J Inno Sci Eng, 2025, 9(1):54-61

DOI:https://doi.org/ 10.38088/jise.1570132

Research Article

The Impact of Internal Energy Consumption on Efficiency and Emissions in Maritime Transport

Onur Elma [1*], **Özgür T. Kaymakçı** [1], **Hasan Mercan** [2]

[1] *Department of Electrical and Electronics Engineering, Çanakkale Onsekiz Mart University, 17100 Çanakkale, Türkiye*

[2] *Department of Marine Sciences and Limnology, Çanakkale Onsekiz Mart University, 17100 Çanakkale, Türkiye*

ARTICLE INFO

Received Date: 19/10/2024
Accepted Date: 28/02/2025

Cite this paper as:
Elma, O., Kaymakçı, Ö.T., Mercan, H. (2025). *The Impact of Internal Energy Consumption on Efficiency and Emissions in Maritime Transport.*Journal of Innovative Science and Engineering. 9(1): 54-61

*Corresponding author: Onur Elma
E-mail:onurelma@gmail.com

Keywords:
Gen-set Efficiency
Maritime Transport Emissions
Energy consumption
System analysis

ABSTRACT

Maritime transportation plays a crucial role in moving passengers, vehicles, and freight. However, emissions from this sector have become a focus of environmental concerns. Therefore, accurate analysis is important to reduce ship emissions and develop more efficient solutions. The study investigates the energy usage and emissions of a ferry, which is an example of analyzing the impact of internal energy consumption on efficiency and emissions in maritime transport. The analysis concentrates on the fuel consumption of the gen-set. Although the main engine is responsible for most of the ferry's emissions, the gen-set, running at an average load of 37.5%, also significantly contributes to emissions. By using emission factors for pollutants such as CO_2, NOx, SOx, CO, and PM, the study calculated the emissions from both the main engine and the gen-set. The results show that the gen-set is accountable for 10% of the total emissions despite its lower load. These points to the potential for enhancing electrical energy efficiency on board, primarily through load optimization, gen-set modernization, and waste heat recovery. By implementing these strategies, the ferry can decrease fuel consumption, reduce emissions, and transition to a more sustainable and environmentally friendly operation. The findings underscore the importance of focusing on the ferry's electrical energy efficiency to minimize its overall environmental impact.

1. Introduction

As a critical sector that drives a large portion of global trade, maritime transport creates significant environmental impacts in terms of energy consumption and emissions. Traditional fossil fuels used to meet the energy needs of ships result in high greenhouse gas emissions. The environmental issues caused by this have accelerated the industry's pursuit of sustainability and emission reduction. According to the International Maritime Organization (IMO), maritime transport accounts for nearly 2.5% of global greenhouse gas emissions, contributing approximately one billion tons of CO2 annually [1]. This significant environmental impact underscores the importance of targeted efforts to reduce emissions within the shipping sector. The regulations and targets of the International Maritime Organization (IMO) aim to significantly reduce emissions by 2030 and 2050, and in this context, initiatives to increase energy efficiency are encouraged [2].

In addition, an important cause of emissions on ships is the gen-sets that provide the electrical energy demand. In other words, the internal energy consumption of ships is a critical factor that directly affects their efficiency and emissions. As additional information, a gen-set is a combination of a generator and an engine (typically a diesel internal combustion engine). Similarly, load rates refer to the proportion of a generator's maximum rated capacity that is currently being utilized. Higher load rates generally improve fuel efficiency and reduce specific emissions, whereas lower load rates can lead to inefficiencies and increased fuel consumption per unit of power generated. In addition, power quality problems can arise due to electrical disturbances such as voltage fluctuations, harmonics, and reactive power imbalances, which may negatively impact the stable operation of onboard electrical systems, leading to efficiency losses and increased maintenance requirements. In this context, analyzing the impact of internal energy consumption on efficiency and emissions in maritime transportation is of vital importance for the sustainability and future of the sector. Ships consume significant amounts of energy to operate their propulsion systems, generate electricity, power their air conditioning and cooling systems, provide lighting, and meet all other operational needs. This energy consumption increases operating costs by increasing fuel costs, while also causing environmental problems by causing greenhouse gas emissions and air pollution. The impact of internal energy consumption on efficiency is directly related to fuel consumption and therefore emissions. More efficient energy use means less fuel consumption, which provides both economic and environmental benefits. For example, measures such as energy-efficient lighting systems, heat recovery systems, optimized route planning, and speed control can reduce ship energy consumption and increase efficiency.

