National Aviation Academy

International Journal of Transportation Research and Technology

e-ISSN: 3079-6075

DOI: 10.71108/transporttech.vm01is01.03

Research Article

Shipping Towards Decarbonization by Holistic Approach

Mehmet Ziya Sogut*

Piri Reis University, Istanbul, Türkiye

Timescale of article

Received: 31 August 2024
Accepted: 29 November 2024
Published: 24 December 2024

Corresponding author

Mehmet Ziya Sogut
mzsogut@pirireis.edu.tr

Keywords

Shipping, Container Ships, Decarbonization, Efficiencies, Sustainability

Cite this article as:

Sogut, M. Z. (2024). Shipping Towards Decarbonization by Holistic Approach. *International Journal of Transportation Research and Technology*, 1(1), 30-41. DOI: 10.71108/transporttech.vm01is01.03

Abstract

Despite increasing sectoral demand, maritime transport should improve its ability to manage its fossil fuel-based environmental impacts. In particular, it is important that the International Maritime Organization (IMO) develops regulations in this context and works to support this change in sectoral structures. This study examines the performance of container ships, which are widely used in the sector, with a holistic approach depending on possible consumption patterns. Energy and exergy efficiencies based on the first and second laws of thermodynamics were found to be 39.99% and 22.62% respectively. On the other hand, the improvement rate (IP value) was determined to be 54.26%. At the end of the study, recommendations were developed, in particular on possible action steps towards decarbonization.

1. Introduction

The maritime industry, which accounts for approximately 90% of global trade and economic activity, is acutely aware of its responsibility in addressing climate change and is engaged in a significant transformation to eliminate its environmental impacts. Maritime transport, which has traditionally relied on fossil fuels, is a substantial contributor to global greenhouse gas (GHG) emissions, accounting for an average of 3% of such emissions and being energy intensive (IMO, 2021; Zhuo & Wang, 2022). Efforts to combat climate change, which have developed under the responsibility of sectoral stakeholders, have now gained a new structure with decarbonization targets under the responsibility of the International Maritime Organization (IMO) (IMO, 2021). The maritime sector has a considerable impact on global CO_2 emissions due to its reliance on fossil fuels. In the context of rising demand, fuel consumption in this sector is largely uncontrolled, largely due to the competitive nature of the industry. The primary emission sources in the sector are the combustion of heavy fuel oil (HFO) and marine diesel oil (MDO) in ship engines (Seyam et al., 2023; Sogut, 2024a). In particular, maritime transport is dependent on technologies that have a direct impact on the emission of pollutants beyond CO_2, including sulphur oxides (SOx) and nitrogen oxides (NOx). While these contribute to an increase in global emissions, they also give rise to air quality issues and present a threat to the sustainability of the environment. In this context, the International Maritime Organization (IMO) has established ambitious targets with the objective of reducing greenhouse gas emissions from shipping. Among the key milestones, the objective of achieving a 50% reduction in total annual greenhouse gas emissions by 2050 in comparison to 2008 levels has been identified as a priority target, with the aspiration to achieve zero emissions in the long term (IMO, 2021). These targets have been supported by a number of interim measures, including the introduction of stricter regulations governing the sulphur content of fuels and the implementation of improved energy efficiency standards for newbuilds. Nevertheless, the decarbonization objective, along with all IMO initiatives, has been conceptualized in a more comprehensive manner, thereby facilitating the evolution of a forward-thinking approach. The decarbonization trajectory is beset with challenges, including the high cost of new technologies, the necessity to develop infrastructure (e.g. refueling stations for alternative fuels) and the complexity of retrofitting existing vessels (Ammar & Seddiek, 2023). However, these challenges also present opportunities for innovation, investment and leadership in the sector, given the intensity and conventionality of industry processes and the rapid pace of change. In practice, the maritime sector requires the collaboration of numerous stakeholders, including governments, shipping companies, technology providers and research institutions, to surmount these challenges. The establishment of public-private partnerships and the promotion of international cooperation in advancing the requisite technological developments and policy frameworks provide the fundamental structures for the future sustainable growth of the sector.

The entropy-based approach represents a robust analytical and engineering methodology that can be effectively deployed across a range of disciplines, including thermodynamics, information theory and optimization. It offers a valuable means of evaluating the environmental impact of systems. The concept of entropy, which measures the degree of disorder or uncertainty due to irreversibilities in a system, forms the basis of this approach. In the context of system solutions and applications, the entropy integral approximation algorithm facilitates the generation of efficient results for structural evaluations conducted directly within the system and its interactions with the surrounding environment (Barbieri et al., 2011; Sogut, 2024b). This approach enables the optimization of performance. In general, entropy is understood as a quantitative measure of the level of uncertainty or irreversibility in a system. In thermodynamics, entropy is employed as a quantitative measure of the amount of energy that cannot be harnessed for work due to the presence of irreversibilities within a system. In this regard, it can be regarded as an efficacious instrument, particularly in the context of CO_2 emission regulation pertaining to thermal processes. It is evident that the utilization of existing engine technologies in the maritime sector has the potential to result in a considerable increase in entropy, largely due to the reliance on fossil-based consumption. The primary issue is that it has both environmental implications and potential implications in terms of sectoral responsibilities. In this context, the present study begins with a case study to demonstrate the impact of maritime transport as a sectoral factor. The container example was taken as a basis for evaluation of the potential for entropy-based improvements in the sector, employing an integrated methodology. In particular, this study examines the potential for reducing the irreversibility associated with fossil fuel consumption in terms of power consumption and its environmental consequences.

