assess travel time, required power output, PEMFC system output, ESS output, and hydrogen consumption for both routes.

The simulation results for the demonstration ship model on Route A to B are shown in Figure 6. The power required for a speed of 10 knots was fully met by the PEMFC. Due to the ship's characteristic of maintaining a constant speed, average power usage remains steady, excluding hotel loads. During the departure and arrival phases, the state of charge of the ESS was below the baseline, resulting in the PEMFC generating more power than needed for the motor to facilitate charging. Approximately 6.0 kg of hydrogen was consumed over a 9.5 km distance.

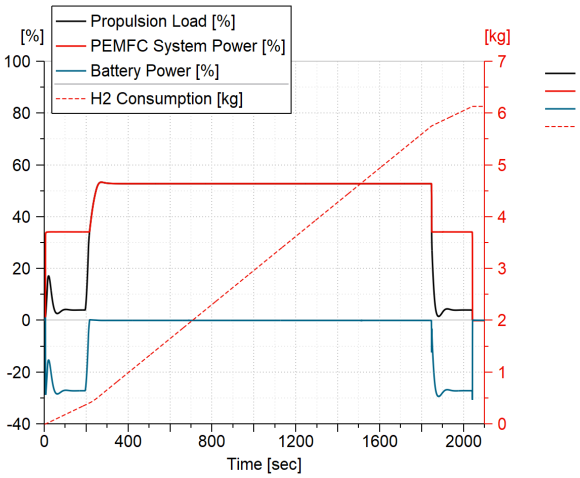

Figure 6. Power consumption of each power source and total hydrogen consumption during route A to B

Figure 7 presents the simulation results for the demonstration ship model on Route B to C. The PEMFC met all power requirements to maintain a speed of 12 knots. Similar to the departure phase, excess power was generated by the PEMFC for ESS charging. In contrast, during the arrival phase, adequate charging was reached, resulting in no additional power generation from the PEMFC. Approximately 13.5 kg of hydrogen was consumed over the 11.5 km distance.

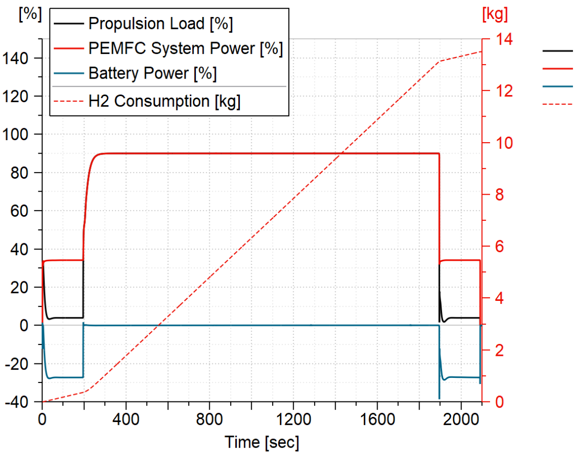

Figure 7. Power consumption of each power source and total hydrogen consumption during route B to C

The simulation of the demonstration ship model has verified that the PEMFC can fully meet the power requirements for a maximum speed of 12 knots. The daily hydrogen requirements can also be calculated the daily hydrogen requirements using Port B as a refueling station. With a 10% safety margin considered for two round trips on each route, a daily hydrogen requirement of 85.6 kg will be necessary. For two refuels per day, 42.8 kg of hydrogen storage capacity will be needed. The simulation enables the design of the required power capacity and hydrogen storage capacity based on the ship's operational profile. Furthermore, optimal fuel storage and configurations for PEMFC systems can be determined based on the PEMFC's operating window settings [11].

4 200KW PEMFC SYSTEM DEVELOPMENT

HD Hyundai Heavy Industries is developing a 200kW PEMFC system, utilizing considerations and demonstration ship development technologies outlined in Chapters 2 and 3.

4.1 Stack Reliability and Orientation

The system is based on Hyundai Motor Company's PEMFC stack, which has proven production reliability. Hyundai's PEMFC stacks are mass-produced in a factory with an annual capacity exceeding 50,000 units and are widely used in passenger cars, trucks, buses, and trams. As one of the most extensively used stacks globally, a consistent maintenance service can be expected. Once the reliability of the stack itself is ensured, stack orientation is considered. To facilitate smooth reactant and product flow, the effects of ship vibrations and tilting should be minimized using anti-vibration mounts and other measures like stack position in the vertical direction relative to the ground. Classification society rules and ISO standards are referenced to mitigate these effects. Studies indicate that high-amplitude oscillations in the vertical direction of the flow channels have the most significant impact on performance; however, the extent of this effect may vary depending on the cell structure and geometry, necessitating a case-specific analysis for each PEMFC stack. [12]

4.2 System Configuration and Safety Design

The conceptual design of a 200kW marine PEMFC system is shown in Figure 8. The system has a compact footprint relative to its power output, with dimensions of 1.9m height, 1.3m width, and 0.7m depth. It consists of a mechanical BOP, including the hydrogen, air, and cooling subsystems, and an electrical BOP, including power conversion and control units.

