ISSN: 2710-0588

Green Shipping: Technological Innovations for Sustainable Development in the Global Maritime Industry

Qianyong Zhang[1,2], Shaojun Zhang[1,*], Chun Zhao[1], Zhirao Yin[1], Rui Sun[1], Xinle Wang[3]

[1] School of ShanDong, JiaoTong University, Weihai 264200, China

[2] Intemational Maritime Academy,Hainan Tropical Ocean University, Sanya, 572000, China

[3] BinZhou MSA, Binzhou, 256600, China

[*]Corresponding author

Abstract

The article aims to investigate the developmental trends of green shipping. In light of the escalating global awareness of environmental protection, green shipping has emerged as a pivotal orientation for the international maritime industry. This paper will delve into the international mandates for green shipping, the stipulations of international regulations, the concrete manifestations of green shipping on vessels, as well as the application of technologies such as wind-assisted propulsion, dual-fuel diesel engines, and hydrogen energy in the realm of environmental sustainability.

Keywords

Green Shipping; Environmental Protection; International Legislation; Dual-Fuel Diesel Engines; Hydrogen Fuel Cells.

1. Introduction

With the vigorous development of the global shipping industry, ship emissions have become a significant environmental issue worldwide. These emissions not only pollute the atmosphere, waters, and soil but also have a severe impact on the ecological environment. To protect the ecological environment, governments and international organizations have strengthened the regulation and management of ship emissions, introducing the concept of green shipping and requiring the shipping industry to minimize emissions as much as possible while ensuring vessel safety [1,2]. Consequently, green shipping has become an inevitable choice for the sustainable development of the global shipping industry and represents the future trend in the maritime domain.

Green shipping can be achieved through technological and management innovations. Technologically, the shipping industry has adopted various measures [3], such as the use of more efficient ship designs, the promotion of gas power generation and electric propulsion technologies, and the development of green fuels [4,5]. Managerially, governments and international organizations have strengthened the supervision and assessment of ships [6], encouraging the shipping industry to adopt sustainable development measures and promote the green transformation of the maritime sector. Despite some difficulties and challenges in practical application, green shipping has already become an inevitable trend in the development of the global shipping industry.

This article aims to systematically study the developmental trends and implementation measures of green shipping, analyze international requirements and regulations for green shipping, and summarize technological and management innovations in the shipping industry

ISSN: 2710-0588

to achieve green shipping. It is hoped that the research presented in this article will provide a reference for the shipping industry to achieve green transformation and promote the sustainable development of the global shipping industry.

2. International Provisions on the Development of Green Shipping in Regulatory Aspects

2.1. Environmental Protection Regulations of the International Maritime Organization (IMO)

The International Maritime Organization (IMO) is an international maritime organization under the United Nations, responsible for establishing international maritime regulations and standards. IMO's environmental protection regulations primarily include the International Convention for the Prevention of Pollution from Ships (MARPOL) and the Ship Energy Efficiency Management Plan (SEEMP) [7].

MARPOL Convention was adopted in 1973 and is one of the most important global environmental regulations, covering various aspects of ship pollution prevention. MARPOL Convention consists of six annexes, with the first annex outlining emission limits and control measures for ships, including sulfur oxides, nitrogen oxides, and volatile organic compounds; the second annex addressing oil pollution prevention measures, such as oil tank cleaning and washing water treatment; the third annex specifying the disposal of ship waste; the fourth annex covering the treatment of ship pollutants; the fifth annex concerning ship garbage control; and the sixth annex dealing with air pollution control, including emission controls for ship exhaust gases and black carbon emissions. Under MARPOL Chapter 6, ships are required to use low-sulfur fuel oil anywhere in the world to reduce the emissions of sulfur compounds and nitrogen oxides.

In addition to MARPOL Convention, international shipping organizations have also developed other relevant regulations and guidelines, such as energy efficiency design guidelines, energy efficiency management guidelines, energy efficiency technology guidelines, NOx technical guidelines, and exhaust gas treatment technical guidelines. These regulations and guidelines primarily cover requirements and recommendations for ship design, operation, maintenance, and emission control, aiming to improve ship energy efficiency and reduce emissions.

Furthermore, international shipping organizations have launched the Ship Energy Efficiency Management Plan (SEEMP) initiative, which mandates that compliant ships must have an effective Ship Energy Efficiency Management Plan (SEEMP).The plan requires energy efficiency management to be implemented in ship design, construction, operation, and maintenance, and through the implementation of energy-saving measures and the use of more environmentally friendly fuels, among other measures, to enhance ship energy efficiency and reduce emissions.