2. Shipping's Role in Decarbonization

This chapter presents an analysis of the sectoral framework for decarbonization, with a particular focus on the frameworks designed to avoid or reduce overall sectoral carbon dioxide emissions. One of the principal concerns associated with rising carbon dioxide levels in the maritime sector is the fact that the environmental impact caused by sectoral demands, along with increasing fossil fuel consumption, is on an upward trajectory. Furthermore, there are significant threats such as global warming and climate change, which are leading to rising sea levels and an increase in natural disasters caused by global emissions. The maritime sector, which plays a key role in global logistics, is expected to contribute significantly to greenhouse gas emissions. Therefore, sectoral responsibilities make significant measures valuable, while decarbonization has emerged as an important goal in the sector. As can be seen in Fig. 1, according to Statista, ocean and maritime shipping accounted for 11% of global shipping sector carbon dioxide emissions in 2020.

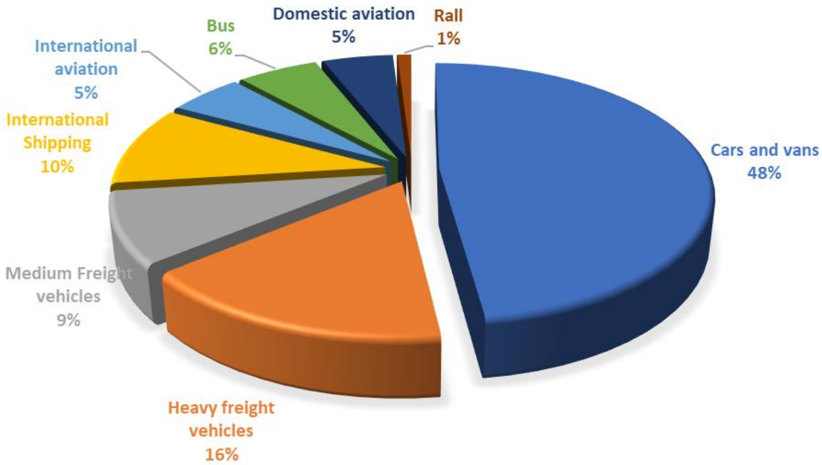


Fig. 1. Distribution of carbon dioxide emission produced by transportation 2022 (Modified from Statista, 2024)

To address this challenge, the maritime sector must embrace a multi-faceted approach to decarbonization. This includes adopting cleaner technologies, improving energy efficiency and exploring alternative fuels (Oloruntobi et al., 2023). Key strategies for reducing emissions in shipping include (Oloruntobi et al., 2023; Koukaki & Tei, 2020; Chuah et al., 2023):

Investing in Innovative Technologies: Advances in technology offer promising solutions for reducing emissions. The development of more efficient engines, the use of renewable energy sources such as wind and solar power and the implementation of electric or hybrid propulsion systems are critical steps toward lowering the carbon footprint of ships.

Enhancing Energy Efficiency: Improving the energy efficiency of ships is essential for reducing fuel consumption and emissions. This can be achieved through measures such as optimizing hull designs, utilizing advanced coatings to reduce drag and implementing energy-saving devices like air lubrication systems.

Adopting Alternative Fuels: Transitioning to alternative fuels like liquefied natural gas (LNG), hydrogen, ammonia and biofuels can significantly cut emissions. These fuels can offer cleaner combustion and lower greenhouse gas emissions compared to traditional marine fuels.

Implementing Operational Measures: Efficient operational practices, such as optimizing routes, reducing speed and better managing cargo loads, can also reduce emissions. These measures can help ships operate more efficiently and minimize their environmental impact.

Regulatory and Market Incentives: Governments and international bodies play a crucial role in supporting decarbonization through regulations and incentives. Policies such as the International Maritime Organization's (IMO) greenhouse gas strategy and carbon pricing mechanisms can drive the industry toward more sustainable practices. By integrating these strategies, the shipping industry can make significant strides toward reducing its carbon footprint and contributing to global decarbonization efforts. The transition to a greener maritime sector is essential for mitigating climate change and ensuring the long-term sustainability of global trade and transport. Decarbonizing the shipping industry is a complex but crucial undertaking, requiring coordinated efforts across technology, operations and policy. Here are the key steps to achieve a more sustainable maritime sector:

Adoption of Cleaner Technologies

Advanced Propulsion Systems: Invest in and implement innovative propulsion technologies, such as electric and hybrid systems, which reduce reliance on fossil fuels and lower emissions.

Renewable Energy Integration: Utilize renewable energy sources like wind, solar and hydrogen fuel cells to power ships or supplement existing power systems.

Energy Efficiency Improvements

Hull and Propeller Design: Optimize ship hull designs and propeller configurations to reduce drag and enhance fuel efficiency.

Energy-Saving Devices: Install technologies such as air lubrication systems, energy-saving devices and waste heat recovery systems to improve overall energy efficiency.

Smart Navigation Systems: Employ advanced navigation tools and software to optimize routes and reduce fuel consumption.

Alternative Fuels

Liquefied Natural Gas (LNG): Transition to LNG, which burns cleaner than traditional marine fuels and produces fewer emissions.

Hydrogen and Ammonia: Explore hydrogen and ammonia as zero-emission fuels. Both have the potential to significantly reduce greenhouse gas emissions.

Biofuels: Use biofuels derived from renewable sources to reduce reliance on fossil fuels and lower carbon emissions.

Operational Efficiency

Speed Optimization: Implement slow steaming practices to reduce fuel consumption and emissions by operating ships at lower speeds.

Load Management: Optimize cargo loads and improve ballast management to enhance fuel efficiency and minimize emissions.

Voyage Planning: Utilize data analytics and voyage optimization software to plan more efficient routes and reduce unnecessary fuel consumption.

Regulatory Compliance and Innovation

International Regulations: Adhere to international regulations and guidelines, such as those set by the International Maritime Organization (IMO), which aim to reduce greenhouse gas emissions and promote sustainability.