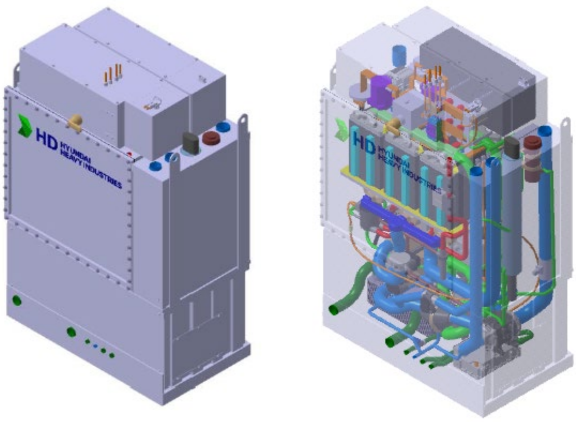

Figure 8. The conceptual design of a 200kW marine PEMFC system

For ship integration, the system is designed to only require media piping and electrical connections for operation. The locations of piping connections must be adaptable based on installation conditions for each SMV. Additionally, when multiple PEMFC systems are arranged in parallel, equipment placement must ensure adequate maintenance access. Additionally, general configuration of BOP components in PEMFC systems is already established at a high technological level. Therefore, BOP design focuses on the maturation of individual components and cost optimization.

Safety measures must be designed to prevent hazards and ensure detection and response in case of system failure. Critical system alarms, along with flammable gas detection sensors, transmit signals through hardwired connections. The hydrogen subsystem and fuel cell stack are enclosed in a dedicated compartment, isolated by partition walls. These partitions include ventilation to minimize the risk of internal fire or explosion. Fail-close fire dampers are installed at air inlets and exhausts. In conclusion, all safety measures are designed to fully comply with applicable standards and regulations.

4.3 Stable and Efficient Operation

The PEMFC stack consists of hundreds of cells, each with long and narrow flow channels that distribute reactants across a large planar surface.

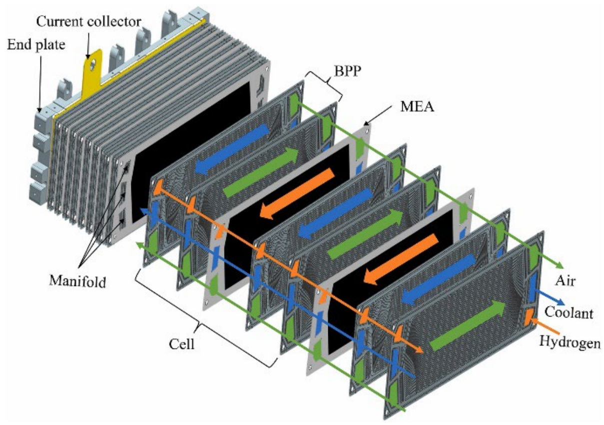

Figure 9. Typical configuration of a PEMFC stack [13]

Under frequent load fluctuations, localized reactant starvation may occur at the reaction site, negatively impacting the lifespan of the stack [11, 14]. However, the ability of PEMFCs to generate stable power output under rapid start-up and frequent load variations, as seen in land-based mobility applications, remains advantageous in maritime conditions. Compared to land-based mobility, ships experience lower load fluctuations, which can enhance stack performance and durability. To optimize this, a detailed load profile analysis is conducted for each ship. Parallel integration of systems, optimization of battery capacity, and required load peak shaving are effective strategies. These optimization approaches reduce hydrogen consumption, with related case studies reporting a 5.3% reduction [15].

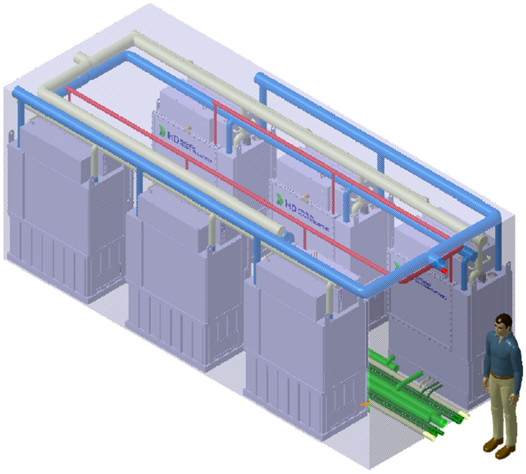

Figure 10. 1MW configuration based on 200kW marine PEMFC system

The net power output of the system reaches a maximum of 200kW, enabling flexible power generation strategies through parallel arrangement of multiple systems. To accommodate varying voltage levels across different vessels, the PEMFC system's voltage is adjusted and adjusted to match the grid voltage range. Over 1MW output is achievable with six systems configured within a 20ft ISO container, as illustrated in Figure **10**10. The integration of PEMFCs' high energy density with space-efficient design results in an estimated 2-3 times reduction in volume versus conventional engines for power outputs up to 10MW, at equivalent power levels. Additionally, there are requirements for integrating the PEMFC system to the ship. The system's vent line must be directly connected to the external atmosphere, necessitating additional equipment. Efficient integration of the system with the cooling configuration that varies depending on the ship is also required. If located near the engine, measures to address vibration and tilting are necessary. These considerations can be more effectively implemented on the ship when the PEMFC system is provided by the shipyard. The 200kW marine PEMFC system utilizing reliable stacks is scheduled for release after completing onshore and offshore demonstrations, prior to the establishment of hydrogen infrastructure.

