National Aviation Academy

International Journal of Transportation Research and Technology

e-ISSN: 3079-6075

DOI: 10.71108/transporttech.vm02is01.02

Research Article

Energy Audit and Management in Shipping: A Case Study Onboard Ship

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Timescale of article

Received: 18 February 2025
Accepted: 25 April 2025
Published: 21 June 2025

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Keywords:

Shipping, Energy Management, Chemical Tanker, Efficiency, Sustainability

Cite this article as:

Sogut, M. Z. (2025). Energy Audit and Management in Shipping: A Case Study Onboard Ship. *International Journal of Transportation Research and Technology*, 2(1), 22-36.
DOI: 10.71108/transporttech.vm02is01.02

Abstract

The sectoral priorities of maritime transportation are expected to focus on reducing fossil fuel-based environmental pollution and shaping sustainable energy management. Despite the International Maritime Organization's (IMO) regulations in this context, the prioritization of energy efficiency and the improvement of its manageability in ships are still anticipated. This study thoroughly examines the energy efficiency and management of a reference chemical tanker, with a particular emphasis on performance and environmental efficiency. The analysis indicates that there is a need for defining energy efficiency targets and improving the optimization process. Based on the ship's load rate and energy consumption behaviors, parameters for energy efficiency rates have been developed, and the environmental impact of the ship can be evaluated using an entropy-based approach. According to histogram analyses, the first energy efficiency target is set at 8.80%, and the second target at 32.58%. Energy efficiency analyses indicate that environmental pollution is approximately 57%, while the entropy approach calculates the energy efficiency rate of the ship at 17.96%. This study should be evaluated as an example of energy audit assessment and exergy analysis for environmental impact assessment to gain energy management behaviour for ships. It provides a contribution to the energy management structure of ships. This study provides an approach for the holistic assessment framework of energy efficiency on ships. It reveals the environmental impact potential for the entropy-based consumption potential of energy consumption. It provides a framework for decision processes.

1. Introduction

Energy management and efficiency have become increasingly important in various sectors, including the maritime industry. The growing global awareness of energy consumption, its environmental impacts, and the economic burden of excessive energy usage can be seen as the main reasons for this change. In 2018, the International Maritime Organization (IMO) established an effective plan to reduce emissions from international shipping by half of the 2008 levels (IMO, 2023). This decision marks a significant step toward ensuring sustainability in the maritime industry and reducing pollution. Specifically, the IMO's decision to reduce the sulfur content in ship fuel from 3.50% to 0.50% outside the Emission Control Areas (ECAs) is an example of this commitment. Additionally, the NOx content in engine exhaust gases has been limited to 17.0 g/kW.h under Annex IV of MARPOL, which is a sign of the growing effort to reduce environmental pollution in the sector (Comer et al., 2024).

Effective energy management plays a critical role in managing energy-related environmental pollutants, such as emissions from chimneys, while ensuring that ships remain within these environmental boundaries. Regulatory actions on vessels have heightened the attention of policymakers in the maritime sector towards pollution caused by energy consumption. Another key factor emphasizing the importance of energy management in the maritime industry is the rising cost of bunker fuel. Compared to the 1980s and 1990s, bunker fuel prices have increased by 75%, now accounting for between 43% and 67% of a ship's operating costs (Schroten et al., 2024). This shift has led to greater emphasis on energy efficiency measures on ships, as fuel costs are expected to continue rising in the long term, creating an evolving managerial challenge (Sogut, 2023). This scenario, along with the regulations set by the International Maritime Organization (IMO), calls for a well-established managerial organizational structure. Indeed, sectoral obligations demand more effective measures, and in response to these challenges, there is an increasing emphasis on data collection regarding fuel consumption, CO_2 emissions, speed optimization, and the maintenance of propulsion systems. These efforts are shaped by plans such as SEEMP (Ship Energy Efficiency Management Plan), reflecting growing awareness of energy efficiency on ships (Çetin & Sogut, 2021). Shipowners, operators, and crews are increasingly recognizing the need to monitor and reduce energy consumption, striving to comply with both environmental regulations and economic objectives.