Carbon Pricing and Emission Trading: Engage with carbon pricing mechanisms and emission trading schemes to incentivize the reduction of greenhouse gas emissions and support the development of low-emission technologies.

Investment in Research and Development

Innovative Solutions: Support and fund research into new technologies and practices that can advance decarbonization, such as alternative fuels and energy-efficient technologies.

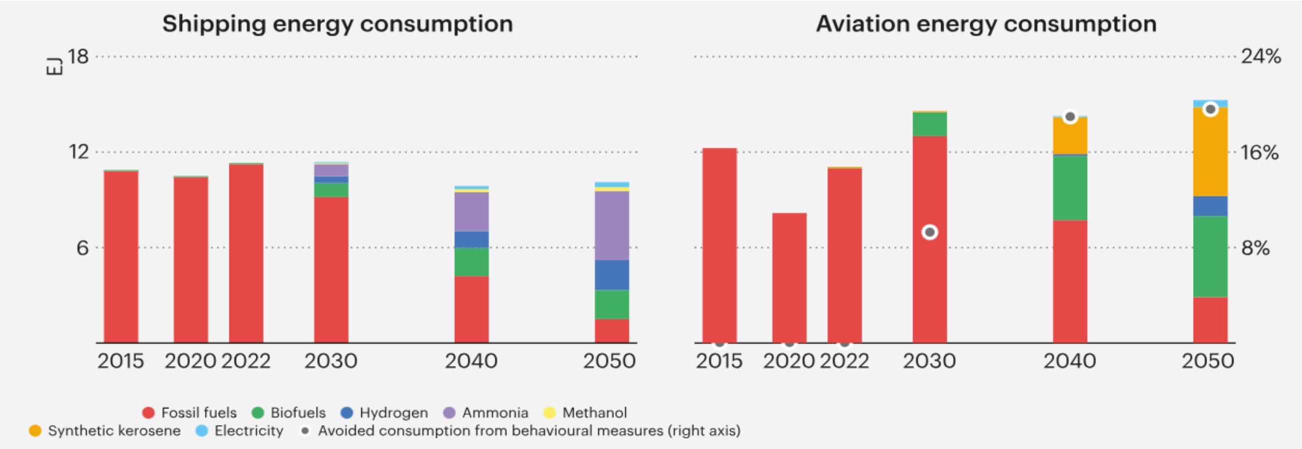
Collaboration and Partnerships: Collaborate with stakeholders, including governments, research institutions and technology providers, to drive innovation and accelerate the transition to a low-carbon shipping industry.

Training and Awareness

Crew Training: Provide training for crews on new technologies, efficient operational practices and environmental regulations to ensure effective implementation of decarbonization measures.

Industry Awareness: Promote awareness of the importance of decarbonization and encourage industry-wide adoption of sustainable practices.

By systematically implementing these steps, the shipping industry can make significant progress toward reducing its carbon footprint, mitigating the impacts of climate change and contributing to a more sustainable future for global trade and transport.



Milestones	2022	2030	2035	2050
Shipping				
International shipping activity (trillion tonne-kilometres)	125	145	165	265
Share in final energy consumption				
Biofuels	0%	8%	13%	19%
Hydrogen	0%	4%	7%	19%
Ammonia	0%	6%	15%	44%
Methanol	0%	1%	1%	3%
Aviation				
International and domestic aviation activity (trillion revenue passenger-kilometres)	6.0	10.9	11.4	16.5
Avoided demand from behavioural measures	0%	9%	14%	20%
Share in final energy consumption				
Biofuels	0%	10%	22%	33%
Synthetic hydrogen-based fuels	0%	1%	4%	37%

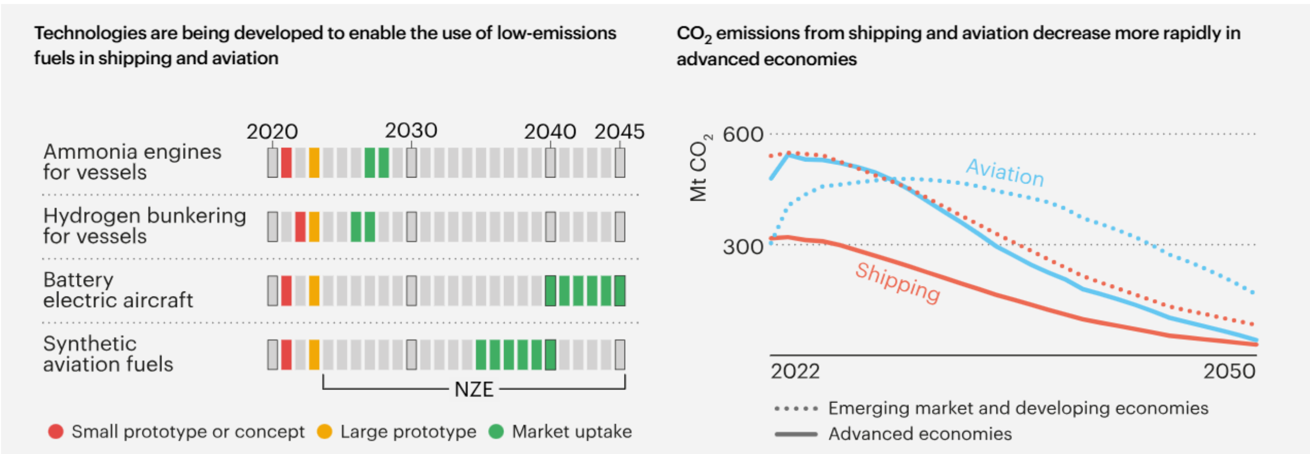


Fig. 2. Emission road of Shipping and Aviation towards 2050 (IEA, 2023)