2.2. Environmental Protection Legislation of the European Union

The European Union has also established a series of environmental protection regulations to protect the marine environment and promote the development of green shipping. Among the most important are the EU Ship Waste Management Directive and the EU Emission Control Areas (ECAs) [8] and others.

The EU Ship Waste Management Directive mandates that ships must classify, store, and dispose of waste according to regulations, including solid waste, oil pollutants, washing water, and sewage generated by ships. The EU Emission Control Areas, on the other hand, designate specific regions where the emissions of harmful substances such as sulfur oxides and nitrogen oxides from ships must be controlled within certain limits.

ISSN: 2710-0588

In summary, these regulations and guidelines from international shipping organizations provide important legal and technical support for the environmental construction of ships, playing a positive role in promoting the development of green shipping.

3. The Application of Wind-Assisted Propulsion Technology in the Field of Eco-Friendly Vessels

Wind is a clean, renewable energy source that can effectively reduce carbon emissions and fuel consumption of vessels, thus garnering increasing attention and application in the field of green shipping. Sail-assisted propulsion refers to the installation of a certain number of sails on a vessel, which utilize wind power to provide a portion of the vessel's propulsion, thereby reducing fuel consumption and carbon emissions. Over the past few decades, sail-assisted propulsion has been considered a traditional and outdated technology, but now, with the continuous progress of technology and the rise of environmental awareness, it has reemerged as a popular technology in the field of green shipping.

One of the most common sail-assisted propulsion technologies is the combination of sails and main engines. This method allows a vessel to utilize both wind and fuel power sources during navigation, thereby reducing fuel consumption and carbon emissions. In this method, sails are mounted on the top of the hull, while the main engine provides additional power. During operation, the main engine adjusts its output power to match the current wind speed and the vessel's speed, maintaining smooth sailing. This method can significantly reduce fuel consumption and carbon emissions, while also enhancing the vessel's speed and stability [9]. The type of vessel will employ the DynaRig sail technology, which not only enables full automation but also features efficiency, safety, and environmental friendliness. It is renowned for being used in some of the world's most luxurious yachts, such as the "Maltese Falcon," and the largest sailing yacht, the "Black Pearl."

According to the U.S. maritime magazine "Maritime Executive" and the offshore-energy website, a sail-assisted hybrid container ship design developed by Veer Company has recently been granted Approval in Principle (AiP) by the American Bureau of Shipping (ABS), marking significant progress in the company's project to build the world's first 100% clean energy ocean-going container ship fleet. According to the plan, Veer Company will initially order two of these vessels, which are expected to be operational by the end of 2024. On September 24, 2022, the first dual-wing sail-assisted VLCC, "Xin Yidun," was successfully named and delivered by Dalian Shipbuilding Industry Group Co., Ltd. (DSIC), China Classification Society (CCS) certified. This vessel is the world's first dual-wing sail-assisted VLCC, equipped with two pairs of new-generation large rigid wing sails, with a height of nearly 40 meters and a total surface area of 1,200 square meters per wing. It meets international front-line requirements such as the Harmonized Common Structural Rules (HCSR), the latest NOx and SOx emission standards, EEDI and EEXI indicators, the EU's Hazardous Substances List in Shipbreaking Convention, and the latest oil company organization standards.

In addition to the method of combining the main engine and sails, there are other sail-assisted propulsion technologies that have also been widely applied in the field of green shipping. For instance, some new sail systems can be controlled by computers, adjusting the angle and position of the sails to keep the vessel at the optimal wind direction and speed. Furthermore, there are wind turbines specifically designed to harness the wind and rotate the turbine, thereby generating electricity to provide additional power to the vessel.

ISSN: 2710-0588

Fig. 1 Sailing-powered vessels (A) Berge Olympus will be equipped with four BAR Tech WindWings by Yara Marine Technologies (B) dual-wing sail-assisted VLCC, "NEW VITALITY" (C) Oceanbird Roll-Roll ship (D) The SkySails system used in Beluga Projects.

4. The Application of Dual-Fuel Diesel Engines in the Green Shipping Sector

The dual-fuel diesel engine is a type of engine that improves combustion efficiency and reduces emissions by simultaneously burning liquid and gaseous fuels. In the maritime sector, the application of dual-fuel diesel engines has also seen development [10].