Among different types of vessels, chemical tankers stand out particularly in the context of energy management and efficiency. The share of chemical tanker capacity in ports has remained at high levels, around 46%, since late 2021, compared to approximately 42% before the outbreak of COVID-19. The congestion of chemical tankers has gradually increased since late 2020, particularly with rising congestion in East Asia and Europe. Additionally, disruptions caused by the war in Ukraine have intensified congestion in the Mediterranean and Black Seas. In Northwestern Europe, the gradual removal of Russian volumes transported by road has led to challenges in terminal capacity, struggling to accommodate recent increases in shipments. This mobility has drawn significant attention due to the high energy consumption associated with chemical tankers. These vessels operate predominantly in open seas and coastal areas, and due to high fossil fuel consumption and low efficiency, they contribute significantly to atmospheric pollution. The energy demand of chemical tankers is primarily driven by complex systems such as cargo transfer, heating, and inert gas systems, which increase fuel consumption and emissions. However, literature indicates that energy efficiency in these systems is addressed through various conceptual approaches. For instance, Baldi et al. (2014) proposed a method to analyze ship energy systems applied to chemical tanker operations. The analysis identified key energy flows and system inefficiencies, with exergy analysis highlighting potential waste energy recovery in exhaust gases, showing that up to 18% of engine power could be recovered. The results emphasized that propulsion was the largest energy consumer (70%), followed by auxiliary heat (16.5%) and power (13.5%). In contrast, Vasilev et al. (2025) examined the challenges of achieving compliance with EEXI, EEDI, and CII standards for tanker energy efficiency. Although the regulations improved efficiency, they found that only 14.8% of vessels met the EEXI standards, with smaller vessels requiring more significant power reductions. The study also showed that tankers operated at less than 60% of their engine power and 8% slower than their design speeds. Sogut (2024) used data from a two-stroke diesel engine to assess the impact of eight alternative fuels on energy and environmental sustainability. Entropy-based thermodynamic analyses for five operations were performed using two indices developed to evaluate environmental impact, assessing the decarbonization of the sector. It was found that the use of liquid hydrogen resulted in an 18% reduction in fuel load. In terms of energy management, particularly in chemical tankers, it is crucial to assess the efficiency of key equipment such as the main engine, diesel generators, boilers, and cargo systems. Given their contribution to overall energy consumption, the effectiveness of these systems directly impacts the vessel's operational costs and environmental footprint. During port periods, fuel consumption increases due to the operation of energy-consuming systems in chemical tankers, such as inert gas systems, cargo transfer systems, and steam generators for cargo heating. This highlights the importance of implementing efficient energy management practices. Therefore, evaluating and improving energy efficiency in chemical tankers is of critical importance for the overall sustainability efforts of the maritime sector.

Currently, there is a limited amount of research regarding energy studies and the manageable framework for chemical tankers. Specifically, the necessity of a direct and sustainable institutional process for energy management on ships is an imperative requirement. This study conducts an energy audit based on a chemical tanker reference, evaluating the vessel's energy efficiency performance.

2. Shipping's Role on Energy Management for Decarbonization

Maritime transportation plays a crucial role as the backbone of global trade, but it also holds a significant share in carbon emissions. Globally, maritime transport accounts for approximately 2-3% of total CO_2 emissions, a proportion that is increasingly emerging as a growing concern. In this context, energy management is a critical element for the success of decarbonization efforts in the maritime sector. The IMO's target to reduce emissions from shipping by 50% by 2050 has further emphasized the importance of energy efficiency strategies and management practices in the industry (Trivyza et al., 2020). Indeed, as shown in Fig. 1, this transition process indicates that the sector's preference is increasingly focused on LNG.

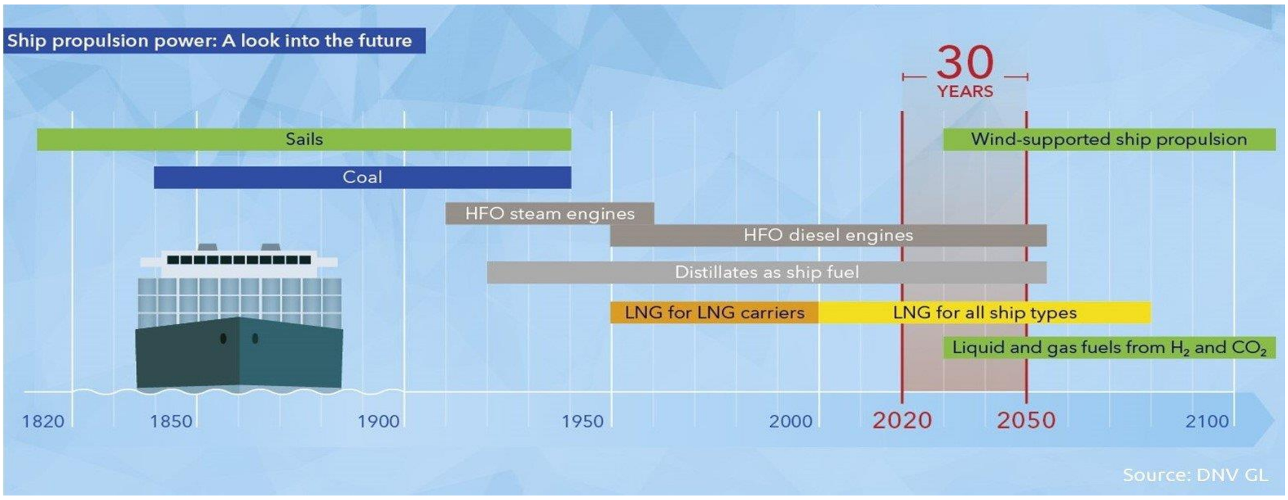


Fig. 1. Sectoral Decarbonization Framework (Dekker, 2021)

