



Liquefied natural gas as a strategic vector for ship energy modernisation

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Abstract. The relevance of the study is conditioned by the need to reduce emissions of harmful substances in navigation, compliance with international environmental standards, and the search for cost-effective solutions for fuel supply to the fleet. The purpose of the study was to analyse the technological, environmental, and economic aspects of the use of liquefied natural gas (LNG) in the marine energy sector to assess its efficiency and implementation prospects. As a result of the study, it was found that the use of LNG in marine energy is an effective solution for reducing environmental impacts and meeting international environmental standards. LNG can significantly reduce emissions of carbon dioxide (CO₂), nitrogen oxides (NO_x) and sulphur oxides (SO_x), which makes it a competitive fuel for vessels operating in emission control zones. Technologically, LNG provides high energy efficiency, in particular, through the use of dual-fuel engines, which allow optimising fuel costs and reducing the negative impact on the environment. Modern marine power plants equipped with cryogenic gas storage and supply systems confirm the effectiveness of LNG in ensuring stable operation of vessels. Economic studies have shown that while the transition to LNG requires significant initial investment in ship refurbishment and infrastructure, in the long run, it can reduce operating costs and the cost of environmental measures, such as installations to reduce sulphur emissions. The practical significance of the study lies in the fact that it contributes to the development of theoretical and practical foundations for the use of LNG as an environmentally friendly and cost-effective fuel in the marine energy sector, which can be used to improve existing technologies and regulations in the field of navigation

Keywords: environmental standards; dual fuel engines; cryogenic systems; operating costs; emission control zones

Introduction

In modern shipping, there is a growing need to adapt to stringent environmental requirements, which are becoming increasingly stringent at the global level. The introduction of environmentally friendly technologies in the marine energy sector is one of the key components for ensuring the sustainable development of maritime transport. Liquefied natural gas (LNG) acts as a promising fuel that can significantly reduce the negative impact of marine engines on the environment, responding to the challenges of reducing carbon

dioxide (CO₂), nitrogen oxides (NO_x) and sulphur (SO_x) emissions. The use of LNG as fuel not only helps to achieve these goals, but also opens up new opportunities for energy efficiency of marine power plants.

LNG is increasingly considered as a promising fuel for navigation, but its use is accompanied by a number of environmental and technical problems that require additional investigation. The study by J. Deng *et al.* (2021) showed that the benefits of using LNG included reduced sulphur emissions, which was an important

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aspect for navigation in emission control zones. LNG has significantly reduced the negative impact on the environment compared to conventional fuels. S. Yao *et al.* (2023) emphasised that the use of LNG provided a reduction in CO₂ emissions, which significantly improved the environmental performance of marine engines. This made LNG a cost-effective choice for carriers looking to reduce their environmental footprint.

A. Elkafas *et al.* (2021) noted that marine engines powered by LNG showed increased energy efficiency, which allowed them to reduce fuel costs. According to their research, this made LNG a competitive option for shipping. Y. Shih *et al.* (2023) noted that the use of combined dual-fuel engines helped to optimise the energy costs of ships, ensuring a reduction in operating costs. This was an important aspect for carriers seeking to reduce overall operating costs. L. Palestini & F. Sassu (2021) argued that cryogenic LNG storage and delivery systems were a prerequisite for ensuring safe and stable operation of vessels. They helped to effectively manage fuel storage and minimise its costs during transportation.

I. Tvedten & S. Bauer (2022) noted that although the transition to LNG required significant initial investment, it allowed for reduced fuel costs and environmental measures in the long term. This made LNG a profitable option for shipping companies. E. Orysiak *et al.* (2024) noted that the development of LNG bunkering infrastructure was crucial to support the growing demand for this fuel. The introduction of new terminals and stations for refuelling ships helped to reduce costs and ensure a reliable supply. G. Satta *et al.* (2021) suggested that the construction of new LNG bunkering terminals was an important step in expanding the use of this fuel in shipping. This ensured a stable fuel supply and compliance with environmental requirements. S. Barberi *et al.* (2021) argued that LNG significantly reduced pollution levels in ports and coastal areas, which helped to improve the environmental situation. This was important for shipping companies operating in such regions. M. Cassar *et al.* (2021) emphasised that LNG was a key factor in meeting environmental regulations and standards of international organisations, in particular, on reducing emissions. The use of this fuel was an important step towards ensuring the sustainable development of navigation. Thus, although the issues of using LNG in shipping have been studied and show significant benefits of this fuel from an environmental and economic standpoint, there are a number of issues that require further study to achieve the full implementation of the potential of LNG in shipping.