5 CONCLUSION

PEMFC technology holds significant potential for achieving carbon neutrality in maritime applications. Its advantages, including high system efficiency, rapid load variation, and excellent spatial efficiency, make it suitable for main and auxiliary power sources in SMVs. However, practical application requires comprehensive assessment of GHG emission reduction, stack quality, system efficiency, spatial efficiency, and safety considerations.

Simulation results from a 350 kW demonstration ship model indicate that PEMFC systems can effectively operate under various conditions, including constant speed navigation and ESS charging. Additionally, based on the simulation results, the required hydrogen storage capacity and refueling frequency for ship operation scenarios were evaluated.

HD Hyundai Heavy Industries' 200 kW maritime PEMFC system is expected to play a crucial role in achieving carbon neutrality goals for the shipping industry, in conjunction with future hydrogen infrastructure. Through continuous technological development and demonstration, HD Hyundai Heavy Industries will deliver products with economic feasibility and maturity, substantially contributing to the carbon neutralization of maritime transport.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

ESS	Energy Storage System
GHG	Green House Gas
PEMFC	Proton Exchange Membrane Fuel Cell
SMV	Small and Medium-sized Vessel
TtW	Tank to Wake
BOP	Balance of Plant

7 ACKNOWLEDGMENTS

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8 REFERENCES AND BIBLIOGRAPHY

[1] Naef, Qasem. and Gubran, Abdulrahman. 2024. A Recent Comprehensive Review of Fuel Cells: History, Types, and Applications, *International Journal of Energy Research*, 2024: 36

[2] Rania, M. G. Tabbi, W. Hegazy, R. Samer, A. and Ali, A. 2023. Boosting Power Density of Proton Exchange Membrane Fuel Cell Using Artificial Intelligence and Optimization Algorithms, *Membranes*, 13(10): 817

[3] Changjong, K. Sanghoon, C. Sungmin, C, Youngseung, N. Sangwon, K. and Dongkyu, K. 2023. Review of hydrogen infrastructure: The

current status and roll-out strategy, *International Journal of Hydrogen Energy*, 48(5): 1701-1716

[4] Jun-Yup, Park. Jong-Yeon, Jung. and Yu-Taek, Seo. 2023. Investigation of Applying Technical Measures for Improving Energy Efficiency Design Index (EEDI) for KCS and KVLCC2, *Journal of Ocean Engineering and Technology*, 37(2): 58-67

[5] Riina, O. and Ulla, T. 2023. Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries, *Sustainability*, 15(23): 16170

[6] Jinghui, Z. Huijin, G. Yuchen, X. Shaobo, P. Weikang, L. Yanbo, Y. Zixi, W. and Tiancai, M. 2023. A review on the sealing structure and materials of fuel-cell stacks, *Clean Energy*, 7(1): 59-69

[7] Dharmjeet, M. Junru, W. Rajesh, K. Jorben, M. Frank, B. and Veerle, V. 2024. A Review of Proton Exchange Membrane Degradation Pathways, Mechanisms, and Mitigation Strategies in a Fuel Cell, *Energies*, 17(5): 998

[8] Gregory, K. William, G. and Julie, F. 2022. Heavy-Duty Fuel Cell System Cost, *DOE Hydrogen Program Record*, 23002

[9] Youngtak, C. Gyuyeong, H. Dela, Q. G. and Sungwon, H. 2022. Artificial neural network-based model predictive control for optimal operating conditions in proton exchange membrane fuel cells, *Journal of Cleaner Production*, 380: 135049

[10] Ahmed, G.E. Massimo, R. Eleonora, G. Loredana, M. and Aristide F.M. 2023. Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives, *Processes*, 11(1): 97

[11] Mathan, C. Karthikeyan, P. Karthik, B. and Oisik, D. 2022. A study of the influence of current ramp rate on the performance of polymer electrolyte membrane fuel cell, *Scientific Reports*, 12: 21888

[12] Wen, X. Qiu, Y. Zhan, Z. and Xiao, L. 2022. Investigation of Ship Vibration Effects on the Gas Distribution and Output Voltage of a Proton Exchange Membrane Fuel Cell, ACS Omega, 7: 24

[13] Diankai, Q. Linfa, P. Peiyun, Y. Werner, L. and Xinmin, L. 2021. Review on proton exchange membrane fuel cell stack assembly: Quality evaluation, assembly method, contact behavior and process design, *Renewable and Sustainable Energy Reviews*, 152: 111660

[14] Ming, C. Kai, W. Naiyuan, Y. and Tiancai, M. 2022. Study on the degradation of proton exchange membrane fuel cell under load cycling conditions, International Journal of Hydrogen Energy, 47(91): 38736-38746

[15] Wei, C. Pan, G. Xiaoyan, X. Yi, G. and Zhanxin, M. 2023. A power allocation strategy for fuel cell ship considering fuel cell performance difference, Scientific reports, 13: 9905