Innovative Technologies for the Maritime Industry: Hydrogen Fuel as a Promising Direction

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1 Introduction

Shipping is one of the largest sources of global greenhouse gas emissions, accounting for approximately 2.9% of total emissions. The International Maritime Organization (IMO) has set ambitious targets to reduce these emissions, including a goal of reducing greenhouse gas emissions from shipping by at least 50% by 2050. Maritime transportation accounts for about 11% of global fuel consumption, or about 10 million barrels per day. It is important to note that in the current situation of competition between alternative fuels, ships largely set the trend in favor of one or another type of fuel. Significant volumes of fuel consumption by maritime transport justify the mass production of refined products, the construction of fuel bases and infrastructure in general, setting the course for a certain type of fuel and relying on it in other market segments. For example, after the ban on the use of marine fuel oil in 2024, only diesel fuel will remain. This provides an opportunity for the maritime transport industry to reconsider its position in the short term before this date and take steps that are more active to adapt to the new standards, including in the context of considering alternative options.

Hydrogen is one of the alternative fuels being explored for use in shipping. As a fuel, hydrogen has a number of advantages over traditional fossil fuels such as diesel and fuel oil. One of the main advantages is that burning hydrogen produces only water as a by-product, making it a clean, emission-free fuel. However, the use of hydrogen as a fuel in shipping is fraught with challenges. One of the biggest challenges is the storage and transportation of hydrogen, which needs to be compressed or liquefied

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for storage on board. This requires specialized equipment and infrastructure, which are currently limited. Another challenge is the cost of hydrogen production, which is still relatively high compared to traditional fuels. However, as hydrogen production and storage technology improves and demand for clean energy grows, the cost of hydrogen is expected to decline.

Thus, the competitiveness of alternative marine fuels in the new regulatory framework is investigated in [1]. The marine fuels of the future and how alternative fuels affect the optimal economic speed of large container ships are studied in [2]. Research paper [3] proposes an assessment of life-cycle greenhouse gas emissions when using alternative marine fuels using the example of an oil tanker (VLCC). The article [4] explains the reasons for the unilateral abolition of indirect subsidies for marine fuels. Achievements in the field of alternative marine fuel research and future trends and application of alternative marine electricity (AME) in cruise ports are proposed in [5, 6]. The gaps in knowledge about marine hybrid fuel cell power plants and alternative fuels and the role of cold ironing in maritime transport emissions are presented in [7, 8]. The use of alternative fuels for maritime decarbonization, taking into account the specifics of maritime environmental risks and solutions from the point of view of international law, is discussed in [9]. Ensuring the safety of navigation in terms of reducing environmental impact, technical and operational measures to reduce greenhouse gas emissions and increase the environmental and energy efficiency of ships [10, 11]. The principles of using hydrogen-powered engines on mixed navigation vessels and other problems of port infrastructure and navigation safety are considered in [12, 13]. In [14, 15], the use of hydrogen-powered engines on mixed navigation vessels is analyzed. Different issues concerning the safety of ship operations and safety of marine environment considered in [14, 16–18]. Review of ship information security risks and safety of maritime transportation issues in [19]. Efficiency of port operations and stability indicators examined in [20, 21]. Marine diesel engines operation performance research presented in [22, 23]. Alternative fuel and technologies and updates on potential of biofuels in shipping [24, 25].

In [26] authors investigated the effectiveness of using hydrogen fuel as an alternative to oil and gas fuels and concluded that the use of hydrogen fuel would reduce the environmental impact and improve energy efficiency. In [27] considered the advantages and disadvantages of fuel cells in comparison with traditional energy sources on ships and conclude that fuel cells are a promising option for ship transport. Paper [28] considers issues of improving the energy efficiency of container ships using hydrogen fuel. In sources [29, 30] devoted to the technical and economic analysis of the possibility of using hydrogen fuel on ferries in Indonesia and proposed review of research on hydrogen energy storage technology. Review of hydrogen fuel technology on ships and description of fuel cell systems developed for marine applications in [30]. This review [31] of articles and research examines the prospects for using hydrogen fuel cells on ships and analyzes the possibilities of introducing this technology into marine transportation. The paper [32] analyzes the possibility of using hydrogen energy in the marine industry and discusses the technological, economic, and environmental aspects of hydrogen use on ships. The prospects of using hydrogen as a fuel for ship traffic and discuss technological and economic aspects of introducing this technology into maritime transport proposed in [33–35].