The aforementioned structural requirements serve as indicators that signal impending change within the transport sector. In particular, the sectoral roles of aviation and maritime transport demonstrate considerable potential for effective action in this regard. In the present era, the instruments that precipitate sectoral transformation directly entail the implementation of structural instruments, particularly those pertaining to low-carbon technologies. The advent of new opportunities, particularly in the domain of energy sustainability, has the potential to facilitate the control and management of CO_2 emissions. Alternative options such as LNG, hydrogen and ammonia in the maritime sector, along with the proposed sectoral studies on carbon-free fuel preferences, offer promising avenues in this regard. Indeed, the International Energy Agency (IEA) has developed a framework study encompassing both sectors with respect to 2050 targets. According to this report; the projected growth in the consumption of bioenergy, hydrogen and hydrogen-based fuels in the shipping and aviation sectors is set to increase from less than 1% of total energy consumption today to nearly 15% by 2030 and up to 80% by 2050. Furthermore, in order to achieve significant decarbonisation in these two transport modes, enhanced energy efficiency in shipping by 2030 and demand reduction driven by behavioural changes in aviation by 2050 will be essential. The sectoral framework is subjected to a separate analysis in the report, with a breakdown provided in Fig. 2.

3. Holistic Approach for Engineering

A holistic approach (Fig. 3) to engineering entails the integration of diverse perspectives and disciplines, the simplification of the problem domain and the comprehensive addressing of complex problems. In contrast to a narrow focus on technical specifications or isolated components, this approach emphasises the interconnectedness of systems, taking into account how engineering solutions affect and are affected by social, environmental and economic factors. By adopting principles from areas such as systems thinking, sustainability and human-centred design, engineers can develop solutions that not only meet functional requirements but also promote long-term resilience and benefit society as a whole. This broader perspective ensures that engineering projects are not only effective, but also ethical and sustainable and address both current and prospective needs.

Fig. 3. Holistic approach for engineering (Modified from; Torres, 2014)

The holistic approach offers a perspective that directly supports decision-making processes in terms of the holistic effects of thermodynamic systems (Close et al., 2024; Blondel-Canepari et al., 2024). Thermodynamic laws offer a foundational methodology for engineering solutions. The First and Second Laws of Thermodynamics represent the fundamental principles that govern the behaviour of energy in physical systems. The First Law, also known as the Law of Conservation of Energy, postulates that energy cannot be created or destroyed, but rather transformed from one form to another. This law serves to reinforce the fundamental principle that the total energy of an isolated system remains constant. In practical terms, this signifies that the quantity of energy entering a system and the quantity of energy exiting the system must be equal to the variation in the internal energy of the system. This principle is of paramount importance to the comprehension and engineering design of systems where energy transformations are a fundamental aspect of their functionality. To illustrate, in a heat engine, thermal energy is transformed into mechanical work, yet the total amount of energy remains unaltered in accordance with the First Law. The Second Law of Thermodynamics introduces the concept of entropy, which may be defined as a measure of disorder or randomness in a system. The second law of thermodynamics states that in any natural thermodynamic process, the total entropy of a system and its environment always increases with time. This implies that energy transformations are inherently inefficient, with some of the energy dissipated as heat, which causes entropy to increase. It also emphasises the direction of spontaneous processes, indicating that systems evolve towards greater disorder and equilibrium. The thermodynamic approach guides the design and optimisation of energy systems, improving efficiency and informing understanding of natural phenomena. The analysis of fossil fuel-dependent processes is conducted in relation to mass flow dynamics. These dynamics are examined under steady-state conditions and equilibrium, as described by Cengel and Boles (2014) and Moran et al. (2011). This approach focuses on the energy flow inherent in processes and cycles across all systems. By applying an energy balance to identified energy users, insights can be gained into the environmental consequences of energy use in transportational vehicles.

$$\dot{Q} - \dot{W} + \sum \dot{E}_{in} - \sum \dot{E}_{out} = 0 \tag{1}$$

Where, $\dot{Q}$ and $\dot{W}$ are the net heat and net work produced from boundaries of the system input and output. This structure is directly related to the quantitative values resulting from the defined mass flows. For dead state conditions where energy systems exist, the real extent of possible irreversibility is related to exergy analyses. For such systems and their components, the exergy balance as a function of the dead state temperature for each user behaviour is as follows;

$$\sum(1 - \frac{T_0}{T_k})\dot{Q}_k - \dot{W} + \sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \dot{E}x_{dest} = 0 \tag{2}$$

$\dot{Q}_k$ refers to the heat transfer rate of passing from boundaries of the system, Ex states to the exergy flow of the system passing from boundaries, $\dot{E}x_{dest}$ refers to the exergy destruction of the flow related to seeing the limits of the irreversibility. Flow-induced exergy flow for the system where there is a phisycal processes (ψ);

$$\psi = (h - h_0) - T_0(s - s_0) \tag{3}$$

ψ –Flow exergy (kW)

h –Enthalpy (kJ/kg)

T_0 –Surrounding temperature (K or °C)

s –Entropy (kW/K.kg)

Exergy flow is directly based on the enthalpy (h) and the entropy (s) potentials at the surrounding temperature (T_0) (Cornelissen, 1997). The degree of irreversibility of the system, which refers to the environmental influence in processes, depends directly on the amount of entropy produced. The Gouy-Stodola theorem states that the environmental influence for entropy production is directly due to the irreversibility in the system and depends on the exergy destruction (Moran et al., 2011; Dincer & Rosen, 2012):

$$\dot{E}x_{dest} = T_0\dot{S}_{gen} \tag{4}$$

$\dot{E}x_{dest}$ –Exergy destruction (kW)

T_0 –Surrounding temperature (K)

$\dot{S}_{gen}$ –Entropy generation (kW/K)

