Electrification of Maritime Vehicles: Exploration of Key Battery Technologies and Sustainable Development Pathways

Ke Liu
College of Mechanical and Transportation Engineering, China University of Petroleum, Beijing, 100000, China

Keywords: Electrification of Maritime Vehicles, Batteries, Hybrid Power Systems.

Abstract: Despite significant advancements in the electrification of land transportation, maritime electrification still faces unique challenges such as diverse vessel types and complex routes. Lithium-ion batteries provide substantial energy storage and rapid recharge rates. but they are costly and pose safety risks. Fuel cells, on the other hand, provide high efficiency and zero emissions but are expensive and technologically complex. This paper explores the prospects of electrification for maritime vehicles, focusing on the application potential of lithium-ion batteries and fuel cells. Additionally, it discusses the use of hybrid power systems combining internal combustion engines and electric motors in maritime vehicles. As technology advances, further breakthroughs will be made in the electrification of maritime vehicles, contributing to the achievement of the global Sustainable Development Goals. In addition, the paper also introduces new concepts such as shore power systems, cold ironing, and isolated energy systems to promote sustainable maritime operations and the development of green ports, aiming to integrate renewable energy for environmental goals.

1 INTRODUCTION

In contemporary society, the proliferation of electrical devices has been remarkable, encompassing everything from small mobile devices to private cars and large public transportation systems. The trend toward electrification has become an unstoppable force, driven by two primary necessities: environmental and economic demands. The rise in global green-house gas emissions and the dwindling reserves of fuels have accelerated the demand for transportation electrification. Over the past decade, advancements in battery and power electronics technologies have significantly accelerated the electrification of land transportation. As land transportation electrification progresses rapidly, the focus has shifted towards the greening of maritime and aviation sectors (Qazi et al., 2023). The greenhouse effect and harmful exhaust emissions from vehicles have severely impacted the environment, making the shift towards more environmentally friendly electrical equipment an inevitable direction for future development. Additionally, electrification not only protects the environment but also enhances efficiency and reduces maintenance costs, offering a promising outlook for electric vehicles.

However, the process of electrification is not without its challenges. Firstly, electrification does not necessarily equate to environmental improvement. In many cases, the operation of electric vehicles still relies on high-pollution fossil fuels. Therefore, the rational development and use of electric vehicles are crucial; otherwise, electrification may become a superficial effort with no real environmental benefit. Secondly, while the complete realization of electrification seems imminent, it also faces numerous obstacles. Technological advancements and scientific research require substantial investments in human and material resources, and the necessary infrastructure and support measures demand significant funding. Moreover, when the investment in electrification reaches a certain threshold, the costs may exceed the benefits, leading to financial inefficiency. Therefore, it is crucial to evaluate the costs and development progress in other sectors when advancing the electrification process. Vehicle electrification can be subdivided into three categories: land, sea, and air. This paper focuses on the electrification of maritime vehicles. Unlike land vehicles, maritime and aviation vehicles are large in size, and under current infrastructure and technological conditions, developing fully electric large maritime or aerial vehicles is unrealistic. Therefore, current research still heavily relies on fuel.

Liu, K.
Electrification of Maritime Vehicles: Exploration of Key Battery Technologies and Sustainable Development Pathways.
DOI: 10.5220/0013933400004914

In *Proceedings of the 2nd International Conference on Renewable Energy and Ecosystem (ICREE 2024)*, pages 308-313
ISBN: 978-989-758-776-4

To save fuel, reduce costs, and save time, the research direction for the foreseeable future is hybrid models that combine oil and electric power. The main limiting factor in this process is fuel technology. Without groundbreaking advancements in battery technology, such as creating high energy density batteries, the electrification process can only progress gradually. There is significant research potential in areas such as circuit optimization, strategy formulation, and navigation systems. Progress in these fields will greatly advance the electrification process. Therefore, analysis, summarization, and prediction in this domain will provide valuable insights for the energy industry.