4.1. The Working Principle of Dual-Fuel Diesel Engines

Dual-fuel diesel engines employ a gas injection system and a diesel injection system to supply fuel simultaneously. During normal operation, the diesel system provides a certain amount of fuel, while the gas system also supplies a corresponding amount. The fuels mix in the cylinder and are ignited to generate power. By adjusting the ratio of diesel to gas, the consumption and emissions of the fuel can be controlled .The conventional dual-fuel configuration as shown in Fig.2.

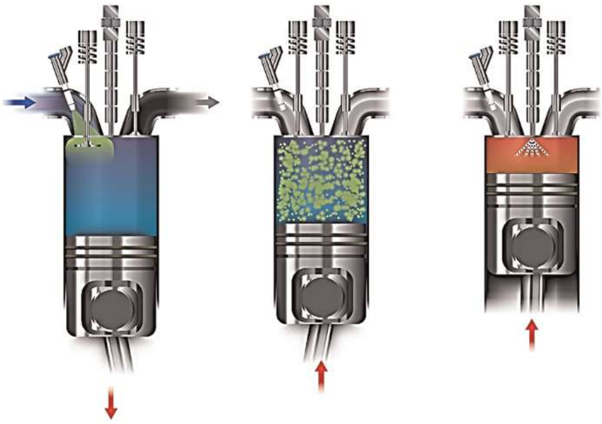

Fig. 2 Illustration of conventional dual-fuel configuration (green) LNG and (red) diesel in (blue) the air[11]

4.2. The Application of Dual-Fuel Diesel Engines in the Maritime Sector

The application of dual-fuel diesel engines in the maritime sector is primarily reflected in two aspects: emission reduction and efficiency improvement.

Firstly, dual-fuel diesel engines can reduce emissions from vessels. Compared to traditional diesel engines, dual-fuel diesel engines can decrease nitrogen oxide (NOx) and particulate matter (PM) emissions, thereby reducing environmental pollution. This is of significant

ISSN: 2710-0588

importance for the international shipping industry, which is increasingly focused on environmental protection.

Secondly, dual-fuel diesel engines can improve the fuel efficiency of vessels. The use of gas fuel can enhance combustion efficiency, leading to fuel cost savings compared to traditional diesel engines. For ship operators, this can reduce operating costs and improve economic efficiency.

4.3. The Development Prospects of Dual-Fuel Diesel Engines

With the continuous enhancement of environmental protection requirements in international shipping, the prospects for the application of dual-fuel diesel engines in the maritime sector are broad. Particularly in the construction of new vessels, dual-fuel diesel engines can serve as a green and environmentally friendly power option. Moreover, with the ongoing development and maturation of technology, the performance and efficiency of dual-fuel diesel engines will continue to improve.

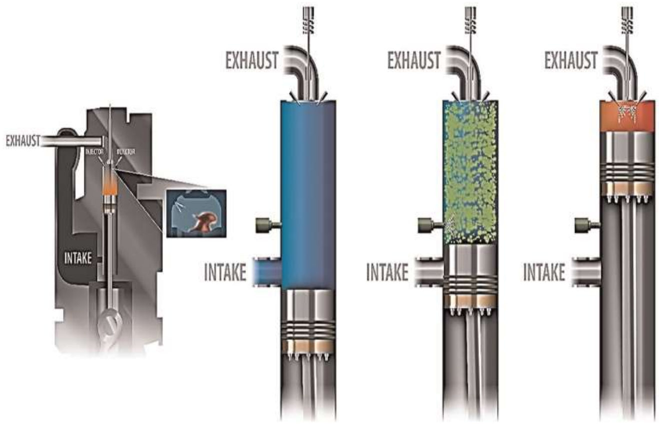

Fig. 3 Dual-fuel with two-stroke engines. (green) LNG and (red) diesel in (blue) the air[11]

5. The Application of Hydrogen Fuel in the Green Shipping Sector

Hydrogen energy, a green and efficient secondary energy source, is poised to play a pivotal role in energy transition due to its wide availability, high combustion heat value, and pollution-free nature. Hydrogen fuel cells, offering high efficiency and low noise, are emerging as a preferred power source for vessels, including ferries and cargo ships.The HyMethShip concept are shown in Fig.4.