All structures consume energy and their environmental performance is a function of their efficiency. In particular, in exergy analysis, the performance of systems depends directly on the effect of the work produced. In fact, the exergy efficiency of a system is defined by the standard exergy efficiency, which is developed based on the data obtained at the inlet and outlet conditions of the flow process. In this context, exergy efficiency is used (Moran et al., 2011);

$$\eta_{Ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{5}$$

η_{Ex} –Exergy Efficiency

$\sum \dot{E}x_{in}$ –Total Exergy input (kW)

$\sum \dot{E}x_{out}$ –Total Exergy output (kW)

$\dot{E}x_{dest}$ –Exergy destruction (kW)

All processes are subject to an assessment in terms of their operational issues and potential for improvement. An important indicator for reducing environmental impact is the potential for improvement in entropy production. Improvement potential for such processes (Van gool, 1997):

$$\dot{IP} = (1 - \eta_{Ex})(\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out}) \quad (6)$$

IP−Improvement rate (kW)

η_{Ex} −Exergy Efficiency

$\sum \dot{Ex}_{in}$ −Total Exergy input (kW)

$\sum \dot{Ex}_{out}$ −Total Exergy output (kW)

4. Results and Discussion

This study presents an entropy-based model to demonstrate the environmental impact of maritime transport. It takes container transport, which has significant potential in maritime transport, as a basis and assesses the environmental impact and potential for improvement in the sector from a holistic perspective. The data obtained directly points to a proposed potential for the development of decarbonisation. The data used in the study is directly based on the European Union (EU) maritime sector report. It refers to a holistic assessment of the diesel consumption and possible power ranges of the container ships used as reference in the study. The data relating to the container ships used as reference in the study are shown in Fig. 4.

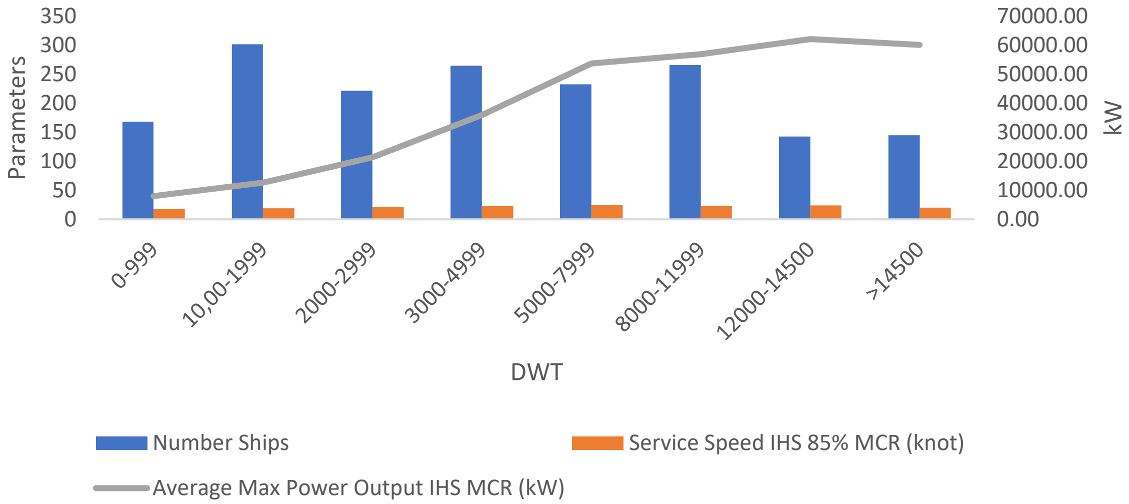


Fig. 4. Data of container

Container ships are divided into eight categories. These distributions can be seen directly as reference values defined for the average power and fuel consumption of the ships. Based on these data, the energy consumption performance of the ships was calculated separately and their energy efficiency was considered separately based on their unit fuel consumption behaviour. The distributions are shown in Fig. 5.

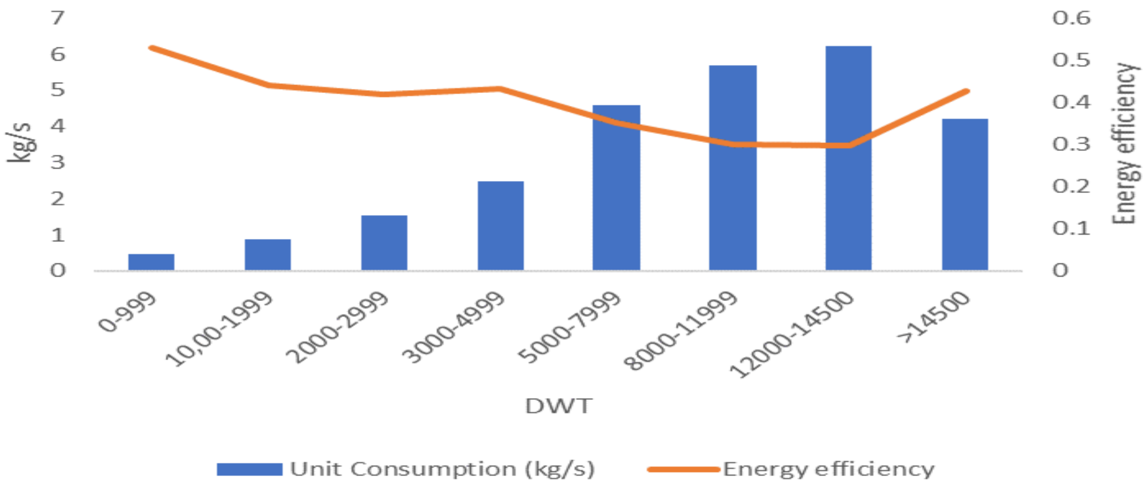


Fig. 5. Energy efficiency for average unit consumption

The average unit consumption of the vessels varies between 0.45 kg/s and 6.2 kg/s, while the efficiency scale shows a variation between approximately 29% and 53%. The most efficient structures are container consumptions in the range 0-999 DWT. The most efficient group within this structure are the ships in the 12000-14000 DWT range. This consumption performance of the vessels was evaluated together with the demand directly related to the engine power. Accordingly, their distribution is shown in Fig. 6.