In terms of emissions, greenhouse gases emitted by ships are a major contributor to global climate change. Recent studies highlight the importance of comparing different maritime transport methods for efficiency and emissions reductions. For instance, hybrid diesel-electric ferries show a 12% improvement in efficiency over traditional full-diesel ferries, while high-speed passenger ships have up to 79% lower efficiency than medium-speed passenger ships. Similarly, energy consumption and emissions analysis of electric container ships suggests that transitioning to electric propulsion can offer substantial environmental benefits. These comparisons provide valuable insights into optimizing maritime energy efficiency [3]. The internal energy consumption of ships directly affects the amount of these emissions. Energy efficiency measures and the use of alternative fuels play an important role in reducing the carbon footprint of ships. In this context, increasing the energy efficiency of ships is an important issue. For this purpose, significant effects can be achieved in the efficiency of gen-sets according to their loading rates. In a study, it was stated that up to 22% emission reductions were achieved when the gen-sets were operated at 80% load rate instead of 40% [4]. In addition, ships are equipped with very different power systems depending on their intended use and design parameters. Hybrid propulsion systems and zero-emission ferry concepts have been studied extensively as potential solutions to reduce fuel consumption and emissions in maritime transport. Energy optimization strategies for small passenger ferries with hybrid propulsion indicate that adopting hybrid and electric propulsion systems can significantly improve efficiency while meeting operational demands [5]. Some ships may even have microgrids. This can lead to an increase in power electronics-based converters, which can lead to power quality problems. Power quality problems are also important in terms of internal consumption efficiency and energy continuity [6]. Pulse loads on some ships, such as cranes, may have an impact on the voltage profile of the power systems. Such voltage fluctuations can also negatively affect the stable operation of gen-sets, causing efficiency problems [7]. The unique off-grid configuration of ships necessitates an in-depth examination of power quality conditions, as the reactive power demand, the primary source of voltage and frequency fluctuations, has the potential to create circumstances that could negatively impact gen-sets. Consequently, existing power quality standards and assessment methodologies might be inadequate to fulfill the distinctive requirements of ship microgrids. The incorporation of novel techniques, such as ship system modeling and signal processing methods, could prove essential for effectively addressing power quality concerns [8]. Different methods can be used to increase the efficiency of gen-sets on ships. One of these studies proposed an optimization method to determine the best operating schedule of gen-sets for the next day of the ship's trip under the pre-trip strategy [9]. In this way, fuel savings and emissions reduction are achieved by operating gen-sets at the most suitable loads. Another solution to reduce emissions is low carbon, LNG etc. fuels [2]. Another study has shown that significant gains in energy and exergy efficiency are achieved with an energy production system operating with the waste heat of the main drive engine [10]. In addition, load sharing applications for gen-set are emerging as an important operational efficiency enhancing measure that does not require any investment among the types of energy saving applications for ships [11]. Another issue is the timing of maintenance of these systems. Proper and periodic maintenance of gen-sets also contributes significantly to efficiency. A study showed a 21.6% reduction in carbon emissions after a timed turbo charger overhaul [12]. Also, alternative energy sources can be used instead of directly from gen-sets to provide the ship's energy needs. For this purpose, energy storage systems and solar and/or wind energy systems can be utilized in existing ships [13]. Thus, significant reductions in ship emission rates can be achieved. When literature studies are examined, it is seen that considerable research has been done on reducing emission releases on ships. In addition, it is seen that the correct determination of ship internal energy consumption and categorization of load demands are not considered necessary, and the focus is more on energy sources and fuel types. However, with today's technological possibilities, the new concept in existing classical electrical networks and the applicability of the dual-sided management logic on ships will provide more effective benefits in maximizing efficiency.