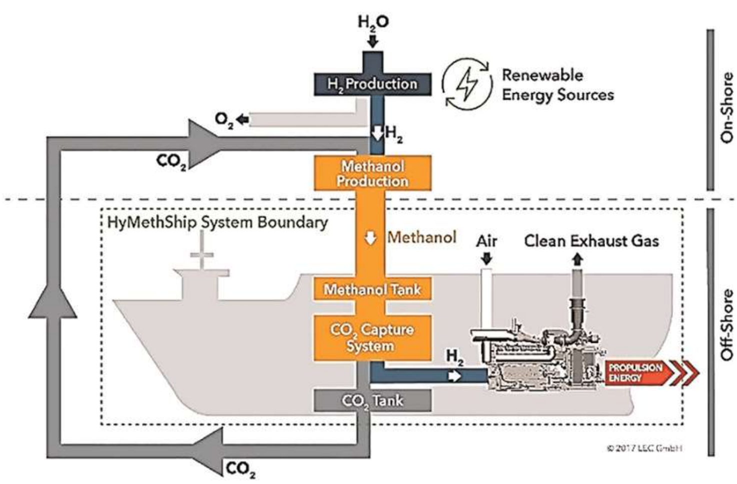

Fig.4 HyMethShip concept[12]

ISSN: 2710-0588

Since November 2022, there has been notable progress in hydrogen fuel cell vessel development. Fincantieri delivered the "Viking Neptune," the first ocean liner with hydrogen fuel cells, marking a step forward in commercialization.

The EU, Japan, and the US are advancing hydrogen and fuel cell technologies, with the EU's Hydrogen Strategy investing over 450 billion euros in a comprehensive hydrogen economy. These regions are leading the way in hydrogen-powered vessel manufacturing and commercialization.

Japan is focusing on large-scale hydrogen-powered vessels, with companies like Kawasaki Heavy Industries and Iwatani Materials driving research and development through initiatives like HYSTRA. The aim is to achieve a commercial hydrogen energy supply chain by 2030.

Hydrogen and hydrogen-based fuels are ideal for the shipping industry's decarbonization efforts. As technology improves, the use of hydrogen-powered vessels is expanding, with applications in lakes, rivers, and nearshore areas, and emerging trends in large vessels and submarines.

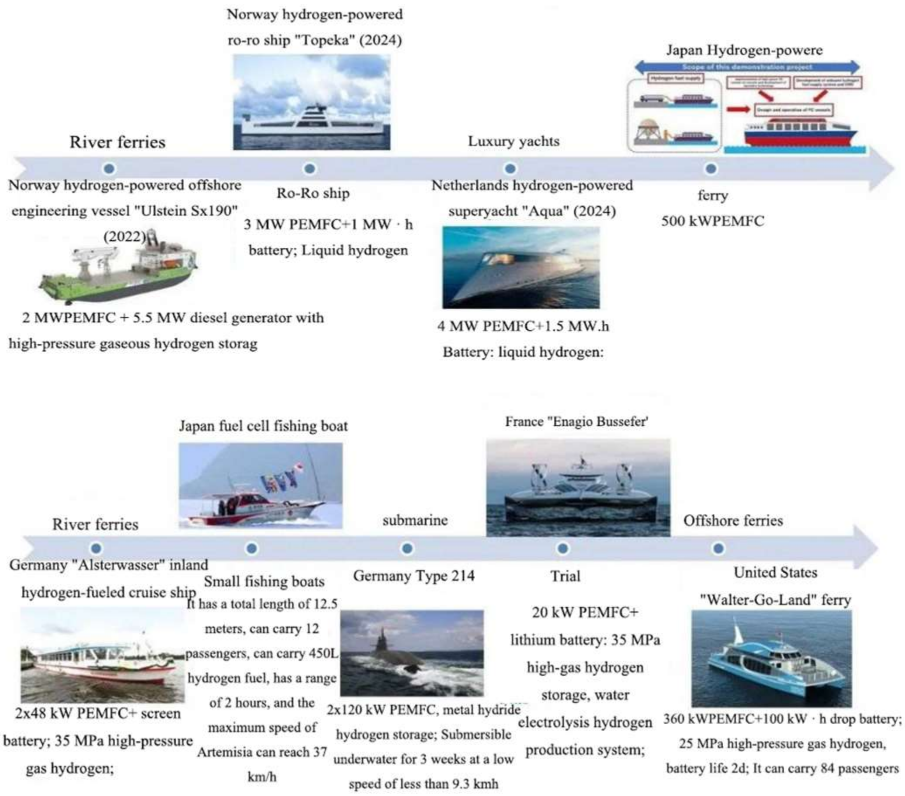

Fig. 5 Hydrogen-powered vessel under development

Hydrogen fuel cells are suitable for a variety of inland waterway vessels and can serve as the primary power for small vessels or as auxiliary power for large vessels at the current stage. The main type used is the proton exchange membrane fuel cell (PEMFC), which has a significant power gap compared to traditional diesel engines. Some developed countries have successfully developed and demonstrated various types of hydrogen-powered vessels, such as the German "Alsterwasser" pleasure boat, the Japanese fuel cell fishing boat, the French "Energy Observer" yacht, the American "Water-Go-Round" ferry, and the South Korean "Gold Green Hygen" hydrogen-powered tourist boat. Future research and application will be furthered, including

ISSN: 2710-0588

the Norwegian "Ulstein SX190" offshore engineering vessel, the "Topeka" roll-on/roll-off ship, and the Italian "ZEUS" test vessel.