Energy management in ship operations and maritime transportation aims not only to reduce fuel consumption but also to minimize environmental impacts. Ship owners and operators are taking steps to reduce carbon emissions by adopting environmentally friendly technologies and energy-efficient operational practices. One of the key elements of energy management is optimizing vessels to improve fuel efficiency. This involves various strategies, including optimizing the ship's speed, considering environmental factors such as wind and currents, implementing energy recovery systems, and utilizing next-generation, lower-emission engine technologies. Energy efficiency also provides economic benefits by reducing operational costs for vessels. Especially with rising bunker fuel prices, the savings achieved through energy efficiency offer a significant competitive advantage for ship operators (Yuan et al., 2023). Additionally, the use of low-carbon alternative fuels and improvements in ship design are crucial factors contributing to the decarbonization process in maritime transportation. For example, alternative fuels such as liquefied natural gas (LNG) and ammonia are playing a significant role in reducing emissions by replacing traditional fossil fuels. To meet the targets set by the IMO, innovative research and developed technologies in energy management and efficiency are accelerating the transformation process within the industry (Liu et al., 2024). Furthermore, it is emphasized that ship operators and industry stakeholders must take on greater responsibility for monitoring, reporting, and managing carbon emissions. Plans such as the SEEMP guide ship operators in achieving energy efficiency goals and systematizing monitoring processes. These plans help develop strategies for more efficient operations by monitoring a vessel's energy consumption. The maritime sector plays a vital role in achieving decarbonization through energy management. Efforts to reduce carbon emissions provide significant advantages in terms of both environmental sustainability and economic efficiency (Godet et al., 2023). This process requires the collaboration of all stakeholders in the industry and the development of innovative solutions.

IMO regulations play a significant role in shaping the manageability of energy in the maritime sector, which is based on fossil fuel consumption. Specifically, new regulations related to MARPOL Annex IV and the Reduction of Carbon Emissions in the Open Sea have made the adoption of various technological innovations mandatory in order to limit carbon emissions from ships and reduce environmental impacts (Akac & Anagnostopoulou, 2024). IMO's carbon emission targets for 2030 and 2050 have also directed ship operators towards energy efficiency-enhancing systems. While these targets have made technological change essential, it has become inevitable for ships to reassess how they manage energy and prioritize efficiency as a key step. Indeed, efforts to increase engine efficiency, transition to alternative fuel systems, and develop ship designs that promote energy efficiency can be seen as significant steps to comply with the regulations set by the IMO.

Energy Management Systems (EMS) on ships and the mandatory SEEMP within the industry are crucial for ensuring compliance with IMO and MARPOL regulations. However, energy management must be based on a disciplined process management approach. Such systems provide ship operators with significant advantages in monitoring, optimizing energy consumption, and improving performance (Wang et al., 2024). Moreover, low-emission technologies, energy storage systems, and the integration of renewable energy sources offer vital tools for ship operators to achieve sustainability goals in the face of pressures from IMO regulations. As a result of these regulations, the maritime sector has adopted a more transparent and innovative approach to energy efficiency and environmental responsibility (Jasmi & Fernando, 2018). Notably, in July 2011, the International Maritime Organization (IMO) introduced mandatory measures aimed at increasing the energy efficiency of international shipping during the 62nd session of the Marine Environment Protection Committee (MEPC 62) (Shi, 2016). One of the key outcomes of these decisions was the adoption of the first global energy efficiency standard for the maritime sector, known as the EEDI, which aims to reduce greenhouse gas (GHG) emissions. This index consists of technical requirements applied to new ships, setting a minimum energy efficiency level based on CO_2 emissions per ton-mile, depending on ship type and size. Additionally, the SEEMP is designed to enable ship operators to monitor and manage ship performance as an operational measure to cost-effectively increase energy efficiency. The primary objective of these mandatory regulations is to ensure the construction of ships that are 30% more energy-efficient than those built in 2014 by the year 2025 (Baroudi et al., 2021).