While existing studies on maritime transport emissions focus mainly on fuel types, alternative energy sources, or compliance with environmental regulations, research on internal energy consumption and its direct impact on ship efficiency remains limited. This study fills this gap by providing a detailed case study of a ferry operating in real-world conditions. Unlike previous studies, which often rely on theoretical models or broad estimations, our approach is based on actual operational data, offering a data-driven analysis of gen-set efficiency, load management, and emissions reduction strategies. The results highlight key opportunities for improving energy efficiency by optimizing internal energy consumption, which can be applied to various ship types. Thus, this study contributes to maritime sustainability research by shifting the focus from fuel alternatives to onboard energy optimization, providing a practical framework for industry professionals and policymakers.

In this study, the efficiency potentials in internal electrical energy consumption in ships were categorized and analyzed. In addition, an efficient analysis was made on the parameters of a ferry carrying passengers and vehicles. The effects of reducing emissions, especially on ferries operating close to cities and used effectively on cabotage lines, have been demonstrated.

2. Energy Consumption and Emissions on Ships

Ships are among the most energy-intensive forms of transportation due to their size, propulsion systems, and onboard energy demands. Energy consumption on vessels can be broadly categorized based on different electric load demands, which typically fall into three categories: propulsion systems, auxiliary systems, and passenger loads as given in Figure 1. Understanding the nuances of these load demands and their impact on energy efficiency and emissions is essential for improving ship performance and reducing their environmental footprint.

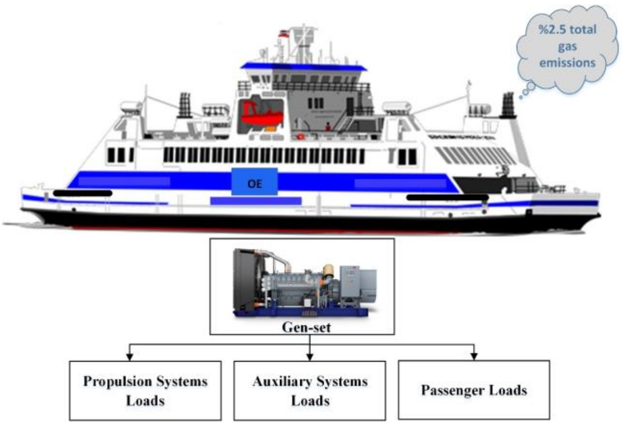

Figure 1: Energy consumption on vessel.

Propulsion Systems: The propulsion system, responsible for moving the vessel, is the largest energy consumer on most ships. This system primarily consists of the main engines, which are powered by marine diesel or heavy fuel oil. Modern ships may also utilize gas turbines or dual fuel engines that can switch between diesel and liquefied natural gas (LNG). The choice of propulsion system heavily influences fuel efficiency and emissions.

Electric propulsion, where the ship's propellers are driven by electric motors instead of mechanical systems, has gained traction in recent years, especially in cruise ships and ferries. Electric propulsion allows for more flexibility in load distribution and can improve efficiency by decoupling engine speed from propeller speed. However, the primary challenge remains the fuel consumption of the gen-set sets that power these electric motors, which, depending on the fuel used, can result in high levels of emissions.

Auxiliary Systems: Auxiliary systems include essential functions such as lighting, ventilation, cargo handling, and navigation equipment. These systems, though not as energy intensive as propulsion, still demand significant power, particularly in large vessels. The trend toward more automated and energy-efficient auxiliary systems has led to reductions in energy consumption. For example, the adoption of LED lighting, energy-efficient HVAC systems, and automated engine management systems contribute to overall fuel savings.

Passenger Loads: Hotel loads refer to the energy used to meet the needs of passengers and crew onboard, particularly on cruise ships and ferries. This includes heating, air conditioning, water desalination, and other amenities. As the demand for luxurious accommodations increases, so do the hotel loads, making energy efficiency improvements in these systems vital for reducing overall fuel consumption. Efficient energy management systems, combined with renewable energy sources such as solar panels for auxiliary loads, have begun to offset some of the energy demand in these areas.