The purpose of the study was to investigate the potential of LNG for the modernisation of marine energy, considering the environmental, technological, and economic aspects of its use. Research objectives:

1. To consider the impact of LNG use on reducing harmful gas emissions, and its energy efficiency in marine engines.

2. To investigate the economic benefits of switching to LNG, in particular, the cost of investment in the relevant infrastructure and the economic efficiency of this transition.

3. To evaluate the technical aspects related to the use of cryogenic LNG storage and supply systems.

Materials and Methods

This study focused on the use of LNG as a strategic energy source for the modernisation of ship power systems. The study covered the technological and economic aspects of LNG implementation in the marine sector, with a focus on its environmental benefits and energy efficiency. It addressed the issue of switching from conventional marine fuel to LNG in response to the update of environmental regulations, in particular, the requirements introduced by the International Maritime Organisation in the work of L. Kirval & U.Y. Çalışkan (2022). These upgrades were aimed at minimising pollution of the oceans and seas, including discharges, oil and air pollution.

The material basis of the study was data that were used to compile tables comparing the impact of LNG use on reducing harmful gas emissions and energy efficiency of marine engines. In addition, the economic benefits of switching to LNG were considered. All the materials shown in the tables were obtained from sources H. Jang *et al.* (2021) and B. Jesus *et al.* (2024). The research started by analysing the environmental impact of LNG, comparing it with conventional marine fuels such as diesel and coal. Special attention was paid to the potential of LNG to reduce harmful emissions, such as SO_x, NO_x, particulate matter (PM), and CO₂. This aspect highlighted the role of LNG in meeting environmental requirements and ensuring pollution reduction. Attention was also drawn to its ability to help meet the sulphur restrictions set by MARPOL Annex VI and the Act to Prevent Pollution from Ships (2024). In addition, the study delved into technological challenges and solutions related to the introduction of LNG in shipping. The infrastructure required for LNG implementation was also investigated. These technological aspects were critical to ensuring the safe and efficient operation of LNG vessels, especially given the need for highly specialised LNG storage and management equipment.

The study also examined the economic feasibility of switching to LNG, considering both the initial investment costs of upgrading ships and building the necessary infrastructure, and long-term operating savings. The financial benefits of LNG, in particular, the stability of fuel prices and reduced operating costs, were compared with the instability and rising cost of conventional marine fuel. Special attention was paid to the economic consequences of LNG introduction in the shipping industry, in particular, such factors as return on investment and payback periods.

In addition, the study examined problems related to the development of LNG bunkering infrastructure.

The current state of LNG supply networks at key global shipping hubs, including the role of ports such as Singapore, Shanghai, and Rotterdam in supporting LNG-powered vessels, was considered. Graphic materials were also provided that illustrated the structure of these networks and their interaction with shipping routes. The study discussed innovative solutions, such as floating LNG terminals, that can help to overcome infrastructure constraints in remote regions and promote widespread LNG adoption.

Results

Shipping faces new challenges due to growing environmental requirements and the need to reduce emissions of harmful substances. One of the key areas of the industry's development is the gradual transition to cleaner fuels, with LNG attracting particular attention. The use of this fuel allows shipping companies to meet international environmental standards, reducing air pollution, and improving the energy efficiency of ships. One of the main regulatory documents defining environmental requirements for shipping is MARPOL Annex VI and the Act to Prevent Pollution from Ships (2024). According to it, from January 1, 2020, the sulphur content in marine fuel should not exceed 0.5%, and in emission control zones – only 0.1%. These restrictions force ship-owners to abandon conventional fuel oil, which contains a significant amount of sulphur, and look for alternative solutions.

LNG offers a number of environmental benefits that make it an attractive option for shipping. It does not contain sulphur, which completely eliminates SO_x emissions without using additional cleaning systems, such as scrubbers. Burning natural gas helps reduce CO₂ emissions by 20-25%, which is an important step in the fight against climate change. In addition, the level of NO_x emissions when using LNG was reduced by 85% compared to conventional fuels, and the amount of PM was reduced to almost zero (Yeo *et al.*, 2022). The efficiency of LNG-powered engines is usually 5-10% higher than that of diesel engines. This reduces fuel costs and reduces operating costs, making LNG more efficient in terms of energy resources. However, despite the obvious advantages, the widespread introduction of LNG in shipping is accompanied by a number of

challenges. One of the main problems is the insufficiently developed infrastructure for LNG storage and bunkering. Unlike conventional marine fuel, natural gas requires special cryogenic tanks capable of maintaining temperatures of -162°C. This creates additional technical and financial difficulties, because the construction of the corresponding terminals requires significant capital investments. In addition, upgrading the fleet and equipping ships with LNG storage and delivery systems requires significant initial investment, which may be too much for some shipping companies (Van Biert *et al.*, 2021).