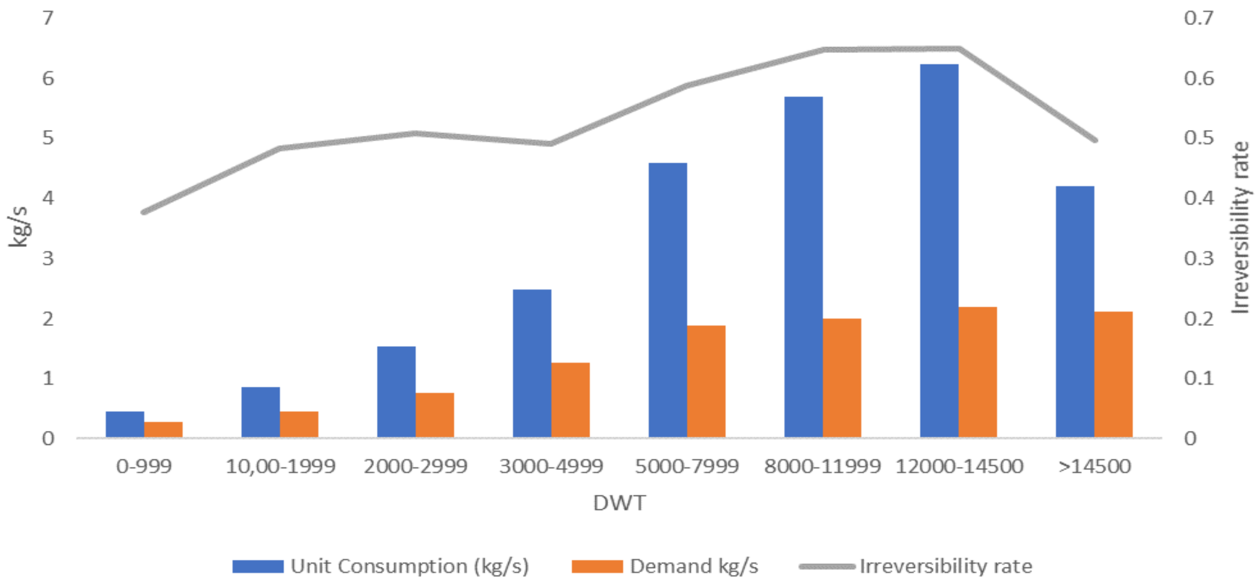


Fig. 6. Demand management of the ships considering irreversibility rate

Irreversibility in ships is the most important problem area that can be defined for process control. The actual energy requirement due to thermal necessity in ships is considered as demand. By comparing the consumption behaviour of the ship with the possible demand, the possible irreversibility rate can be found. While the average consumption for these ships is 3.26 kg/s, the actual consumption demand required by the engines is calculated as 1.37 kg/s. According to this consumption behaviour, the overall irreversibility rate of the ships is found to be approximately 58%. This value is a problem point in terms of consumption behaviour of ships. The consumption behaviour of the ships was evaluated with reference to 25 C ambient and 1 Atm pressure conditions. Accordingly, the exergy performance of the ships is given in Fig. 7.

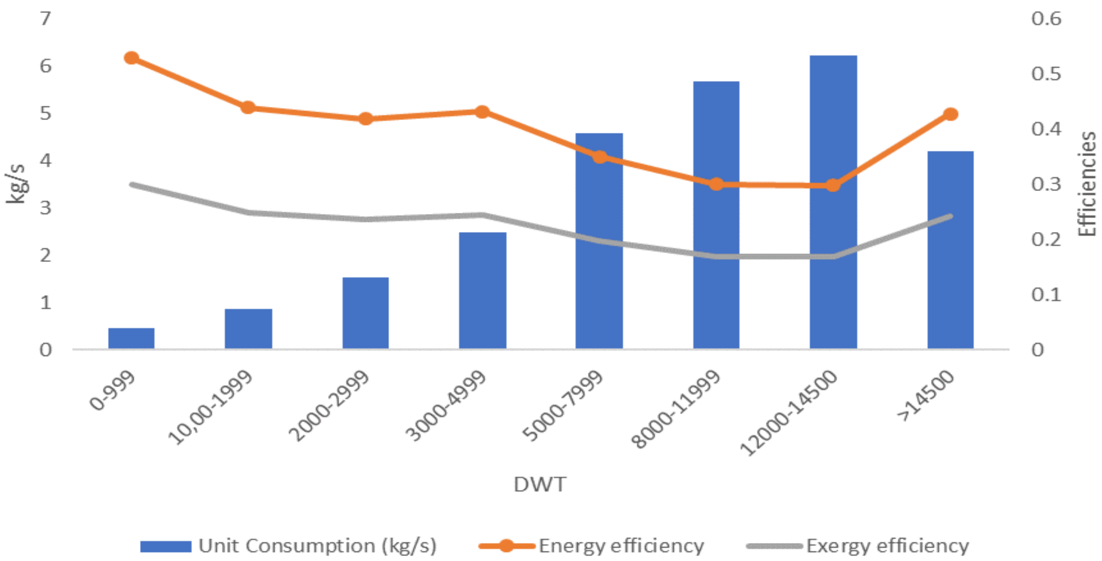


Fig. 7. Efficiencies and unit consumptions

While energy efficiency expresses a quantitative value in terms of thermodynamics, exergy efficiency directly expresses the quality of irreversibility in the environmental conditions defined for ships. In this respect, the exergy efficiency of ships directly shows a dimension of the maximum work they can produce in the environmental conditions in which they are located. While the average exergy efficiency for the defined structures is 22.62%, it shows that the efficiency range varies between 16.89% and 29.99%. Exergy efficiency can also be seen as a measure of exergy destruction and its rate of evolution. The exergetic parameters for the reference ships are shown in Fig.8.