2.1. Emissions from Ships

Emissions from maritime transport have significant environmental implications, particularly in port areas where ship exhaust emissions contribute to local air pollution. Research on cruise port emissions suggests that anchorage limitations and berth constraints can exacerbate air pollution by increasing fuel consumption during maneuvering and berthing. These findings highlight the necessity of energy-efficient solutions and optimized operational strategies to mitigate emissions in ferry and passenger ship operations [14]. Ship emissions are primarily the result of fuel combustion in propulsion engines and onboard gen-sets. These emissions include carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) [15]. The number of emissions produced varies significantly based on the size of the vessel, the type of fuel used, and the operational profile of the ship.

In particular, ferries, which often operate in coastal or inland waters, have characteristic emission profiles due to their frequent stops, variable speeds, and relatively short distances. Ferries typically use large diesel engines for main propulsion and smaller auxiliary gen-sets for onboard power. The emissions from ferries are generally higher in proportion to their size compared to other vessels due to the frequent engine idling and low-speed maneuvers they perform.

Emissions on Ferries: In ferries, the main propulsion engines are the primary source of CO_2 and NOx emissions, particularly when the vessel is at high speeds or under full load. However, gen-sets, which provide power for hotel loads and auxiliary systems, also contribute to emissions, especially when the ferry is docked or operating at lower speeds. On some ferries, gen-sets may account for up to 30-40% of the total emissions, particularly in vessels with high hotel loads (e.g., passenger ferries with substantial lighting, heating, and air conditioning requirements). The emission details relation with ship size and main usage has been given in Table 1 [1].

Table 1: Emission details by ship size and usage.

Ship Size/Type	Main Usage	CO_2 Emissions (tons/year)	NOx Emissions (kg/year)	SOx Emissions (kg/year)
Small (< 5,000 GT)	Coastal ferries	3,000 - 5,000	15,000 - 25,000	5,000 - 7,000
Medium (5,000 - 20,000 GT)	Cargo ships, ferries	10,000 - 25,000	50,000 - 100,000	10,000 - 20,000
Large (> 20,000 GT)	Cruise ships, large tankers	50,000 - 100,000	150,000 - 300,000	50,000 - 80,000

Managing energy consumption and emissions on ships requires an understanding of the ship's load demands, efficient use of propulsion and auxiliary systems, and adherence to global emission regulations. Ferries face unique challenges due to their operational profile, making them a key focus for emission reduction strategies. Therefore, under the following section, a case study is presented on a ferry that operates between the island and mainland of Turkey, transporting both passengers and vehicles. The case study specifically examines the ferry's energy consumption and the associated emission values.

3. Case Study: Internal Energy Consumption in a Ferry

The case study focuses on the energy consumption and emission profile of a ferry operating between the ports of Bozcaada and Geyikli in Turkey which is shown in Figure 2.

The study analyzes how much fuel is consumed by the ferry's main engine and gen-sets, and how this fuel consumption leads to emissions based on the energy demand. Additionally, strategies to reduce these emissions are evaluated, aiming to improve energy efficiency and achieve a more sustainable operation.

The ferry travels approximately 7 km between the two ports. The ferry’s average speed ranges from 7 to 8.5 knots, allowing it to cover the distance in roughly 30 minutes. The ferry operates four trips per day, making it a critical vessel for local transport. The ferry is equipped with:

- Main Engine: 515 kW (1 engine)

- Gen-set: 2 x 120 kW gen-sets, where only one operates at a time

- Average Power Consumption: 45 kW.

The ferry schedule shows four round trips between Geyikli and Bozcaada, as shown in Table 2. Each one-way trip takes approximately 30 minutes. The ferry departs from Geyikli at set times and arrives at Bozcaada 30 minutes later, followed by a return trip starting from Bozcaada. This pattern repeats throughout the day, ensuring consistent travel between the two ports.