Table 1. Hydrogen fuel cell vessels

Number	Vessel	Participating Institutions	Power Source	Construction Date	The vessel information
1	Enetgy Oboerver	Corvus Energy	solar photovoltaics, wind energy, and fuel cells, with a 126KW fuel cell on board. The ship is equipped with 168 square meters of solar panels.	2020	Length:30.5m Width:20.8m Tonnage:28t Max speed:11kn
2	Hydroville	Compagnie Maritime	two 441W diesel/hydrogen dual-fuel internal combustion engines. On board, there are 12 hydrogen storage tanks with a capacity of 205L each (20MPa) and two 265L fuel tanks.	2017	Length:140m Width:2m Tonnage:141t Max speed:27kn
3	Neso H2	Rederi Lovers	Two sets of 30KW PEMPC and one set of batteries. Output power is 70kW. The high-pressure hydrogen storage method is 35MPa - hydrogen storage capacity is 24kg.	2012	Length:21.9m Width:4.2m
4	MS Forester	Thyssen Krupp Marine Systems.DNV	A 100kW SOFC supercapacitor system is installed as auxiliary power. The SOFC fuel cell can utilize hydrogen, methanol, and other fuels as fuel.	Stage I:2009~2017 StageII :2017~2022	Length:92.5m Width:17m

Currently, the power output of marine hydrogen fuel cells is not high. For ten-thousand-ton vessels, the power demand is in the megawatt level, much higher than the kilowatt-level demand for automotive systems. Given the limited power of individual cells, a large number of cell units are required. Considering the limited space on board, the integration technology for high-density, large-power marine hydrogen fuel cell systems still needs breakthroughs. Countries are vigorously developing hydrogen energy fuel cells. Major hydrogen fuel cell companies in the world, as shown in Table 2.

The effective thermal efficiency of existing hydrogen internal combustion engines ranges from 35% to 45%, while the efficiency of PEMFC systems is between 50% and 60%. Although the efficiency of hydrogen internal combustion engines is relatively low, their power output can reach high values (currently up to the megawatt level) and has been used in tugboats and ferries. In terms of cost, hydrogen internal combustion engines are significantly less expensive than PEMFC systems; for instance, the cost of a 100 kW power generation unit based on current hydrogen internal combustion engine technology is only 50% that of a PEMFC system. It is predictable that with the development of vessel hydrogen storage technology and the improvement of hydrogen energy infrastructure, hydrogen internal combustion engines will

ISSN: 2710-0588

find widespread application in vessels. For example, the hydrogen internal combustion engine-powered tugboat "Hydrotug" and the ferry "Hydro Bingo" developed by Belgium and Japan. Japanese companies (such as Kawasaki Heavy Industries, Ltd. and Yanmar Co., Ltd.) are actively developing hydrogen internal combustion engines, including medium-speed four-stroke engines, medium-high speed four-stroke engines, and low-speed two-stroke engines [13].

Table 2. The world's major hydrogen fuel cell companies and their development status.

Company	Development Process
Ballard(Canada)	The world's largest proton exchange membrane fuel cell company, with over 400 megawatts of proton exchange membrane fuel cell products.
Hydrogenics(Canada)	With over 60 years of experience in the design, manufacturing, and installation of commercial hydrogen systems, fuel cells, and megawatt-scale energy storage solutions.
BloomEnergy(USA)	The largest startup company in the field of solid oxide fuel cells.
UTCPower(USA)	With 50 years of innovation experience, it is the world's leading fuel cell manufacturer, having designed, manufactured, and installed over 300 stationary fuel cells in 19 countries across six continents.
AtrexEnergy(USA)	Since 2000, more than $100 million has been invested in the research and development of remote generators using solid oxide fuel cells.
ArcolaEnergy(British)	Leading in the development and deployment of fuel cell electric vehicles in the UK and other regions.
AFCEnergy(British)	With ten years of R&D experience, it has developed the most efficient alkaline fuel cell in history.
SFC Energy(Germany)	A leader in the field of hybrid solutions for stationary and portable power generation, with a total of over 40,000 fuel cell units sold to date.