Another important issue is the technical operation of LNG vessels. Maintenance of cryogenic systems requires highly qualified personnel who can work with new technologies. This will require additional costs for crew training and adaptation of operational standards. But despite these challenges, the prospects for using LNG in shipping remain extremely high. The infrastructure for LNG storage and refuelling is actively developing, and technological progress contributes to reducing the cost of systems required for its use. Many shipping companies have already started implementing this technology, as it not only helps meet environmental standards, but also allows optimising fuel costs in the long term (Adekoya *et al.*, 2024).

Thus, LNG is a strategic area for the modernisation of marine energy. It ensures environmental safety, reduces harmful emissions, and promotes the transition to more sustainable marine logistics. However, for the full implementation of this technology, it is necessary to solve the issues of infrastructure development, reducing the cost of fleet modernisation and training specialists. Despite these challenges, trends in shipping suggest that the role of LNG will only grow in the coming decades, forming a new environmental standard for maritime transport. The use of LNG in shipping is an important step towards improving energy efficiency and reducing the impact on the environment. Conventional marine power plants are undergoing modernisation to meet modern environmental standards, and LNG is becoming a key fuel in this transition. Its use can significantly reduce emissions of harmful substances, reduce operating costs, and improve the overall performance of vessels (Table 1).

Table 1. Impact of LNG use on reducing harmful gas emissions and energy efficiency in marine engines

Parameter	LNG	Diesel fuel	Coal
CO ₂ emissions (t/GWh)	0.185	0.22	0.82
So ₂ emissions (g/kWh)	0	2.1	4
NO _x emissions (g/kWh)	0.05	0.25	0.5
PM emissions (g/kWh)	0	0.03	0.15
Energy efficiency	Higher efficiency (45-55%)	Average (35-45%)	Low (30-40%)

Source: compiled by the author based on H. Jang *et al.* (2021)

Modern marine LNG power plants show an increased efficiency factor compared to conventional diesel engines. This helps to reduce fuel costs and optimise energy consumption. An important area of development is the introduction of combined power systems that allow combining the operation of different types of engines to achieve maximum efficiency. Such systems provide the ability to switch between fuel types, which is especially important in conditions of unstable prices and regulatory changes. There are several main types of engines that can run on LNG. Dual-fuel engines are the most common option, as they can run on both LNG and diesel fuel. This gives shipping companies additional flexibility in choosing their energy source. Another option is gas engines with spark ignition, which operate exclusively on LNG. They provide even lower emissions, but require specialised fuel supply systems and some changes to the vessel's design (Lähde & Gi-chaskiel, 2021).

LNG storage on board ships is a technologically complex process. Since LNG is stored at a temperature of about -162°C , special cryogenic tanks are used for this purpose. They are equipped with multi-layer insulation and vacuum systems that minimise gas evaporation. This reduces fuel losses and ensures safe operation of the vessel. An important aspect is also the control of gas evaporation, which allows the use of evaporated gas in marine power plants, preventing its loss. Fuel supply systems play a key role in the stable operation of LNG vessels. The Fuel Gas Supply System provides control of the fuel supply to engines by regulating its pressure and temperature. This allows avoiding power drops and ensuring efficient operation of engines in various operating modes. Some systems also include re-cooling mechanisms that allow some of the evaporated gas to be returned to a liquid state for later use (Jeong *et al.*, 2024).

As of 2025, there are several modern engine models on the market that are already actively used in shipping. One of the most efficient is the MAN ME-GI, a high-pressure dual-fuel engine that provides minimal fuel loss and low emissions (Kim *et al.*, 2022). Another option is the WinGD X-DF, which runs on LNG at low pressure, which reduces methane emissions and improves the overall environmental friendliness of the vessel (Domić *et al.*, 2022). Despite the significant advantages, the introduction of LNG in shipping faces certain challenges. The main ones are the need to develop appropriate infrastructure, the high cost of fleet modernisation, and the need for specialised skills to service new technologies. However, global trends indicate a gradual increase in the share of vessels running on this fuel (Stolz *et al.*, 2022). Thus, the technological development of marine energy based on LNG is a strategic area for the modernisation of the industry. State-of-the-art engines, efficient fuel supply systems, and upgraded gas storage methods ensure high energy efficiency and significant emission reduction. In the future, the use of LNG will contribute to further greening of shipping, optimising costs and ensuring the stable development of sea transportation. The transition of global shipping to LNG is one of the most important areas of modernisation of marine energy. This is due not only to environmental requirements, but also to potential economic benefits. The use of conventional marine fuels, such as fuel oil or diesel, is becoming less attractive due to rising environmental compliance costs and volatile oil prices. On the other hand, LNG can reduce operating and environmental costs, get financial incentives, and improve overall ship efficiency. However, despite these advantages, the transition to LNG is accompanied by certain challenges, such as significant initial investment, the need for infrastructure development, and the cost of staff training (Table 2).