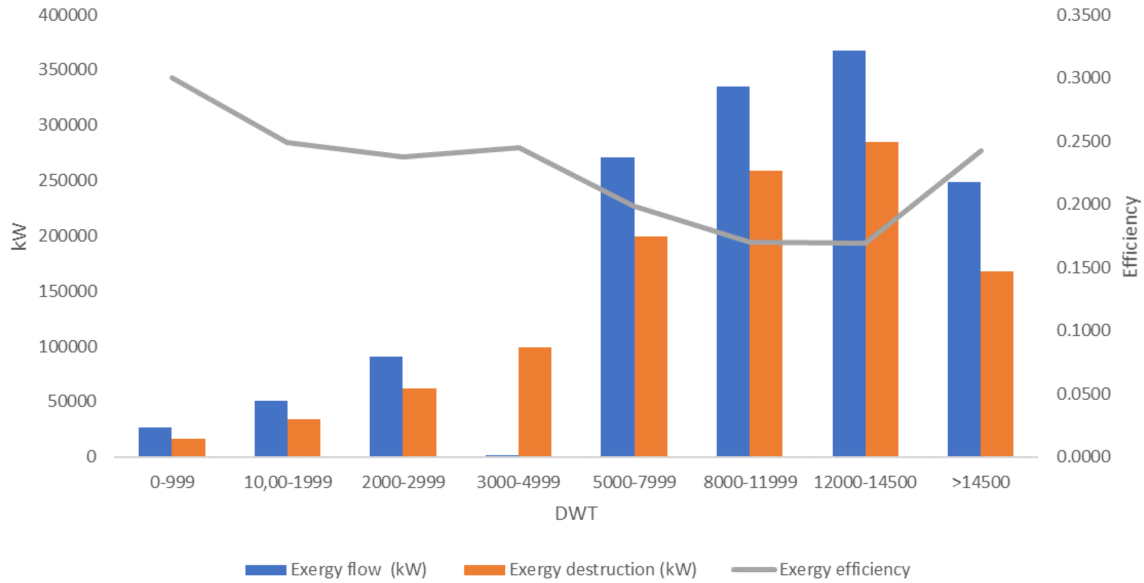


Fig. 8. Exergetic parameters

According to the exergy flows, it can be seen that the linearity of the consumption behaviour has changed, especially for ships above 8000 DWT. This structural effect has a direct impact on ship performance and consumption efficiency. The effect of the consumption behaviour of the ships directly affects the exergy destruction and entropy production in the ships. These consumption perturbations can be due to many reasons together with operational uncontrolled. For this reason, it would be a good choice to control the operational data in terms of process engineering. However, especially the exergy destruction should be considered together with possible improvements in the ships. For this purpose, the Improvement Rate (IP) and its potential effects are shown in Fig. 9.

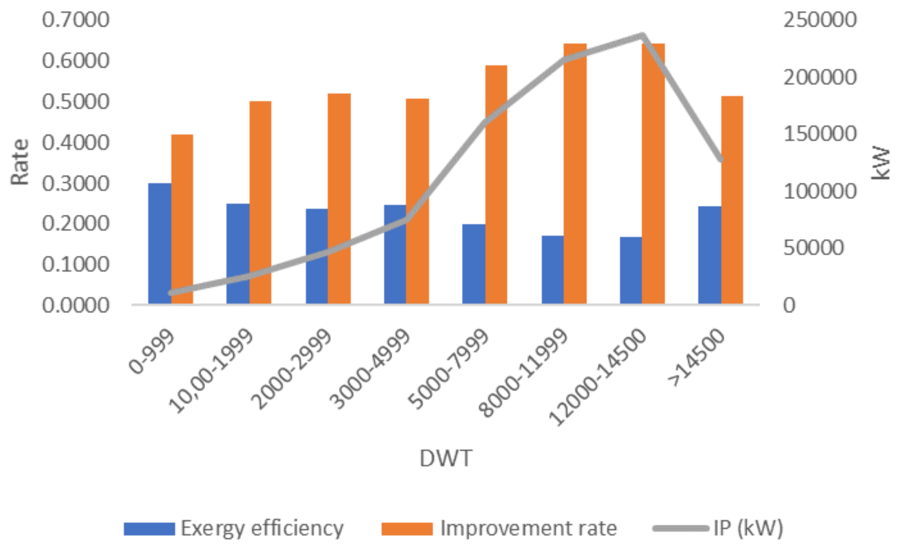


Fig. 9. IP rate of the ships

According to the analyses, the average IP rate for ships was found to be 54.26%. However, the IP rate varies between 42.01% and 64.39%. This value shows how large the irreversibility is for exergy flow. The improvement rate due to exergy flow can be expressed as a rational value for engineering solution. As seen in this study, engine efficiency for container ships shows similar characteristics to literature examples (Tian et al., 2021). This provides information on the evaluation of direct energy performance, especially for diesel engines and their environmental pollution potential due to their irreversibility.

5. Conclusions

This study has been developed primarily to show the impact potential of maritime transport and the energy and exergy analysis of the reference container ships with a holistic approach. In this context, the performance data of the referenced container ships are as follows.

1. The average energy efficiency of the referenced container ships is 39.99.
2. While the average exergy efficiency of the ships is 22.62%, the exergy destruction rate is 77.38.
3. The IP rate due to exergy flow in ships was found to be 54.26% on average.