Sectorial expectations have been defined as improving energy efficiency and reducing fossil fuel consumption and environmental impacts on ships. Indeed, the largest source of greenhouse gases in maritime transport is the burning of fossil fuels to generate energy. However, energy efficiency on ships can be achieved through processes that include several simple steps, from the design phase to operation and monitoring stages. The IMO, by developing the concepts of EEDI and SEEMP during MEPC 62, aimed to enhance energy efficiency in both new and existing ships at the design and operational levels. These measures not only enable ships to operate more sustainably but also prioritize the reduction of operational costs and environmental pollutants. The IMO's energy efficiency processes focus on reducing fuel consumption and greenhouse gas emissions in the maritime industry. Key initiatives like the EEDI and SEEMP aim to enhance energy efficiency through design improvements and operational practices. These processes apply to both new and existing ships, encouraging sustainable design, continuous monitoring, and performance optimization. By implementing these measures, the IMO seeks to promote environmentally responsible shipping while reducing operational costs and the industry's overall environmental impact. All of these processes have, in fact, emerged as steps that support the change targeted by the IMO, as illustrated in Fig. 2.

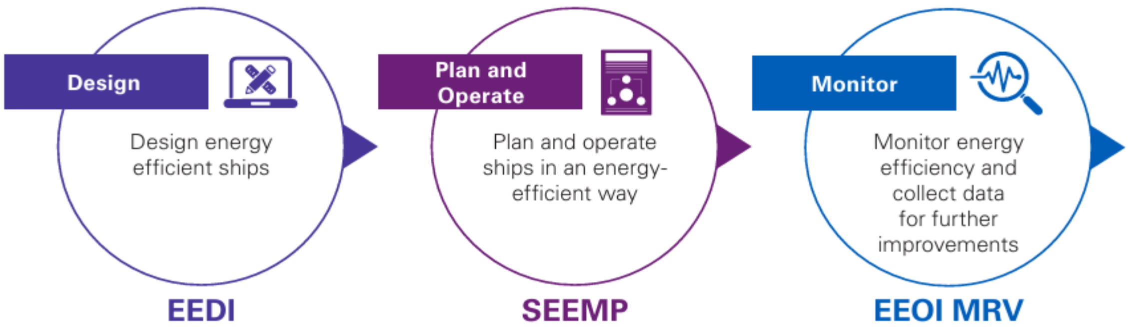


Fig. 2. IMO's Energy efficiency processes (KPMG, 2021)

3. Energy Audit and Management

3.1. Holistic Framework

Energy management on ships, in conjunction with the SEEMP, incorporates a structural perspective that contributes to the effective management of energy due to energy costs and environmental impacts. In ship operations, the priority is to develop a sustainable energy management model based on energy efficiency without causing operational disruptions. Regardless of whether a vessel has an institutional model such as the ISO 50001 Energy Management System, ship operators must establish an infrastructure to continuously monitor the points of highest energy consumption. These monitoring processes are based on minimizing risks that could affect operational processes and collecting energy data. In maritime operations, energy consumption is often monitored based on data derived from specific sailing conditions or previous operational habits, or according to institutional standards. However, this typically leads to an evaluation based on prior performance or specific sailing references, rather than the actual outcomes of ship energy efficiency. Maritime operations are influenced by numerous external factors, particularly weather conditions and routes, which can directly impact energy consumption and operational efficiency. Energy management should aim to achieve continuous improvement in energy consumption without compromising service and operational efficiency. In particular, the ISO 50001 Energy Management System provides an institutional framework that supports continuous improvement in energy efficiency under all circumstances. This system, as outlined in Fig. 3, aims to ensure the effective management of energy in ship operations, based on a cyclic process.