Table 2. Economic benefits of switching to LNG, cost of infrastructure investment, and cost-effectiveness of the transition

Parameter	Derivative of switching to LNG
Initial investment (USD million)	50-100 (depending on the type of vessel)
Operating expenses (per year)	Cost reduction by 15-30% (compared to diesel)
LNG cost (per 1 MWh)	40-60 USD/MWh
Operating savings (per year)	5-15% of total expenses
Return on investment	3-6 years depending on the scale of the project

Source: compiled by the author based on B. Jesus *et al.* (2024)

One of the key economic benefits of using LNG is reduced operating costs. Prices for conventional petroleum products are subject to fluctuations, which complicates long-term financial planning for shipping companies. However, the cost of LNG is more stable, and in some regions, it is much lower, which makes it economically attractive (Xiuzhen *et al.*, 2022). Due to cleaner LNG combustion, engines experience less

wear, which reduces maintenance costs and increases their service life.

The transition to LNG is accompanied by a number of financial and technical challenges. The most significant of these is the high cost of the initial investment. The construction of new LNG-powered vessels or the conversion of existing vessels to run on this fuel requires significant costs for the installation of cryogenic

LNG storage systems, modernisation of fuel systems, and replacement of engines. These costs can be a serious barrier for many shipping companies, especially those operating in the low-margin cargo segment, such as general cargo transportation, container transportation, or raw material transportation.

Another important aspect is the cost of staff training. Working with LNG requires special knowledge and skills, as this fuel is stored at ultra-low temperatures (-162°C) and requires special safety measures. Shipping companies should invest in training crew and technical personnel to ensure safe operation of vessels and avoid the risks associated with the use of cryogenic fuel. It should also be considered that the infrastructure for providing LNG vessels is not yet evenly developed in all regions of the world as of 2025. Although the number of LNG bunkering terminals is gradually increasing, their availability remains limited in some seaports. This can create logistical difficulties for vessels that use LNG as their main fuel, and require additional planning of routes and stops to replenish their fuel reserves.

Thus, the cost-effectiveness of switching to LNG is determined by the balance between initial costs and long-term benefits. Despite the high initial costs of implementing LNG, lower operating costs, financial incentives, and savings on environmental measures can make this transition economically feasible in the long run. However, heavy fuel remains the most cost-effective option even with a high carbon tax, suggesting that switching to LNG may not be economically feasible for many shipping companies at this stage due to high initial investment and lack of adequate infrastructure to provide LNG vessels (Sagin & Poberezhny, 2022). In the long run, global trends to reduce emissions and strengthen environmental standards will further increase the popularity of LNG in shipping. Infrastructure development and technology improvements will ensure its wider adoption, which will contribute to the sustainable development of the marine industry and increase its economic efficiency.

LNG infrastructure is one of the key aspects that will determine the future of shipping in the context of the transition to clean energy sources. The introduction of this fuel at a broad level requires the creation of an efficient and scalable infrastructure for LNG storage, transportation, and bunkering. Despite the successful development of certain infrastructure elements in some regions, there are still significant limitations at the global level that make it difficult to implement large-scale LNG in shipping. These include the lack of sufficient infrastructure for LNG bunkering, the high cost of upgrading vessels to use this fuel, and the uneven development of LNG supply networks in different parts of the world. In addition, large initial investments in the installation of the necessary equipment and technologies can be a significant barrier for many shipping companies, especially those operating

in low-margin segments. In 2023, major international ports, in particular Rotterdam, Singapore, and Shanghai, became important hubs for LNG bunkering due to the presence of developed LNG terminals (Dewiatena & Bahagia, 2023). These terminals allow efficient storage and regasification of LNG, ensuring uninterrupted fuel supply for vessels running on this fuel.