Thus, despite all these challenges, there are already examples of ships using hydrogen as fuel. In general, although hydrogen is a promising alternative fuel for shipping, there are still a number of technological, logistical and economic challenges that need to be addressed before it can be widely implemented as a mainstream fuel. Therefore, the purpose of the article is to explore the potential of using hydrogen fuel as an alternative to traditional fossil fuels in the maritime industry. The article discusses the current state of the industry, challenges and opportunities associated with the use of hydrogen fuel, as well as potential benefits from the introduction of this alternative energy source.

2 Materials and Methods of the Study

Undoubtedly, more accurate and thorough research is needed to assess the environmental footprint of alternative fuels, from raw material extraction to environmental emissions, in order to make a decision on the choice of the preferred fuel for international shipping. A separate issue is the assessment of the consequences of alternative fuels spills, which requires laboratory and experimental studies of spills, especially at low temperatures, high wind speeds, etc. Of additional interest is the degree of long-term impact of alternative fuel blends on the aquatic environment. Environmental problems and rising fuel prices are leading to the need to find new solutions for shipping. There are not many alternatives. At the same time, the legislation has already determined the conditions for the use of LNG (liquefied natural gas), followed by methanol and biofuels.

According to experts, it will not take long to develop the IGF Code for LNG and hydrogen. In order to meet the requirements by 2050, it will be necessary not only to switch the fleet to another, environmentally friendly fuel, but also to develop new technologies to reduce greenhouse gas emissions from ships. Hydrogen fuel has also become a potential solution to achieve these goals, but its implementation is not without challenges. The full cycle of renewable hydrogen production is shown in Fig. 1.

One of the main advantages of hydrogen fuel is its zero emissions profile. When hydrogen is burned, the only byproduct is water vapor, making it a clean and renewable energy source. In addition, hydrogen fuel has a high energy density, which means it can provide more energy per unit weight than traditional fossil fuels. This could lead to smaller and more efficient marine engine systems. H_2 is more than just another interesting alternative marine fuel option that is being actively considered for use on ships. Hydrogen is either liquefied (a cryogenic liquid with a temperature of −240 °C) and placed in compression tanks or stored as a chemical compound. Today, H_2 is produced from natural gas and electrolysis. The latter can be carried out at solar and wind power plants simultaneously with electricity generation. Produced from renewable energy sources, hydrogen becomes one of the cleanest fuels, with

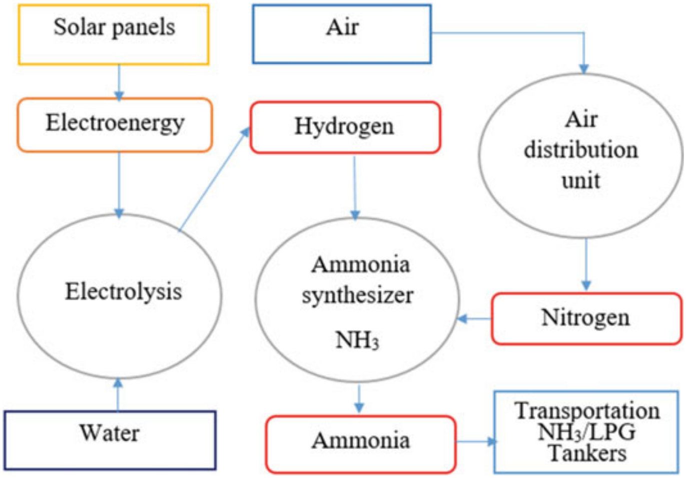


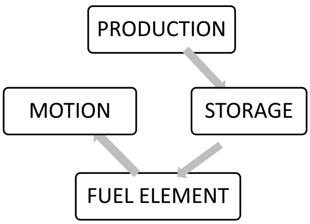
Fig. 1 Production cycle of renewable hydrogen

zero greenhouse gas emissions. The most efficient energy generator for hydrogen is fuel cells. Both hydrogen and fuel cell production is well developed, but they still remain uncompetitive in terms of price compared to conventional marine engines.

There are several ongoing projects and initiatives exploring the use of hydrogen fuel on ships. In 2020, the world's first hydrogen fuel cell vessel was launched in France, and several other countries, including Japan, Norway, and South Korea, are already investing heavily in hydrogen fuel technology for shipping. However, the widespread adoption of hydrogen fuel on ships is still in its early stages and requires further technological progress and infrastructure development.