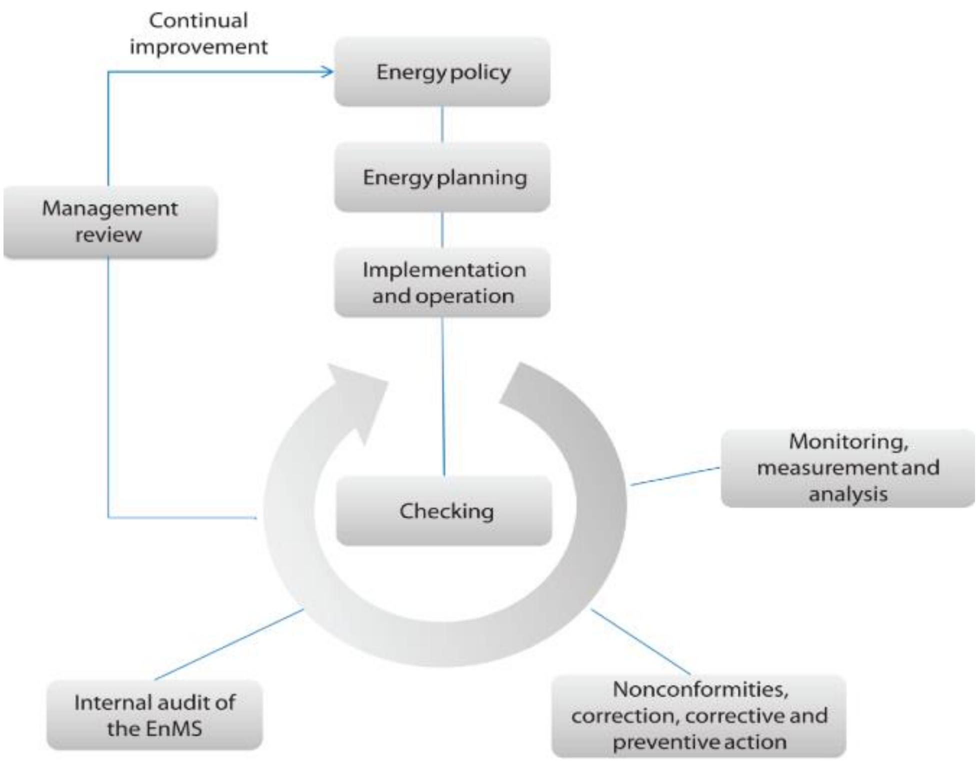


Fig. 3. Energy management system (EMS) cycle (International Organization for Standardization, 2011)

The ISO 50001 Energy Management System establishes the corporate energy management infrastructure in ship operations while defining the scope and boundaries of ship operations. In line with these definitions, the ship's significant energy consumers and current energy status should be analyzed. Within this framework, it is generally recommended to conduct a preliminary survey for ship energy management. The preliminary survey, also known as an energy audit, helps determine the ship's energy efficiency performance. The energy audit may vary depending on the ship's type and operational characteristics, but within the defined scope and boundaries, a detailed analysis should be conducted for significant energy consumers based on the types of energy used. As discussed in this study, an energy audit for a ship is examined in detail according to the methodology defined in Fig. 4.