In summary, hydrogen fuel cell technology is a zero-emission, high-efficiency energy source with broad application prospects. In the maritime field, hydrogen fuel cell technology can effectively address vessel emissions, achieving green and sustainable development. Although there are some challenges in terms of technology, cost, and safety, with the continuous advancement of technology and policy support, it is believed that the demonstration application and commercial promotion of hydrogen-powered vessels will become increasingly widespread. As a major shipbuilding and shipping nation, China should actively seize the opportunity of hydrogen-powered vessel development, accelerate the research and development of hydrogen-powered vessel technology and demonstration applications, and promote the rapid development of hydrogen-powered vessels, contributing to the construction of a green and low-carbon shipping system.

6. Conclusion

With the increasing awareness of environmental protection, green shipping has become a focal point of international attention. The international community has put forward a series of requirements for the control of ship pollution emissions, as well as for ship design and construction. The implementation of green shipping on vessels has become an inevitable trend in the shipping industry.

The application of technologies such as wind-assisted propulsion, hydrogen energy, and dual-fuel diesel engines can effectively reduce energy consumption and emissions from vessels, thereby diminishing environmental pollution. These technologies will be more widely adopted in the future and will also drive the development of green shipping.

ISSN: 2710-0588

To achieve the goals of green shipping, the collective effort of the global shipping industry is required. Governments, shipowners, classification societies, shipbuilders, shipping companies, and other relevant parties need to strengthen cooperation and jointly promote the development of green shipping, contributing to global environmental protection and sustainable development.

References

[1] Sunwoo Kim, Joungho Park, SungKu Heo, et al. Green hydrogen vs green ammonia: A hierarchical optimization-based integrated temporal approach for comparative techno-economic analysis of international supply chains, Journal of Cleaner Production, Volume 465, 2024, 142750.

[2] TSVETKOVA A, HELLSTRÖM M, SCHWARTZ H, et al. A transition towards clean propulsion in shipping: The role of PESTLE drivers and implications for policy, Marine Policy, 2024, 161: 106002.

[3] YUAN J, GU H, NIAN V, et al . Influence of system boundary conditions on the life cycle cost and carbon emissions of CO2 transport. International Journal of Greenhouse Gas Control, 2023, 124: 103847.

[4] CORRUBLE P, TLICHE Y, RADHOUI H. Financing decarbonization through wind-powered vessels. Marine Policy, 2024, 165: 106163.

[5] WU M, LI K X, XIAO Y, et al. Carbon Emission Trading Scheme in the shipping sector: Drivers, challenges, and impacts. Marine Policy, 2022, 138: 104989.

[6] ZHOU Y, LI X, YUEN K F. Sustainable shipping: A critical review for a unified framework and future research agenda. Marine Policy, 2023, 148: 105478.

[7] TADROS M, VENTURA M, GUEDES SOARES C. Review of the IMO Initiatives for Ship Energy Efficiency and Their Implications. Journal of Marine Science and Application, 2023, 22(4): 662-680.

[8] Zhang, Shuanghong et al. "Challenges and countermeasures for international ship waste management: IMO, China, United States, and EU." Ocean & Coastal Management ,2021, 213: 105836.

[9] NYANYA M N, VU H B, SCHÖNBORN A,. Wind and solar assisted ship propulsion optimisation and its application to a bulk carrier. Sustainable Energy Technologies and Assessments, 2021, 47: 101397.

[10] YUKSEL O. A comprehensive feasibility analysis of dual-fuel engines and solid oxide fuel cells on a tanker ship considering environmental, economic, and regulation aspects. Sustainable Production and Consumption, 2023, 42: 106-124.

[11] Curran S, Onorati A, Payri R, et al. The future of ship engines: Renewable fuels and enabling technologies for decarbonization. International Journal of Engine Research. 2024;25(1):85-110.

[12] Zelenka J, Wermuth N, Lackner M, et al. The HyMethShip project: innovative emission free propulsion for ships. In: 29th CIMAC world congress on internal combustion engines, 2019.

[13] KIM S, PARK J, HEO S, et al. Green hydrogen vs green ammonia: A hierarchical optimization-based integrated temporal approach for comparative techno-economic analysis of international supply chains. Journal of Cleaner Production, 2024, 465: 142750.