Rotterdam is an important commercial port and the largest LNG bunkering terminal in Europe (Fig. 1). Due to its strategic location on the North Sea coast and high level of infrastructure development, Rotterdam has become a major LNG supply hub for international vessels. The port provides the ability to bunker LNG of various types to ships moving between Europe, Africa, and North America. LNG is a more environmentally friendly fuel, so many shipowners are switching to it due to strict environmental requirements, such as SO_x and NO_x emission reduction standards. Rotterdam is actively developing infrastructure for LNG bunkering, including the creation of new LNG processing terminals, investments in the development of technologies for gas storage and supply. This makes the port attractive for shipping companies looking to reduce harmful gas emissions and reduce fuel costs. As Rotterdam is a major transit hub, this development also contributes to the increased use of LNG in other parts of Europe (Zannis *et al.*, 2022).

Singapore is one of the largest and most developed ports in the world, which is actively developing infrastructure for servicing ships using LNG (Fig. 2). Singapore is considered an important hub for bunkering vessels running on alternative fuels, in particular LNG. This significantly contributes to an increase in the number of such vessels in the Southeast Asian region, where demand for environmentally friendly fuel is increasing due to stricter emissions regulations. Singapore's infrastructure includes several terminals for receiving and storing LNG, and systems that ensure efficient bunkering of this fuel. In addition, the Singapore government actively supports this process by investing in new technologies and providing incentives for shipping companies to switch to LNG. In particular, local port authorities encourage investment in infrastructure, which reduces overall costs for shipowners and encourages the spread of LNG in the region (Du & Li, 2023).

Shanghai is an important commercial port and one of the main centres for the development of LNG infrastructure in China (Fig. 3). Since China is the largest consumer of energy resources in the world, and one of the largest air pollutants, the country is actively working on switching to cleaner energy sources, in particular LNG. Shanghai plays a key role in this process through the development of specialised LNG storage and processing terminals. In addition, Shanghai is part of ambitious national initiatives to reduce emissions and develop infrastructure for green technologies, including the introduction of LNG as an alternative to conventional fuels. However, it is worth noting that one of the

challenges for the wider use of LNG in other parts of China is its availability and cost. Remote regions face difficulties in LNG delivery due to the lack of developed

infrastructure and high transportation costs. These factors create certain barriers to the expansion of LNG use in the country (He *et al.*, 2023).



Figure 1. Graphic image of the port of Rotterdam

Source: Port of Rotterdam cargo throughput decreased in 2024 (2025)



Figure 2. Graphic image of the port of Singapore

Source: Hiteshk (2019)



Figure 3. Graphic image of the port of Shanghai

Source: M. Bruno (2022)

However, despite the growing number of such terminals, many regions, especially in Africa, South America, and parts of Asia, face a lack of infrastructure to provide the necessary level of LNG supply (Yin & Lam, 2022). This limits opportunities for shipping companies seeking to switch their fleets to cleaner energy sources, as they are forced to plan their routes based on existing bunkering terminals. As a result, LNG vessels have limited access to some ports and routes, which creates additional costs and logistical difficulties.

One solution that helps to reduce these limitations is the introduction of floating LNG terminals. Floating terminals are mobile installations that can store, regasify, and supply LNG to ships without the need to build expensive stationary ground terminals. Floating terminals can provide LNG supplies in remote or insufficiently secured ports, where the construction of stationary infrastructure is economically unprofitable. This allows significantly increasing the coverage of regions where the necessary infrastructure for bunkering is not available, and reducing dependence on geographical factors. Floating terminals are particularly useful in cases where fast and cost-effective provision of new LNG ports is required (Khoiriyah *et al.*, 2023).

Notably, the development of LNG infrastructure is stimulated by state programmes and international initiatives. Many countries seeking to reduce greenhouse gas emissions actively support investment in LNG infrastructure development. For example, in the European Union, there is the Connecting Europe Facility programme, which provides soft loans and grants to shipping companies and enterprises that invest in the creation of LNG bunkering terminals and the development of infrastructure for its transportation. The terms of lending and receiving grants include concessional loans on favourable terms for projects that meet the programme's criteria. The application process includes submitting a detailed business plan and technical documentation. To receive grants, a company must submit an application containing a description of the project, its impact on the environment and economy, and an implementation plan. Competition for grants is high, so it is important to prepare high-quality documentation (Connecting Europe Facility, 2021). Such support not only encourages infrastructure development, but also encourages shipping companies to invest in the transition to cleaner energy sources. In particular, one example is Norway, which actively supports the use of LNG in navigation through preferential programmes and subsidies. Norway, as part of its strategy to reduce carbon emissions and meet its obligations under the Paris Agreement, provides financial incentives for companies that switch to using LNG. In particular, Norway provides tax breaks and subsidies for shipping companies that upgrade their vessels to use LNG instead of conventional diesel fuel. As part of the Green Shipping Programme, the Norwegian government allocates up to

50% of the cost of upgrading ships, including switching to LNG, and also provides soft loans to finance such initiatives. Through these measures, Norway encourages shipping companies to reduce their harmful gas emissions and supports the development of LNG bunkering infrastructure in their ports. According to the Norwegian Maritime Administration, shipping companies can receive funding of up to NOK 2 million (approximately EUR 200,000) for a modernisation project that includes switching to LNG as the main fuel for the ship.