Potentially, hydrogen can be used on a large scale as a fuel for ships. It is argued that a significant reduction in the cost of producing zero-carbon hydrogen is expected in the next 10–15 years due to the development of the global hydrogen economy. However, the direct use of hydrogen on large-tonnage vessels–in internal combustion engines or in fuel cells in combination with electric motors–poses problems due to its low volume density. For a long voyage, hydrogen storage would require too much physical volume. The use of hydrogen fuel on ships can be achieved through the following cycle consisting of production, storage, fuel cells, and actual movement (Fig. 2).

Fig. 2 Hydrogen utilization cycle on ships



Hydrogen can be produced by various methods other than electrolysis through steam reforming of natural gas or biomass gasification. The hydrogen is stored on board the ship in high-pressure tanks, cryogenic tanks or in the form of metal hydrides. The stored hydrogen is fed into a fuel cell, which converts the chemical energy of hydrogen into electrical energy through an electrochemical process. The electrical energy generated by the fuel cell is used to power the ship's electric motor, which essentially propels the ship forward. The hydrogen storage system is carried out in high-pressure cylinders (a 40-foot container with 25 MPa cylinders holds 794 kg of hydrogen, a 40-foot container with 50 MPa cylinders holds 1050 kg of hydrogen). In liquefied form at a temperature of −252 °C, a 40-foot container holds about 2.478 kg of hydrogen using LOHC (Liquid Organic Hydrogen Carrier), which are organic compounds that can absorb and release hydrogen as a result of chemical reactions. 1 m^3 of LOHC can produce 57 kg of hydrogen. A 40-foot container can hold about 3.200 kg of hydrogen, and given the need to store the "discharged" liquid, about 1.600 kg of hydrogen.

The formula for optimizing a marine engine using hydrogen will depend on various factors, such as the type and size of the vessel, the specific design of the hydrogen engine, operating conditions, and performance goals. However, a general formula that can be used as a starting point is:

$$P = (r\, Q_B) / \gamma \tag{1}$$

where P–the mass flow rate of hydrogen, the amount of hydrogen fuel consumed by the engine per unit of time (kg/s); r–higher heating value of hydrogen or the amount of thermal energy released during the complete combustion of one unit of hydrogen (MJ/kg); Q_B–engine efficiency, percentage of fuel energy converted by the engine into useful work; γ–specific gravity of hydrogen, i.e. the density of hydrogen gas relative to air.

One of the most important factors in optimizing the operation of a vessel using hydrogen as fuel is to maximize the efficiency of the main engine. This can be achieved by various methods, including optimizing the fuel injection system, adjusting the ignition timing, and modifying the combustion chamber design. An example is the formula for optimizing the performance of a hydrogen-fueled ship's engine:

$$\eta = [(P_{in} - P_{out})/P_{in}] \times Q_{in}/H_{H2}, \tag{2}$$

where η–engine efficiency, P_{in}–power consumption (kW), P_{out}–power output (kW), Q_{in}–hydrogen fuel consumption (in kg/h), H_{H2}–heating value of hydrogen (MJ/kg).

The given formula takes into account the power input and output of the engine, as well as the consumption of hydrogen fuel and the heat of combustion of hydrogen. The difference between the power input and output is divided by the power consumption to determine the engine efficiency. The hydrogen fuel consumption is multiplied by the heating value of hydrogen to determine the energy consumed by the engine.

Additional factors such as air-to-fuel ratio, compression ratio, and exhaust gas recirculation rate can be taken into account to further optimize engine performance. By carefully adjusting these factors, you can achieve the maximum possible efficiency from the engine and minimize fuel consumption, emissions, and other environmental impacts. Using the formula presented here, the output power of a hydrogen engine can be calculated, which can then be used to optimize the design and operation of the marine engine and the ship as a whole. Other factors such as propeller type and size, hull design, and operating conditions must also be considered to achieve the best performance and efficiency.

The formula for optimizing a marine engine for hydrogen fuel may include the following elements:

1. Calculation of engine efficiency that can be estimated using the engine's coefficient of performance (thermal efficiency), which determines the ratio of energy released during engine operation to energy input. Engine efficiency:

$$\eta = \dot{W} / \dot{Q}_u \times 100\% \tag{3}$$

where: $\dot{W}$–useful power output by the engine; $\dot{Q}_u$–heat input to the engine.

2. Selecting the optimal way to store hydrogen in various forms, such as liquid hydrogen, compressed hydrogen, or hydrogen absorbed on nanoparticles. The model can take into account the cost and energy efficiency of each storage method to select the best option. Mass energy density can be found as:

$$H_2 = \dot{W} / m, \tag{4}$$

where m–mass of hydrogen stored in a certain form.