This paper thoroughly discusses the current state of maritime vehicle development, infrastructure equipment, the application and prospects of hybrid power systems, and the research and application of batteries. Additionally, it explores promising concepts such as S2S, CI, and IES. By integrating these topics, the paper analyzes the process of maritime vehicle electrification and extends the discussion to the entire energy and environmental system.

2 LITHIUM-ION BATTERIES

These batteries are popular in modern applications because they offer substantial energy storage capacity and do not suffer from the memory effect. The essential parts of this battery are the cathode, separator, anode, and electrolyte. During the charge process, energy conversion is achieved through the movement of lithium ions. Given their efficient energy storage and long lifespan, Lithium-ion batteries are vital for the progress of maritime vehicle electrification. Current technological frontiers are focused on the improvement and application of lithium-ion batteries, striving for breakthroughs in battery technology to enhance the performance and sustainability of electric vehicles.

In recent years, ships have extensively adopted lithium-ion batteries because of their high cycle life and substantial energy density，but they continue to encounter several challenges in commodity transportation and battery compartments control. This paper analyzes such safety risks of lithium-ion batteries in maritime applications, including thermal abuse, spontaneous combustion, and deformation from collisions. Methods to simplify large-scale battery modeling through numerical simulation and spontaneous combustion theory are proposed. The importance of precise monitoring of battery parameters and the improvement of cooling and ventilation systems is emphasized. Future research will focus on large-scale risk analysis to refine relevant regulations and standards, thereby enhancing the safety control of lithium-ion batteries in maritime transportation and vessel application (Yin et al., 2024).

Lithium-ion batteries provide several benefits, such as high energy density, lack of memory effect, storage stability, lightweight, and fast charging speeds. Specifically, their high energy density enables a significant amount of energy to be stored in a compact space, which is particularly important for maritime vehicles requiring substantial energy reserves. Additionally, the absence of memory effect makes lithium-ion batteries more flexible in charge and discharge management, suitable for long-duration sea voyages. In terms of storage stability, the low self-discharge rate of lithium-ion batteries ensures minimal energy loss over extended periods of inactivity, providing a significant advantage for maritime vehicles needing long-term energy reserves. Moreover, the relatively small size and weight of lithium-ion batteries facilitate easier transport and installation, while their efficient charging speeds further enhance user convenience.

Although maritime transportation emissions are relatively lower than those of other industries, the climate problem has heightened market and regulatory demands for reducing these emissions, thereby promoting the electrification of the shipping industry. Batteries, particularly lithium-ion batteries, are critical to the energy transition in maritime transport. Battery Energy Storage Systems (BESS) offer advantages in terms of energy efficiency and operational costs, making them suitable for various ship types and missions. In the future, with advancements in solid-state batteries and sodium-ion batteries, fully electric ships will see wider application. The integration of batteries requires the optimization of shipboard electrical grids and energy management systems to ensure high survivability and reliability (Trombetta et al., 2024).

However, lithium-ion batteries also have several notable drawbacks. Firstly, there is the issue of high cost. Lithium-ion batteries require the use of rare metals such as cobalt and nickel, which not only increase material costs but also make the production process complex and expensive. Additionally, the maintenance and infrastructure requirements for lithium-ion batteries are high, necessitating the establishment of comprehensive battery management systems and charging facilities, further escalating the overall cost. Secondly, there are safety concerns. The highly reactive nature of lithium metal and the high energy density of the batteries can lead to explosions or leaks if the batteries are mechanically or chemically damaged, posing significant safety hazards. Finally, there is the environmental impact. The production and disposal of lithium-ion batteries can result in environmental pollution, necessitating the establishment of robust environmental protection measures and recycling systems to mitigate negative impacts on ecosystems. Considering these pros and cons, research and application of lithium-ion batteries need to strike a balance between technological advancement and environmental protection.