One of the companies that actively invests in the development of infrastructure for LNG is Maersk, one of the largest container carriers in the world. Maersk is actively working to convert its vessels to LNG and invests in the construction of new bunkering stations and the expansion of existing infrastructure for the supply of LNG. As part of its environmental initiatives, the company plans to operate more than 12 of its new LNG vessels by 2030. In addition, Maersk is investing in expanding its network of bunkering terminals around the world, including ports in Europe and Asia, to ensure a continuous supply of LNG for its vessels. For example, in 2021, the company announced cooperation with the Port of Rotterdam to expand the LNG bunkering infrastructure, and is also negotiating with other ports to build additional terminals. Maersk's investments in the transfer of the fleet to LNG and infrastructure development can amount to hundreds of millions of dollars. For example, for the construction of one new bunkering station, a company can spend up to EUR 50 million on a project. This demonstrates the company's serious efforts to provide a more sustainable and cost-effective way of transportation in the shipping industry.

Thus, despite the existing challenges associated with the development of infrastructure for LNG, the use of floating terminals, active support from states and private investors help to solve these problems. In the future, the development of bunkering infrastructure, in particular, through floating terminals and the expansion of the network of ports providing services for LNG, will allow shipping to fully switch to environmentally friendly energy sources, which will contribute to the sustainable development of the marine industry as a whole.

Discussion

Analysis of the results of the study showed that the introduction of LNG in shipping contributed to a significant reduction in harmful emissions. In accordance with the environmental regulations MARPOL Annex VI and the Act to Prevent Pollution from Ships (2024), vessels that used LNG as fuel showed a significant reduction in SO_x and NO_x emissions, and also PM. In addition, switching to LNG has reduced CO_2 emissions, which confirmed its compliance with modern requirements for decarbonisation of shipping.

This problem was also investigated by A. Singh & S. Shanthakumar (2022), where the results confirmed

that the MARPOL Annex VI environmental regulations impose strict restrictions on harmful emissions from marine transport, in particular, on sulphur in marine fuel. These regulations significantly reduced the level of air and ocean pollution, which contributes to the preservation of the marine ecosystem. As a result, these measures increase the environmental responsibility of sea carriers and encourage the introduction of the latest technologies to reduce emissions. The study by A. Hoang *et al.* (2023) also showed that decarbonising shipping is an important step in combating climate change by focusing on reducing CO₂ emissions in this sector. Switching to alternative fuels such as LNG, hydrogen, and ammonia can significantly reduce harmful gas emissions. This strategy is essential for achieving the global goals of reducing emissions and ensuring the sustainable development of the marine industry. The implementation of environmental regulations is only part of a broader strategy to reduce pollution from marine transport. Since these regulations focus on limiting SO_x and NO_x emissions, they do not cover all aspects of environmental sustainability, such as greenhouse gas emissions. Therefore, it is important to integrate these requirements with other international initiatives that include a broader approach to decarbonising shipping and using the latest technologies to reduce the environmental impact of the industry as a whole.

Technological analysis has shown that modern marine power plants, in particular, dual-fuel engines and gas engines with spark ignition, provide increased efficiency and reduce fuel consumption. In addition, the use of cryogenic LNG storage systems helped to effectively control the processes of fuel evaporation and its supply to engines. However, it turned out that such systems required significant capital investments and careful monitoring of temperature conditions, which could complicate their operation. Z. Rony *et al.* (2023) concluded that LNG-based marine power plants are becoming increasingly popular due to their environmental benefits, as LNG contributes to reducing SO_x, NO_x, and CO₂ emissions compared to conventional fuels. They provide high energy efficiency, since LNG combustion occurs more cleanly, which has a positive effect on engine efficiency and reduces operating costs. Such technologies are actively supported by international organisations as part of their commitments to reduce the environmental impact of shipping.