3. Consideration of technical constraints. Hydrogen engines may require special technical requirements, such as a special fuel supply and storage system, as well as additional cooling systems. The model can take into account the costs of these additional systems and calculate their impact on engine efficiency. In order to take into account technical limitations: Engine power = (displacement x number of cylinders x number of revolutions per minute x mechanical efficiency factor) / (4 × stage):

$$P = (V_b \times n_c \times N_{max} \times \eta_m) / (4 \times \kappa), \tag{5}$$

where V_b–engine capacity; n_c–number of cylinders; N_{max}–maximum engine speed; η_m–mechanical efficiency; κ–compression ratio.

4. Determining the environmental impact: The model can calculate the emissions of pollutants during the combustion of hydrogen and take into account the environmental impact of the engine:

$$E = \left(V_f \times \left(CO_f / C_x\right) \times M_\times\right) / \left(V_e \times \rho_f\right), \tag{6}$$

where V_f–volume of fuel burned per cycle; CO–the amount of carbon monoxide emitted during fuel combustion; C_x–carbon content in the fuel; M_x–carbon molar mass; V_e–volume of pollutant emissions; ρ_f–fuel density.

5. Cost calculation: the model can take into account the cost of developing and producing the engine, the cost of purchasing and storing hydrogen, and the cost of maintaining and repairing the engine:

$$C = (C_r + C_m) / N, \quad (7)$$

where C_r–cost of research and development; C_m–production costs; N–number of engines manufactured. The cost of hydrogen:

$$C_{H_2} = {}^{C_f}\!/_{H_{LHV}}, \quad (8)$$

where C_f–cost of fuel; H_{LHV}–lower heating value of hydrogen.

Again, this algorithm is only a general example and may vary significantly depending on the specific engine model and its parameters, as well as operating conditions. In order to calculate most accurately the optimal parameters of an engine for hydrogen fuel, it is necessary to conduct a detailed analysis of technical and economic parameters, as well as take into account factors that affect the efficiency of the engine, such as pressure, temperature, rotational speed, and others. Therefore, specialized personnel using appropriate software and equipment should carry out the calculation of the optimal parameters. Considering these elements can help develop an optimal formula for optimizing a marine engine for hydrogen fuel.

Hydrogen is the most environmentally friendly fuel produced from renewable energy. Liquid hydrogen may be used in the future, but it has a rather low volumetric energy density, which leads to the need for large storage facilities.

The Tier III standard refers to the limitation of nitrogen oxides (NO_x) emissions for ships running on LNG or hydrogen in order to reduce the environmental impact of shipping. For internal combustion engines with the Otto cycle running on LNG or hydrogen, NO_x emission limits are set at 3.4 g/kWh. In order to achieve the Tier III standard for internal combustion engines with an Otto cycle running on LNG or hydrogen, it is necessary to use various technologies to reduce NOx emissions, such as the use of a catalytic converter, exhaust gas recirculation systems, high-temperature combustion systems, etc.

Therefore, in order to achieve the Tier III standard for Otto-cycle internal combustion engines running on LNG or hydrogen, many different NO_x reduction technologies must be used to make these engines less harmful to the environment. In terms of nitrogen emissions, Otto-cycle internal combustion engines fired with LNG or hydrogen do not require exhaust gas after treatment equipment to meet the Tier III standard. In most cases, dual-fuel engines operating on a diesel cycle are not suitable for meeting the standard. Analytical data on the level of nitrogen emissions when using different types of fuel is presented in Fig. 3.

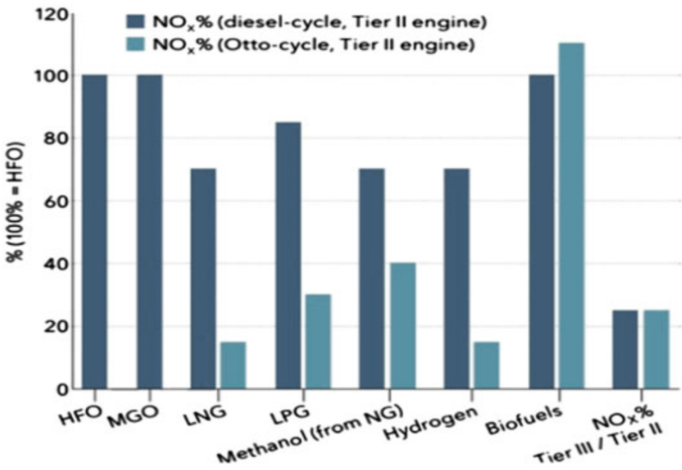


Fig. 3 Nitrogen emissions from different fuels (*Source*: *DNV GL*)