Figure 2: A ferry operating between the ports of Bozcaada and Geyikli in Turkey.

Table 2: Schedule of the ferry

Trip No	Departure Time (Geyikli)	Arrival Time (Bozcaada)	Departure Time (Bozcaada)	Arrival Time (Geyikli)	Sailing Duration (minutes)
1	08:00	08:30	09:00	09:30	30
2	11:00	11:30	12:00	12:30	30
3	15:00	15:30	16:00	16:30	30
4	19:00	19:30	20:00	20:30	30

The ferry uses diesel engines for both propulsion and electricity generation. This analysis focuses on the energy consumption and emissions generated by the ferry's main engine and gen-sets. Additionally, the study explores ways to optimize energy efficiency and reduce emissions.

3.1. Emissions and Electrical Energy Consumption in Ferry

Fuel consumption on a ferry primarily comes from two main sources. The first is the main propulsion engine, which is responsible for the vessel's movement and maneuvers [16]. The second source is the gen-set/s, which produce the electrical power required on board. Together, these two systems are the primary contributors to the ship's overall emissions.

While the main engine is the primary source of fuel consumption and emissions, the gen-set also contributes significantly to overall emissions. In this study, the harmful gas emissions were calculated based on the operational characteristics of the ferry’s main engine and gen-set. The carbon emission factor for diesel engines was assumed to be an average of 220 g/kWh [17], [18]. Also, the emission factors of pollutants caused by the engines have been given in Table 3 [19], [20].

$$E = FC \times EF \quad (1)$$

where E represents the emission rate (g/kWh), FC is the fuel consumption in kg/hour, and EF is the emission factor given in grams per kilogram of fuel consumed.

Table 3: Emission factors of pollutants caused by engines.

Pollutant	Full Name	Emission Factor
CO_2	Carbon Dioxide	3.16 kg per kg of fuel
NOx	Nitrogen Oxides	15 g/kWh
SOx	Sulfur Oxides	1.75 g/kWh
CO	Carbon Monoxide	1.5 g/kWh
PM	Particulate Matter	0.15 g/kWh

Using these factors, the emissions of the ferry were estimated per one-way trip, as well as on a daily, monthly, and annual basis. Calculations are made separately for the main engine and gen-set, and their totals are also given. These results are presented in Table 4.

Table 4: The emissions of the ferry were estimated per one-way trip, as well as on a daily, monthly, and annual basis.

Metric	One-Way Trip [kg]	Daily Emissions [kg]	Monthly Emissions [kg]	Yearly Emissions [kg]
CO_2 (Main Engine)	179.014	1432.11	42963.36	522720.88
CO_2 (Gen-set)	15.64	12.51	37.54	45674.64
Total CO_2	194.656	1557.25	46717.44	568395.52
NOx (Main Engine)	38.625	30.9	927	11278.5
NOx (Gen-set)	0.3375	2.7	81	985.50
Total NOx	4.20	33.6	1008	12264
SOx (Main Engine)	0.450625	3.605	108.15	1.315.825
SOx (Gen-set)	0.039375	0.315	9.45	114.975
Total SOx	0.49	3.92	117.6	1430.8
CO (Main Engine)	0.38625	3.09	92.69	1127.85
CO (Gen-set)	0.03375	0.27	8.10	98.55
Total CO	0.42	3.36	100.8	1226.39
PM (Main Engine)	0.038625	0.309	9.27	112.785
PM (Gen-set)	0.003375	0.027	0.81	9.855
Total PM	0.042	0.336	10.08	122.64

From these values, it is clear that the gen-set contributes a smaller portion of the total emissions. However, improving the load factor and energy efficiency of the gen-set can help reduce further these emissions. When operating at low loads, the gen-set's efficiency decreases. By improving load management, the gen-set can operate more efficiently. Also, modernizing the gen-set can result in lower fuel consumption and fewer harmful emissions. Newer gen-set technologies are significantly more efficient and environmentally friendly than older models. Moreover, recovering waste heat can substantially enhance the gen-set's energy efficiency. This recovered energy can be used for other onboard needs, thereby reducing overall energy consumption and fuel use.