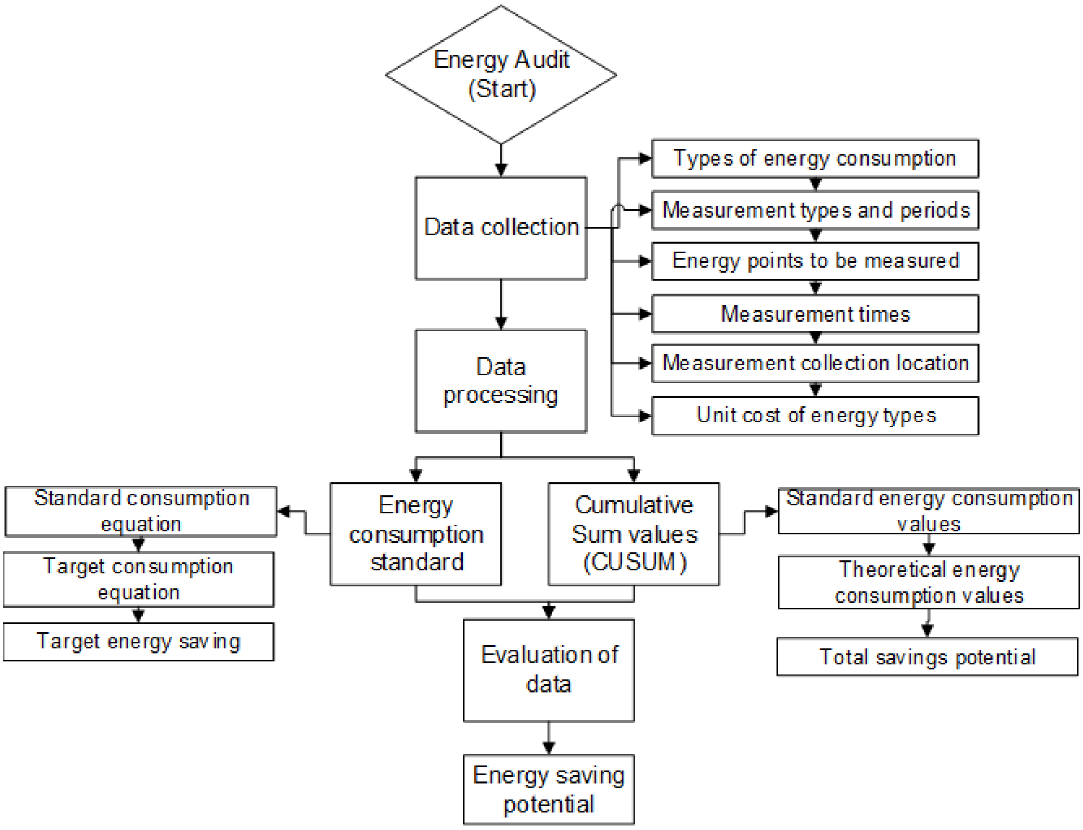


Fig. 4. Flow schema of energy audit

An important phase in energy auditing on ships is the data collection process. This process forms the core data elements of energy management and must be approached with precision. Energy management must define the types of data to be collected, the structure of this data, collection points, and methods. Additionally, the characteristics of the data, types of measurements, and measurement periods and durations must also be specified. Data security and validity are of paramount importance during this process; therefore, calibration of measuring devices should be ensured, and data collection should be carried out on a regular schedule. During data collection periods, recurring behaviors and operational conditions play a critical role in energy consumption evaluations. Thus, sufficient data must be obtained for each selected period, and typically, the number of data sets should not be fewer than ten. In ship operations, energy management systems should continuously monitor and define the data collection process. For example, for weekly measurements, the collection period should be at least ten weeks, and for monthly measurements, data should be collected annually (UNIDO, 2015). In energy-intensive operations, such as those found in ship operations, data flow can be continuously monitored via SCADA (Supervisory Control and Data Acquisition) systems (Gnana et al., 2024). However, different methods may also be developed for non-production energy consumption data and low-energy-consuming structures. This allows the ship's total energy consumption to be accurately tracked, facilitating improvements in efficiency.

3.2. Energy Audit

In ship operations, data collection processes related to energy sources such as electricity and liquid fuels should be defined in a common unit. These data should be subjected to a conversion process before analysis or the monitoring system should be established in line with this structure. The data collected in ship operations are processed and analyzed using an energy consumption standard or cumulative total values approach. The energy consumption standard related to operational processes on ships are defined based on the difference between the current energy consumption of the operation or process and the target energy consumption, as well as the energy performance index. Ship operations are influenced by many variables, which can be classified into two main groups: specific and controllable variables. Specific variables are factors that directly impact the ship operations and determine energy demand. For example, factors such as the ship's speed, sailing time, the cargo it carries, and the route directly affect energy consumption. The standard equation that defines the relationship between energy and these variables are dependent on them (Sogut, 2009). Controllable variables, on the other hand, include factors such as energy systems outside the ship, operational practices, system control, and maintenance standards. These variables are planned and optimized by ship management to minimize energy consumption. Generally, such standard equations are formulated as linear equations, demonstrating that energy requirements are dependent on specific variables. These equations are used to enhance operational efficiency in ship energy management and optimize energy consumption.

$$E = a + b(P) \tag{1}$$

E—Energy (kWh)

a and b—Constants

P—Variable or output

For ship energy efficiency and audit, three different linear equations commonly used in energy management applications related to energy consumption can be employed. However, the equation preferred in this study is the fundamental linear equation that directly evaluates the relationship between ship operations and energy consumption.

In energy audits, regression analyses based on energy consumption data are used to first determine the standard equation. This linear equation forms the basis for setting targets by considering the ship's energy consumption processes. For ship operations, this analysis can be extended to encompass all operational processes. The linear equation calculated based on target values will be in the same form as the standard equation. According to the target conditions, expected energy consumption on the ship should be calculated and compared with the current situation. Evaluations regarding unit energy consumption such as tons/consumption, rpm/consumption, knots/consumption are an important issues in ship management. However, for ships operating in a one-directional manner, energy consumption is typically defined through Specific Energy Consumption (SEC). On ships, SEC is usually expressed as the energy consumed per unit load or per variable. This can vary depending on the defined variable characteristic of the ship. SEC is an important parameter in measuring the ship's energy efficiency, and by calculating customized energy consumption values for each ship operation, efficiency targets can be achieved.

$$SEC = \sum \frac{E_c}{P_o} \tag{2}$$

SEC—Specific Energy Consumption (kWh/unit)

Ec—Energy Consumption (kWh)

Po—Load, or variable (Unit)

In terms of energy audits on ships, the SEC value can be used as an indicator for the ship. An increase in the SEC value may indicate poor performance in ship operations related to energy sources and control issues in energy consumption. However, for such evaluations, energy management must conduct more comprehensive analyses to verify the validity of the defined framework. The energy efficiency performance of ships should be addressed not only with the SEC value but also through a broader data set and a systematic approach.

Another important parameter used to evaluate energy performance is the Cumulative Sum (CUSUM) graph. CUSUM is an analysis method that identifies potential energy savings using the least squares method and cumulatively sums them. These cumulative values help create a graph that reveals the energy-saving potential at the end of a specific period. The CUSUM graph shows the differences between the ship's target energy consumption and actual energy data, determining energy flow trends. The CUSUM graph is created using the cumulative sum of the differences between the ship's energy consumption data and the target consumption data. This graph visually presents the ship's energy-saving potential or changes in energy consumption. Negative regions or values indicate improvements in the ship's energy efficiency, while positive values signal a deterioration in energy consumption (Kedici, 1993).