3 FUEL CELLS

Fuel cells generate electricity by converting hydrogen and oxygen through a chemical process, producing water and heat as the sole byproducts. This clean and efficient process has led to their widespread market application. The primary types include three common variants, with ongoing research on methanol and molten carbonate types. Fuel cells offer advantages such as high energy density, efficiency, quick refueling, stability, and environmental friendliness. They emit no harmful substances, only water, and have low noise levels, aiding in pollution reduction and marine ecosystem protection (Wang et al., 2023).

To meet the IMO goal for reducing shipping emissions, fuel cell technology is regarded as a promising alternative for marine power generation. Research indicates that PEM fuel cells are a top choice due to their high power-to-weight ratio and operational flexibility. Case studies reveal that this fuel cell technology not only substantially cuts emissions but also excels in practical applications. In summary, fuel cells offer substantial potential for green shipping, with clear advantages particularly in advancing decarbonization. Liquid ammonia is regarded as the most ideal hydrogen carrier. An efficiently designed ammonia reforming system can produce hydrogen, which, when combined with PEM fuel cells, can significantly reduce emissions. Although this system's cost is higher than that of diesel engines, its environmental benefits justify the investment (Seyfi et al., 2023).

In the field of maritime vehicles, the application of fuel cells is still in its early stages but has already shown significant progress. The high efficiency and zero-emission characteristics of fuel cells make them a promising alternative to traditional diesel engines. The energy conversion efficiency of fuel cells typically ranges from 40% to 60%, which is significantly higher than that of traditional internal combustion engines. When combined with heat recovery systems, the overall efficiency can exceed 80%. This high-efficiency energy conversion gives fuel cells a distinct advantage in terms of energy efficiency.

Currently, the use of fuel cells in maritime vehicles is still in its early stages, is primarily focused on auxiliary power systems and vessels for short-distance voyages. For example, the world's first hydrogen fuel cell ferry, MF Hydra, launched in Norway in 2021, demonstrated the potential of fuel cells in practical maritime transportation. Additionally, Japan is developing hydrogen fuel cell-powered port handling equipment to reduce carbon emissions from port operations. However, the implementation of fuel cells in maritime applications still faces numerous technical challenges.

First, there are challenges related to the storage and transportation of hydrogen. Hydrogen needs to be stored at low temperatures or high pressures, posing safety risks for maritime transport. Solutions include developing safer hydrogen storage materials and technologies. Secondly, there are challenges related to hydrogen production and supply chains. Currently, hydrogen is primarily produced through natural gas reforming, which generates carbon dioxide emissions. Future green hydrogen production will need to rely on renewable energy sources, such as water electrolysis, to mitigate environmental impacts.

Governments worldwide are actively promoting the adoption of fuel cell technology. For instance, the European Union's "European Green Deal" provides funding to support fuel cell research and development, while the United States encourages hydrogen energy development through various federal programs. It is expected that by 2030, the global fuel cell market will expand significantly, with applications covering maritime transport, land transport, and stationary power systems.

The environmental benefits of fuel cells are considerable. Their only byproduct is water, with no harmful gas emissions. By replacing traditional diesel engines, fuel cells can greatly avoid emissions of various bad gases, helping to address global climate change. Additionally, fuel cells operate with low noise levels, reducing their impact on marine ecosystems and helping to protect the ocean environment.

4 HYBRID SYSTEMS

The electrification of maritime vehicles is a crucial pathway to achieving low-carbon and green shipping, but pure electric systems face numerous challenges. Currently, most applications utilize hybrid power systems, which combine the advantages of internal combustion engines (ICE) and electric motors, making them the primary choice now and in the foreseeable future.

Hybrid systems leverage the strengths of both electric motors and internal combustion engines, offering potential benefits comparable to those of pure electric systems. The principle behind hybrid systems involves using an internal combustion engine to drive a generator that produces electricity, which then powers the electric motor. Alternatively, the internal combustion engine and the electric motor can operate independently or simultaneously to propel the vessel. The main parts of a hybrid system are the electric motor, internal combustion engine, generator, battery pack, and control system.