In this developed approach, it should first be noted that there is an average impact potential of 54.26% for decarbonisation in ships. Process approaches and operational control strategies should primarily be addressed as the reasons for this value. In addition, environmental impact assessments on ships can also be developed as a criterion in this context. In addition to this holistic approach, entropy based environmental impact assessments will provide more realistic results. In particular, the decarbonisation roadmap can be considered as a framework for future studies.

Abbreviations

DWT : Dead Weight Tonnage

IEA : International Energy Agency

IMO : International Maritime Organization

IP : Improvement Potential

References

Ammar, N. R. & Seddiek, I. S. (2023). Hybrid/dual fuel propulsion systems towards decarbonization: Case study container ship. *Ocean Engineering*, 281, Article 114962. https://doi.org/10.1016/j.oceaneng.2023.114962

Barbieri, A. L., De Arruda, G. F., Rodrigues, F. A., Bruno, O. M. & Da Costa, L. F. (2011). An entropy-based approach to automatic image segmentation of satellite images. *Physica A: Statistical Mechanics and its Applications*, 390(3), 512-518. https://doi.org/10.1016/j.physa.2010.10.015

Blondel-Canepari, L., Sarritzu, A. & Pasini, A. (2024). A holistic approach for efficient greener in-space propulsion. *Acta Astronautica*, 223, 435-447. https://doi.org/10.1016/j.actaastro.2024.07.023

Cengel, Y. A. & Boles, M. (2014). *Thermodynamics: an engineering approach* (8th ed.). McGraw-Hill Education.

Chuah, L. F., Mokhtar, K., Ruslan, S. M. M., Abu Bakar, A., Abdullah, M. A., Osman, N. H., Bokhari, A., Mubashir, M. & Show, P. L. (2023). Implementation of the energy efficiency existing ship index and carbon intensity indicator on domestic ship for marine environmental protection. *Environmental Research*, 222, Article 115348. https://doi.org/10.1016/j.envres.2023.115348

Close, J., Barnard, J. E., Chew, Y. M. J. & Perera, S. (2024). A holistic approach to improving safety for battery energy storage systems. *Journal of Energy Chemistry*, 92, 422-439. https://doi.org/10.1016/j.jechem.2024.01.012

Cornelissen, R. L. (1997). *Thermodynamics and sustainable development: the use of exergy analysis and the reduction of irreversibility* [PhD thesis, University of Twente].

Dincer, I. & Rosen, M. A. (2012). *Exergy: Energy, Environment and Sustainable Development*. Elsevier Science.

International Energy Agency (IEA). (2023). *Aviation and shipping*. https://www.iea.org/reports/aviation-and-shipping

International Maritime Organization (IMO). (2021). *International Maritime Organization Fourth Greenhouse Gas Study* 2020. https://www.maritimecyprus.com/wp-content/uploads/2021/03/4th-IMO-GHG-Study-2020.pdf

Moran, M. J., Shapiro, H. N., Boettner, D. D. & Bailey, M. B. (2011). *Fundamentals of engineering thermodynamics*. John Wiley & Sons Inc.

Oloruntobi, O., Mokhtar, K., Gohari, A., Asif, S. & Chuah, L. F. (2023). Sustainable transition towards greener and cleaner seaborne shipping industry: Challenges and opportunities. *Cleaner Engineering and Technology*, 13, Article 100628. https://doi.org/10.1016/j.clet.2023.100628

Seyam, S., Dincer, I. & Agelin-Chaab, M. (2023). A comprehensive assessment of a new hybrid combined marine engine using alternative fuel blends. *Energy*, 283, Article 128488. https://doi.org/10.1016/j.energy.2023.128488

Sogut, M. Z. (2024a). Entropy-based environmental analyses of marine fuel preferences for onboard ships. *Energy*, 305, Article 132260. https://doi.org/10.1016/j.energy.2024.132260

Sogut, M. Z. (2024b). Assessment of entropy-based approach for the environmental impact of the cooling process in clinker production. *International Journal of Exergy*, 44(3/4), 227-243. https://doi.org/10.1504/IJEX.2024.140176

Statista. (2024). *Decarbonization Shipping Industry And Maritime Transport*. https://www.statista.com/statistics/1185535/transport-carbon-dioxide-emissions-breakdown/

Koukaki, T. & Tei, A. (2020). Innovation and maritime transport: A systematic review. *Case Studies on Transport Policy*, 8(3), 700-710. https://doi.org/10.1016/j.cstp.2020.07.009

Tian, Z., Zeng, W., Gu, B., Zang, Y. & Yuan, X. (2021). Energy, exergy, and economic (3E) analysis of an organic Rankine cycle using zeotropic mixtures based on marine engine waste heat and LNG cold energy. *Energy Conversion and Management*, 228, Article 113657. https://doi.org/10.1016/j.enconman.2020.113657

Torres, S. (2014). *Next-Generation MRM: Getting a Big Bang from Breaking Down Traditional Silos*. Talking Logistics. https://talkinglogistics.com/2014/05/15/next-generation-mrm-getting-big-bang-breaking-traditional-silos/

Van Gool, W. (1997). Energy policy: fairy tales and factualities. In O. D. D. Soares, A. M. da Cruz, G. C. Pereira, I. M. Soares & A. J. Reis (Eds.), *Innovation and Technology Strategies and Policies* (pp. 93-105). Springer, Dordrecht. https://doi.org/10.1007/978-0-585-29606-7_6

Zhuo, R. & Wang, H. (2022). Decarbonising Shipping and the Role of LNG: International Law and Policy Trends. In D.S. Olawuyi & E.G. Pereira (Eds.), *The Palgrave Handbook of Natural Gas and Global Energy Transitions* (pp. 319-343). Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-91566-7_13