3.2. Load Factor and Emission Analysis of Gen-set

The gen-set load factor is the ratio of average power consumption to the gen-set's nominal capacity. The gen-set's nominal capacity is 120 kW, but its average instant consumption is 45 kW. Therefore, the calculated values show that the gen-set operates at around 37.5% load. The fuel consumption for the gen-set is taken as 220 g/kWh. Accordingly, the gen-set's average fuel consumption is calculated as 9.90 kg/hour. Based on this fuel consumption, the emissions from the gen-set have been calculated. Emissions from the gen-set andthe main engine are analyzed separately, and their contributions to total emissions are assessed as percentages, which are given in Table 5.

4. Conclusion

The emissions generated during the widespread use of ferries in urban transportation as well as island transportation have attracted attention due to today's environmental concerns. In this context, it is important to conduct accurate analyses in reducing emissions caused by ferries in order to produce more efficient solutions. An analysis of the ferry's energy consumption and emissions reveals that the main propulsion engine is responsible for most of the fuel consumption and emissions, contributing around 90% to the overall CO_2, NOx, SOx, CO, and PM emissions. However, the ferry's gen-set, while operating at only 37.5% of its nominal capacity, still accounts for approximately 10% of the total emissions. Fuel consumption and emissions can be significantly reduced by optimizing the gen-set's load factor. For instance, improving the load distribution or using energy storage solutions could raise the efficiency of gen-set, resulting in lower emissions. Additionally, modernizing the gen-set with more efficient technology could further reduce the ferry's environmental impact.

On the other hand, this study is based on a single ferry operating between Geyikli and Bozcaada. While the findings provide valuable insights into internal energy consumption and emissions reduction strategies, the results may not be directly generalized to all ship types; however, ferry-type ships may have similar internal energy consumption processes. Different vessel sizes, operational conditions, and power system configurations could influence energy efficiency outcomes. Future research should extend the analysis to multiple vessel types, including cargo ships, large ferries, and cruise liners, to validate the applicability of these findings in diverse maritime contexts.

Article Information Form

Funding

We thank Gestaş Deniz Ulaşım Tic. A.Ş. for their technical support. Also, this work was supported by the Office of Scientific Research Projects Coordination at Çanakkale Onsekiz Mart University, Grant number: FBA-2023-4192.

Authors' Contrtibution

The authors contributed equally to the study.

The Declaration of Conflict of Interest/Common Interest

No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

References

[1] IMO, "Fourth IMO GHG Study 2020 Full Report," *Int. Marit. Organ.*, vol. 6, no. 11, p. 524, 2021, [Online]. Available: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth IMO GHG Study 2020 - Full report and annexes.pdf

[2] Z. Wang, B. Dong, M. Li, Y. Ji, and F. Han, "Configuration of Low-Carbon fuels green marine power systems in diverse ship types and Applications," *Energy Convers. Manag.*, vol. 302, no. October 2023, 2024, doi: 10.1016/j.enconman.2024.118139.

[3] C. C. Chou, H. P. Hsu, C. N. Wang, and T. L. Yang, "Analysis of energy efficiencies of in-port ferries and island passenger-ships and improvement policies to reduce CO2 emissions," *Mar. Pollut. Bull.*, vol. 172, no. July 2021, p. 112826, 2021, doi: 10.1016/j.marpolbul.2021.112826.

[4] K. Yiğit, "Examining the Effect of Generator Load Sharing Practices on Greenhouse Gas Emissions for a Ship," *Konya J. Eng. Sci.*, vol. 10, no. 2, pp. 301–311, 2022, doi: 10.36306/konjes.1056500.

[5] M. Kunicka, "Optimisation of the Energy Consumption of a Small Passenger Ferry with Hybrid Propulsion," *Polish Marit. Res.*, vol. 31, no. 2, pp. 77–82, 2024, doi: 10.2478/pomr-2024-0023.