Hybrid systems are widely adopted globally, enhancing energy efficiency and environmental friendliness. Their market share is gradually increasing, with significant applications in passenger ferries, cargo ships, and special-purpose vessels, significantly reducing fuel consumption and pollution emissions. For instance, Norway's electric ferry MF Ampere, Japan's solar hybrid ship Solar Impulse, and the United States' electric cruise ship Spirit of the Elbe all utilize hybrid systems, showcasing their superiority in improving energy efficiency and environmental performance. Research indicates that inland waterway tugboats using hybrid technology can reduce fuel consumption by 62%. Promoting this technology can lead to substantial energy savings (Hayton, 2022).

A significant portion of global trade is conducted via maritime transport. In 2020, approximately 89% of goods were transported by sea. The primary factor driving the growth of maritime transport is the increase in global trade volume. The substantial increase in global trade has brought maritime transport into greater public focus. However, most of the world's merchant ships still rely on harmful fossil fuels. Although HFO is the most environmentally damaging due to its high sulfur content and pollutant emissions, it remains the most widely used fuel because of its low cost and high energy density (Korkmaz et al., 2023).

Governments around the world are vigorously supporting the development of hybrid systems through policies and regulations, including research and development subsidies, tax incentives, and the establishment of technical standards. IMO is promoting the green transformation of the global shipping industry through international cooperation and technological exchange. For example, the European Union and Nordic countries provide financial subsidies and tax incentives, China is increasing its support for green shipping technologies, and the United States Maritime Administration (MARAD) offers research funding and technical support to encourage the adoption of hybrid systems. These policies and regulatory support play a crucial role in driving technological advancements and market applications (Roy et al., 2018).

5 EMERGING ENERGY SOLUTIONS

In the electrification of maritime vehicles and environmentally friendly shipping, three new concepts are of significant importance: Cold-Ironing (CI), shore-to-ship systems (S2S), and isolated energy systems (IES). CI connect docked ships to port power facilities, providing electricity and reducing pollution and noise from internal combustion engine (ICE) power generation. Cold ironing represents a significant innovation in the shipping industry's move towards electrification, switching to shore power during berthing to replace diesel engine power generation (Abu et al., 2023). Although its current application is limited due to high initial costs and unclear benefits, the installation of cold ironing systems will become inevitable with stricter emission regulations.

S2S systems, also known as cold ironing, link vessels to the onshore power grid, significantly cutting emissions and noise by allowing ships to turn off their diesel generators when docked. Although currently limited to a few ports due to high power demands and grid impact, S2S is crucial for shipping electrification (Frković et al., 2024). To achieve ship decarbonization, it needs to be paired with renewable energy sources, making it a promising future solution despite its current limited use.

Isolated Energy Systems (IES) enhance the reliability and flexibility of energy supply by integrating solar power, wind power, diesel generators, and storage systems, making them particularly suitable for long voyages away from ports. Although the initial investment for these systems is relatively high, the long-term benefits are significant, including reduced operating costs, lower fuel consumption, and decreased maintenance expenses, aligning with increasingly stringent environmental regulations. Decarbonizing the maritime industry is a critical research topic, and electrifying fishing vessels offers a solution to reduce emissions and operating costs. Achieving this goal in remote areas with IES poses challenges (Koričan et al., 2023).

The International Maritime Organization (IMO) and national governments are actively promoting the development of these systems through policy support and financial subsidies, encouraging their widespread adoption. By replacing traditional internal combustion engines with these systems, they effectively reduce pollutant emissions and noise, while also improving energy efficiency and environmental performance. These systems are essential for the green transformation of ports and the shipping industry, advancing global shipping towards sustainable development goals.