R. Ratnakar *et al.* (2021) found that cryogenic fuel storage systems are critical to ensuring safe and efficient LNG storage on board ships. These systems help to maintain the necessary low temperature to preserve natural gas in a liquid state, minimising losses during transportation and storage. They not only reduce fuel evaporation, but also contribute to improving overall energy efficiency and reducing the cost of LNG transportation. These results support the above study, as they demonstrate a significant reduction in harmful gas

emissions and improved energy efficiency when using marine LNG power plants. In particular, the analysis showed that the use of LNG as the main fuel on ships can lead to a reduction in NO_x and SO_x emissions, which confirms the high environmental efficiency of this technology. In addition, the integration of cryogenic storage systems allows fuel to be stored in optimal conditions, which contributes to even greater savings and reduces overall energy costs for shipping.

Economic analysis has shown that despite the long-term benefits of LNG, such as reduced fuel costs and lower environmental costs, for many shipping companies switching to LNG at this stage may not be economically feasible. High initial investment in ship upgrades and the need to develop infrastructure for LNG bunkering, and the lack of sufficient support to cover these costs, leave conventional heavy fuel a more profitable option, even with high carbon taxes. It is necessary to emphasise the study by S. Al-Sobhi *et al.* (2021), who also found that the cost-effectiveness of LNG provides significant financial benefits for shipping companies due to its low fuel costs compared to conventional fuels. In addition, LNG helps to reduce operating costs by reducing engine wear and the need for frequent maintenance. The use of this fuel also allows companies to meet environmental standards without the need for additional costs for emission cleaning equipment, which increases their competitiveness in the market.

In turn, H. Ma *et al.* (2023) concluded that financial incentives for shipping companies play an important role in encouraging the transition to environmentally friendly fuels such as LNG. Due to government and international programmes, including subsidies and tax incentives, companies receive support in modernising their fleets, which can significantly reduce the financial burden. Concessional loans for the purchase of new vessels or the adaptation of existing vessels to LNG use provide additional incentives for integrating more sustainable technologies into the industry. These data are consistent with the theses given in the previous section, as they confirm that the economic benefits of LNG significantly exceed the initial costs of upgrading marine power plants. In particular, long-term savings on fuel costs, lower operating costs, and easier compliance with environmental standards make this transition beneficial for shipping companies. In addition, financial incentives provided by the government and international organisations greatly facilitate the implementation of this technology, which once again confirms the feasibility of switching to more environmentally friendly and cost-effective fuel options.

One of the key limitations in the use of LNG remained an insufficiently developed bunkering infrastructure. While major ports such as Rotterdam, Singapore, and Shanghai had LNG terminals, many other ports were not equipped with the necessary capacity to store and refuel LNG vessels. The study showed that

the development of floating LNG terminals could be an effective solution for providing fuel to ships in remote regions, but this required significant capital investment and coordination at the international level.

Research conducted by V. Chimshir *et al.* (2023) confirmed the importance of LNG bunkering infrastructure to ensure a stable LNG supply to ships. This infrastructure includes specialised ports and gas stations capable of handling large volumes of fuel, which reduces the risk of leaks and ensures high safety during refuelling. Its development reduces ship downtime and increases the availability of LNG for sea carriers, which significantly optimises global logistics. D. Polemis & M. Boviatsis (2023) also found that floating terminals are an effective solution for countries or regions where there is no developed infrastructure for natural gas storage and regasification. These mobile platforms help to quickly organise the supply of LNG to remote or isolated places where the construction of stationary terminals is economically impractical. Due to their mobility and rapid installation capabilities, floating terminals provide flexibility in managing gas demand, which is essential for the sustainable development of energy markets in various regions of the world.

Comparing the data obtained in the course of research, it can be concluded that the introduction of LNG bunkering infrastructure and the development of floating terminals are interrelated processes that significantly increase the availability of LNG for the shipping industry. These infrastructure elements create an efficient logistics network that reduces the time spent on refuelling ships and reduces the risks associated with fuel shortages in remote regions. In particular, mobile floating terminals can significantly reduce the cost of building stationary facilities, making the energy infrastructure more flexible and adapted to changing market conditions. The results of the study also showed that shipping companies that were the first to switch to using LNG received competitive advantages in the form of reduced operating costs and compliance with new environmental standards. However, the overall dynamics of the introduction of this fuel in the industry remained slow due to the high cost of technological transition and the need to adapt the regulatory framework.

A. Yao *et al.* (2024) concluded that the competitive advantages of LNG vessels are becoming increasingly obvious to shipowners, as these vessels allow them to meet the requirements of international environmental regulations, in particular, with regard to greenhouse gas emissions. The use of LNG also reduces fuel costs, which contributes to savings in operating costs, in particular, in the long term. In addition, LNG vessels can operate in areas with limited emissions, which allows shipowners to avoid the need to install additional filtration systems, which reduces additional costs. S. Ha *et al.* (2022) found that adapting the regulatory framework is a necessary step to ensure effective implementation

of LNG in the shipping industry. This includes updating international and national legislation regulating the use of LNG as fuel, in particular, in terms of safety and ecology. In addition, standardisation of infrastructure and training of crews to work with LNG create conditions for the smooth functioning of new technologies in navigation.