[6] D. Kumar and F. Zare, "A Comprehensive Review of Maritime Microgrids: System Architectures, Energy Efficiency, Power Quality, and Regulations," *IEEE Access*, vol. 7, pp. 67249–67277, 2019, doi: 10.1109/ACCESS.2019.2917082.

[7] M. Falahi, K. L. Butler-Purry, and M. Ehsani, "Reactive power coordination of shipboard power systems in presence of pulsed loads,"

IEEE Trans. Power Syst., vol. 28, no. 4, pp. 3675–3682, 2013, doi: 10.1109/TPWRS.2013.2253809.

[8] T. Tarasiuk *et al.*, "Review of Power Quality Issues in Maritime Microgrids," *IEEE Access*, vol. 9, pp. 81798–81817, 2021, doi: 10.1109/ACCESS.2021.3086000.

[9] S. I. Taheri, G. G. T. T. Vieira, M. B. C. Salles, and S. L. Avila, "A trip-ahead strategy for optimal energy dispatch in ship power systems," *Electr. Power Syst. Res.*, vol. 192, no. November 2020, 2021, doi: 10.1016/j.epsr.2020.106917.

[10] M. E. Demir and F. Çıtakoğlu, "Design and modeling of a multigeneration system driven by waste heat of a marine diesel engine," *Int. J. Hydrogen Energy*, vol. 47, no. 95, pp. 40513–40530, 2022, doi: 10.1016/j.ijhydene.2022.05.182.

[11] K. Yiğit, "Evaluation of energy efficiency potentials from generator operations on vessels," *Energy*, vol. 257, 2022, doi: 10.1016/j.energy.2022.124687.

[12] A. J. Nyongesa *et al.*, "Experimental evaluation of the significance of scheduled turbocharger reconditioning on marine diesel engine efficiency and exhaust gas emissions," *Ain Shams Engineering Journal*, vol. 15, no. 8. 2024. doi: 10.1016/j.asej.2024.102845.

[13] K. Yiğit, "An Examination of the Potential Usage of Alternative Energy Systems in Ship Technology," *J. Sh. Mar. Technol. J.*, no. December, pp. 2651–530, 2018, [Online]. Available: https://dergipark.org.tr/tr/pub/gdt/issue/42891/518677

[14] G. Ling, C. Han, Z. Yang, and J. He, "Energy consumption and emission analysis for electric container ships," *Ocean Coast. Manag.*, vol. 261, no. August 2024, p. 107505, 2025, doi: 10.1016/j.ocecoaman.2024.107505.

[15] A. Roy and M. Chakraborty, "A review of ship emissions impacts on environmental, health, societal impacts and IMO's mitigation policies," *Reg. Stud. Mar. Sci.*, vol. 81, no. November 2024, p. 103964, 2025, doi: 10.1016/j.rsma.2024.103964.

[16] R. D. Geertsma, R. R. Negenborn, K. Visser, and J. J. Hopman, "Design and control of hybrid power and propulsion systems for smart ships: A review of developments," *Applied Energy*, vol. 194. pp. 30–54, 2017. doi: 10.1016/j.apenergy.2017.02.060.

[17] U.S. Department of Energy, "Fuel Properties Comparison," Alternative Fuels Data Center. Accessed: Sep. 20, 2024. [Online]. Available: https://afdc.energy.gov/files/u/publication/fuel_comparison_chart.pdf

[18] Infineon, "Why ships of the future will run on electricity." Accessed: Oct. 01, 2024. [Online]. Available: https://www.infineon.com/cms/en/discoveries/electrified-ships/

[19] İ. A. Reşitoğlu, K. Altinişik, and A. Keskin, "The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems," *Clean Technol. Environ. Policy*, vol. 17, no. 1, pp. 15–27, Jan. 2015, doi: 10.1007/s10098-014-0793-9.

[20] T. I. Council and on Combustion Engines, "Guide to Diesel Exhaust Emissions Control of NOx, SOx, Particulates, Smoke and CO2," 2008. [Online]. Available: https://www.cimac.com/cms/upload/Publication_Press/Recommendations/Recommendation_28.pdf