In the future, as technology matures and becomes more widely applied, Cold-Ironing System, S2S systems, and IES will see broader adoption worldwide, fostering the development of green ports and environmentally friendly shipping. The introduction and application of these new concepts not only enhance the environmental standards of ports and ships but also provide solid technical support for achieving sustainable development goals. By integrating the analysis of battery technology and hybrid systems, comprehensively exploring these new concepts will help formulate more comprehensive environmental strategies, offering effective solutions for the electrification of future maritime vehicles.

6 PROSPECT

In contemporary society, the electrification of maritime vehicles is crucial for achieving low-carbon and green shipping. Despite facing challenges, the development potential is immense. This paper has discussed lithium-ion batteries, fuel cells, and their advantages and disadvantages, as well as introduced hybrid systems and emerging concepts. While lithium-ion batteries offer high energy density and rapid charging, their cost remains high. Fuel cells are efficient and emit zero emissions but are technologically complex and expensive. Hybrid systems integrate internal combustion engines and electric motors to enhance efficiency and reduce environmental impact. Shore power, shore-to-ship, and isolated energy systems further promote green shipping. Considering all factors, lithium-ion and fuel cells hold the most promise for maritime electrification, requiring a holistic approach to environmental impact and future development.

Hybrid systems in maritime vehicles integrate the benefits of lithium-ion batteries and fuel cells, optimizing energy use through series, parallel, and combined modes to enhance efficiency and environmental performance. Policy and regulatory support have fostered their development. Remote ocean areas primarily rely on solar and wind energy, but intermittent issues necessitate energy storage systems. The development of marine renewable energy sources create new opportunities for multi-source energy systems. This paper has reviewed the fundamentals, current technological status, and future prospects of these hybrid systems.

7 CONCLUSION

In the face of global climate change and the dwindling reserves of fossil fuels, the electrification of maritime vehicles and the pursuit of green shipping are critically important. This paper has explored the prospects and challenges of applying lithium-ion batteries and fuel cells in maritime vehicles. Lithium-ion batteries offer substantial energy density and quick charging capabilities, but they are hindered by high costs and safety issues. Fuel cells are characterized by efficient energy conversion and zero emissions, yet they are also costly. Emerging solutions such as shore power systems, shore-to-ship systems, and isolated energy systems will make maritime vehicles more efficient and environmentally friendly, achieving sustainable development goals.

Government policies and international cooperation are essential in advancing the application of these technologies. Looking forward, with technological advancements, the electrification of maritime vehicles will witness further breakthroughs, contributing to the achievement of global sustainable development goals.

REFERENCES

Abu Bakar NN, Bazmohammadi N, Vasquez JC, Guerrero JM 2023 Renew Sust. Energ. Rev. **178** 113243

Frković L, Ćosić B, Falkoni A, Pukšec T, Vladimir N 2024 Ocean Eng. **302** 117537

Hayton M 2022 Lecture Notes Civ. Eng. **264**

Koričan M, Frković L, Vladimir N 2023 J. Clean Prod. **425** 138997

Korkmaz S, Aykut K, Erginer KE, Yuksel O, Konur O, Colpan CO 2023 Int J. Hydrogen Energy **48** 23279-23295

Qazi S, Venugopal P, Rietveld G, Thiago Batista S, Shipurkar U, Grasman A, Alan JW, Wheeler P 2023 IEEE Electrif. Mag. **11** 74-87

Roy A, Auger F, Dupriez-Robin F, Bourguet S, Tran QT 2018 Energies **11** 1904

Seyfi H, Hitchmough D, Armin M, Blanco-Davis E 2023 J. Mar. Sci. Eng. **11** 1489

Trombetta GL, Leonardi SG, Aloisio D, Andaloro L, Sergi F 2024 Energies **17** 1019

Wang X, Zhu J, Han M 2023 J. Mar. Sci. Eng. **11** 238

Yin R, Du M, Shi F, Cao Z, Wu W, Shi H, Zheng Q 2024 Process Saf. Environ. Prot. **181** 266-293