In fact, the cost of introducing alternative fuels on ships is not the main criterion for choosing a particular technology; it is the cost of fuel that determines this choice. It depends on several factors that are sometimes difficult to predict. According to sources, the lowest price is observed for HFO (marine fuel oil), and only LNG can compete with it. The price for methanol produced from natural gas is higher than for LNG. Biofuels are produced from biomass and are traditionally more expensive than Brent crude oil. These fuels are likely to compete with MGO (diesel fuel) in the future.

As for hydrogen, it is not considered here because it is much more expensive than other fuels. It is absolutely not competitive in the market in terms of price, so it will only have a chance to become widespread if there are significant subsidies or high taxes on conventional fuels.

Undoubtedly, the use of alternative fuels will help shipowners ensure the sustainability of transportation operations in the long term in terms of air pollution. The consequences of spills of new types of fuels, in particular low-sulfur oil, are not well understood, but the effects of marine pollution from spills are a key factor in climate conditions. The use of distillate fuels will lead to an immediate increase in operating costs, and the installation of a scrubber may be a bad investment if a ban on the use of residual fuels is introduced, and the investment in equipment will not pay off in time. Shipowners face even greater risks when building new vessels, which require high capital investments. Oil and oil products have no competitors on the global market in terms of their properties, but regular information about oil reserves being depleted and growing demands stimulate attempts to find a replacement for oil as a fuel and raw material.

Despite the advantages of hydrogen fuel, there are also a number of challenges that need to be addressed for its implementation on ships. One of the main challenges is the high cost of hydrogen production and storage. Although technological advances are reducing costs, it is still more expensive than traditional fossil fuels. In addition, hydrogen is flammable and requires special handling and safety measures, making it a potential safety hazard on board ships. However, hydrogen diesel engines can be developed on the basis of standard medium-speed marine diesel engines or can be modernized to run on hydrogen, so based on such data, it can be noted that the use of hydrogen as a fuel on ships is not a remote prospect from a technical point of view, but a fully realized action.

Based on the study of the use of hydrogen fuel for marine engines, the following conclusions can be drawn:

– Hydrogen fuel is one of the most promising alternative sources of energy for ship traffic, as it allows significantly reducing emissions of harmful substances and reducing dependence on petroleum products.
– Development of a mathematical model to optimize the ship engine for hydrogen fuel can help improve engine efficiency, reduce fuel costs and improve the overall environmental friendliness of marine transport.
– The introduction of hydrogen fuel in marine transport has become possible due to the development of technologies for its production and storage, as well as the creation of the appropriate infrastructure for fueling and transportation.

The prospects for further development and use of hydrogen fuel in maritime transport are very encouraging. The need to reduce emissions of harmful substances and the dependence on petroleum products is growing every year and hydrogen fuel is one of the key elements in solving these problems. In addition, modern technologies for the production and storage of hydrogen fuel continue to improve, which could lead to lower costs and greater competitiveness compared to conventional fuels.

3 Conclusions

Hydrogen fuels have the potential to play a significant role in reducing greenhouse gas emissions from shipping, but their implementation is not without its challenges. Although the technology is still in its early stages of development, ongoing initiatives and projects are paving the way for a cleaner and more sustainable future for shipping. With continued research and development, hydrogen fuel could become a major solution for reducing emissions and mitigating climate change in the shipping industry. The use of hydrogen as a fuel in ships has the potential to reduce greenhouse gas emissions and improve air quality, making it an attractive option for the shipping industry. However, there are still challenges that need to be overcome, including the cost of production and storage, as well as limited infrastructure for hydrogen bunkering of ships. Several sources [36–39] include a study on optimizing port equipment structure, an online discussion about future ship fuels, a summary on alternative fuels and technologies by DNV GL, and an update on biofuels potential in shipping from EMSA. The article discusses the environmental benefits of using hydrogen fuel, including the potential for significant reductions in greenhouse gas emissions and improved air quality. It also explores the technical challenges associated with the use of hydrogen fuel, such as the need for storage and distribution infrastructure, as well as the potential costs and economic impacts of switching to this alternative energy source.

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