When analysing the results of the study, it is clear that the transition to the use of LNG in shipping not only provides significant environmental benefits, but also has economic potential for shipowners. Given the reduction in fuel costs and the need for fewer filtration systems, shipping companies gain additional competitive advantages in the market. However, for the successful implementation of such technologies, it is important to develop the appropriate infrastructure, update the regulatory framework, and ensure that crews are qualified to work with new types of fuel. Overall, the study confirmed that the transition to LNG was a strategically important step for the modernisation of marine energy. Its implementation reduced the negative impact on the environment and also improved the energy efficiency of ships. However, further investment in infrastructure, improvements in fuel storage and supply technologies, and support from governments and international organisations remained necessary to fully integrate LNG into global shipping.

Conclusions

LNG has demonstrated significant potential in the modernisation of marine energy, ensuring compliance with modern environmental standards, improving energy efficiency and reducing operating costs. The study confirmed that the use of LNG as a marine fuel contributes to a significant reduction in emissions of harmful substances, including SO_x , NO_x , and CO_2 . From a technological standpoint, it is established that modern marine power plants, in particular, dual-fuel engines and gas engines with spark ignition, provide a high level of efficiency and safety. Cryogenic LNG storage systems and fuel supply systems that minimise evaporation and energy loss were also investigated.

Analysis of economic aspects has shown that although the transition to LNG requires significant initial investment, in the long run, it can reduce fuel costs and environmental measures. Financial incentives, such as subsidies and concessional lending, contribute to the active adoption of this technology. Infrastructure challenges remain one of the key barriers to the widespread use of LNG in shipping. Despite the development of LNG terminals and bunkering stations, their number is insufficient in regions such as Africa, South America, and parts of Asia, where LNG bunkering infrastructure still requires significant investment and development. The introduction of floating LNG terminals can partially solve this problem by ensuring fuel availability for remote ports.

In general, the results of the study confirmed that the introduction of LNG is a strategically important area for the development of marine energy. Further investment in infrastructure, regulatory improvements, and staff training are needed to effectively implement this transition. A limitation of the study is the lack of analysis of specific regional conditions and practical examples of LNG implementation on certain types of vessels, which limits the universality of the results obtained for all shipping companies. It is necessary to study in more detail the long-term impact of LNG use on the

performance of marine power plants and their adaptation to future alternative fuels.

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Зріджений природний газ як стратегічний вектор модернізації суднової енергетики

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Анотація. Актуальність дослідження зумовлена необхідністю зниження викидів шкідливих речовин у судноплавстві, відповідністю міжнародним екологічним стандартам та пошуком економічно ефективних рішень для паливного забезпечення флоту. Метою дослідження було проведення аналізу технологічних, екологічних та економічних аспектів використання зрідженого природного газу (ЗПГ) в суднової енергетиці для оцінки його ефективності та перспектив впровадження. У результаті дослідження було виявлено, що використання ЗПГ у суднової енергетиці є ефективним рішенням для зниження екологічних впливів та дотримання міжнародних екологічних стандартів. ЗПГ дозволяє значно зменшити викиди вуглекислого газу (CO₂), оксидів азоту (NO_x) і оксидів сірки (SO_x), що робить його конкурентоспроможним паливом для суден, що працюють у зонах контролю викидів. Технологічно ЗПГ забезпечує високу енергоефективність, зокрема завдяки використанню двигунів подвійного палива, що дозволяють оптимізувати витрати на паливо і зменшити негативний вплив на навколишнє середовище. Сучасні суднові енергетичні установки, оснащені криогенними системами зберігання та подачі газу, підтверджують ефективність ЗПГ у забезпеченні стабільної роботи суден. Економічні дослідження показали, що хоча перехід на ЗПГ вимагає значних початкових інвестицій у переобладнання суден та інфраструктуру, в перспективі це дозволяє зменшити експлуатаційні витрати та витрати на екологічні заходи, такі як установки для зниження викидів сірки. Практичне значення дослідження полягає в тому, що воно сприяє розвитку теоретичних і практичних основ використання ЗПГ як екологічно чистого та економічно вигідного палива в суднової енергетиці, що може бути використано для вдосконалення існуючих технологій і нормативних актів у галузі судноплавства.

Ключові слова: екологічні стандарти; двигуни подвійного палива; криогенні системи; експлуатаційні витрати; зони контролю викидів