To create a CUSUM graph, the cumulative sum of the difference between the ship's energy consumption and the target energy consumption must first be calculated. This calculation forms the basis of the ship's energy efficiency management and clearly highlights the differences between the targeted and actual energy consumption.

$$\sum \dot{E}_{c,total} = \sum \dot{E}_{c,con} - \sum \ddot{E}_{c,target} \tag{3}$$

$E_{c,\ total}$—Cumulative total

$E_{c,\, con}$−Real consumption value

$E_{c,\, target}$−Target consumption value

For defining the cumulative total savings potential, target consumption and costs are important parameters as key data. Accordingly, the potential target energy consumption.

$$\sum E_{target} = \sum E_{con}\ (1-\alpha) \tag{4}$$

E_{target}−Target consumption

E_{con}−Real consumption

α−Energy efficiency rate

For energy audits on ships, the CUSUM graph is an important tool that allows for the examination of both target energy savings and energy savings costs for each collected data point (Sogut, 2009). This graph plays a critical role in achieving energy consumption goals and ensuring cost-effectiveness in ship operations. The CUSUM graph provides essential data for monitoring energy consumption and calculating potential savings, thereby enabling more effective energy efficiency improvements and cost management in ship energy management.

3.3. Exergetic Framework

In energy flows, the quantitative structure of the mass form is insufficient to define irreversibility and the environment. Energy is related to the environment in which it is located and the irreversibility rates vary accordingly. In energy system analyses, the maximum work that can be obtained for the environmental conditions in which it is located is expressed directly by exergy and the general exergy balance is as follows.

$$\sum(1-\frac{T_0}{T_k})\dot{Q}_k - \dot{W} + \sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \dot{E}x_{dest} = 0 \tag{5}$$

$\dot{Q}_k$ is the heat transfer rate including to come over from boundaries of the process, Ex refers to the exergy flow rate of the system, $\dot{Ex}_{dest}$ refers to the exergy destruction rate depending on the limits of the irreversibility. The exergy flow passing through the system boundaries depending on the surrounding conditions defines the physical exergy flow and this is (ψ);

$$\psi = (h-h_0) - T_0(s-s_0) \tag{6}$$

ψ −Flow exergy (kJ/kg)

h −Enthalpy (kJ/kg)

T_0 −Surrounding temperature (K or °C)

s −Entropy (kJ/K.kg)

Exergy flow rate directly refers to the enthalpy (h) and the entropy (s) flow rate at the surrounding temperature (T0) (Cornelissen, 1997). The potential of irreversibility rate of the process, which is the surrounding influence, depends directly on the amount of entropy generation. The Gouy-Stodola theorem refers to that the surrounding influence for entropy generation is directly due to the irreversibility in the process and depends on the exergy destruction rate (Moran et al., 2011; Dincer & Rosen, 2012):

$$\dot{Ex}_{dest} = T_0\dot{S}_{gen} \tag{7}$$

$\dot{Ex}_{dest}$ −Exergy destruction(kW)

T_0 −Surrounding temperature (K)

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

All energy processes, energy is consumed feature and their system performance is a function of their efficiency based on the energy flow rate between input and output flows.. In particular,also in exergy analysis, similar of the energy efficiency, the efficiency of systems depends directly on the effect of the net work produced from the exergy flow rate. In fact, the exergy efficiency of a system is defined by the standard flow rate between the inlet and outlet conditions of the flow processes. For this condition, exergy efficiency is (Moran et al., 2011);

$$\eta_{Ex} = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} = 1 - \frac{\dot{Ex}_{dest}}{\dot{Ex}_{in}} \tag{8}$$

η_{Ex} –Exergy Efficiency

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

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

$\dot{Ex}_{dest}$ –Exergy destruction (kW)

All energy systems are subject to an assessment in terms of their operational issues and potential for improvement considering irreversibility rate. An important sustainability indicator for reducing environmental impact is the potential for improvement in entropy generation. Improvement potential (IP) is as given below (Van Gool, 1997):

$$\dot{IP} = (1 - \eta_{Ex})(\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out}) \quad (9)$$

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

In this study, the performance and environmental efficiency of energy management for a reference chemical ship were primarily considered, with a holistic assessment of energy consumption. The reference ship is a chemical tanker with a 6700 kW diesel engine, 180 meters in length, and a 37,000 DWT capacity, operating within the cabotage limits of Turkey. The ship's speed, distance, and daily values for 46 voyages are presented in Fig. 5.

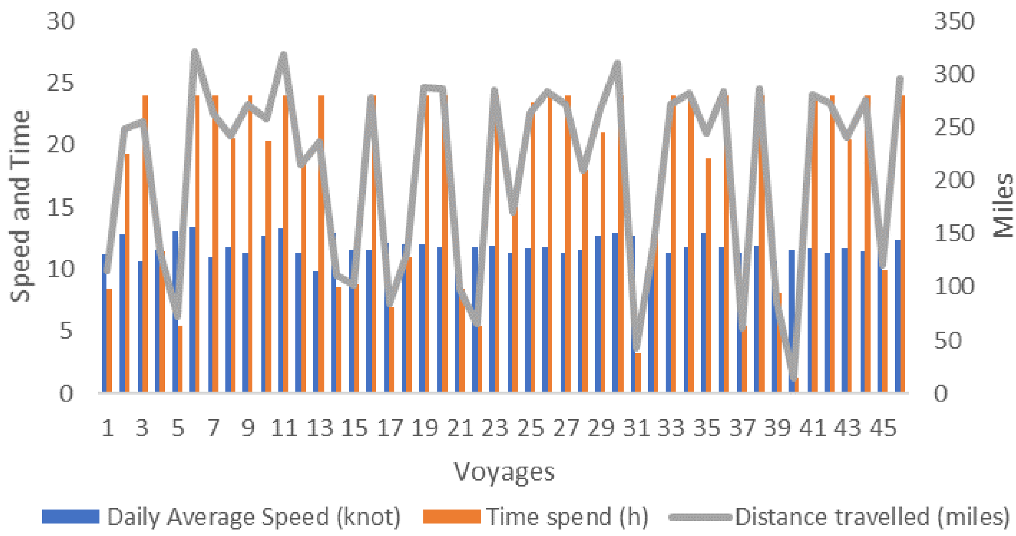


Fig. 5. The relationship between ship speed and distance travelled

When considering the ship's speed and distance data, the average daily speed is 11.28 knots, and the average distance traveled is 209.8 miles. The average time interval for the ship is 17.74 hours. The relationship between the ship's speed and time is directly associated with energy consumption. The relationship between speed, time, and energy consumption shows that as speed increases, the resistance applied to the water and energy consumption also rises. Specifically, the relationship between speed and energy consumption should be carefully considered. It should be noted that lower speeds positively contribute to energy efficiency, but they also result in time loss. These findings should be examined and assessed alongside energy management on ships. In Fig. 6, these values are provided for comparison for the reference ship.

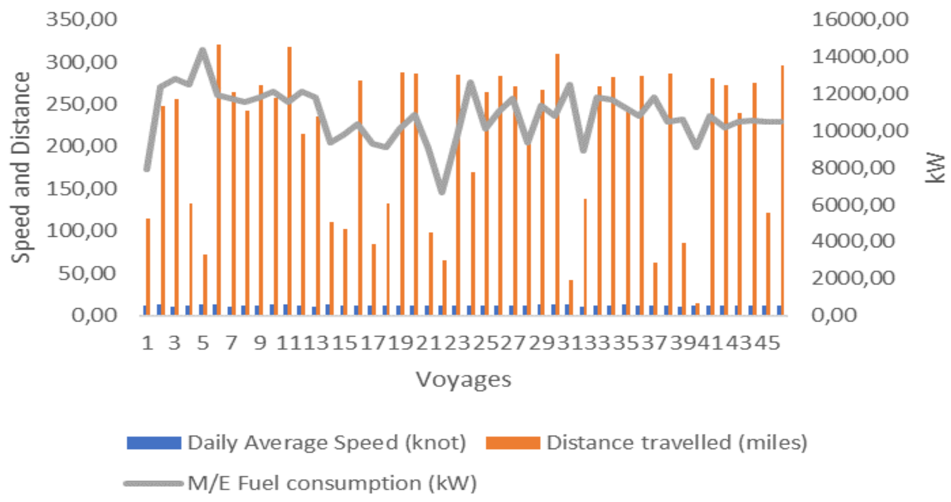


Fig. 6. Relationship between ship speed, distance and energy consumption

The ship's consumption behavior has been evaluated in conjunction with the distance. Specifically, the consumption values per mile under distance conditions were found to be 77 kW/mile. Based on these values, uncontrolled consumption behaviors are observed in the ship's operations. For instance, for the 40th voyage, the consumption per mile was identified as 605.41 kW. This value should not be evaluated in comparison to the ship's overall average in terms of consumption. Furthermore, six voyages with consumption levels exceeding 100 kW/mile stand out as particularly noteworthy. Developing a Key Performance Indicator (KPI) for the ship regarding its consumption should be a parameter to prioritize for evaluation. In this consumption trend, the ship's energy efficiency potential has been examined, and performance based on load rate has been analyzed, as shown in the graph in Fig. 7.

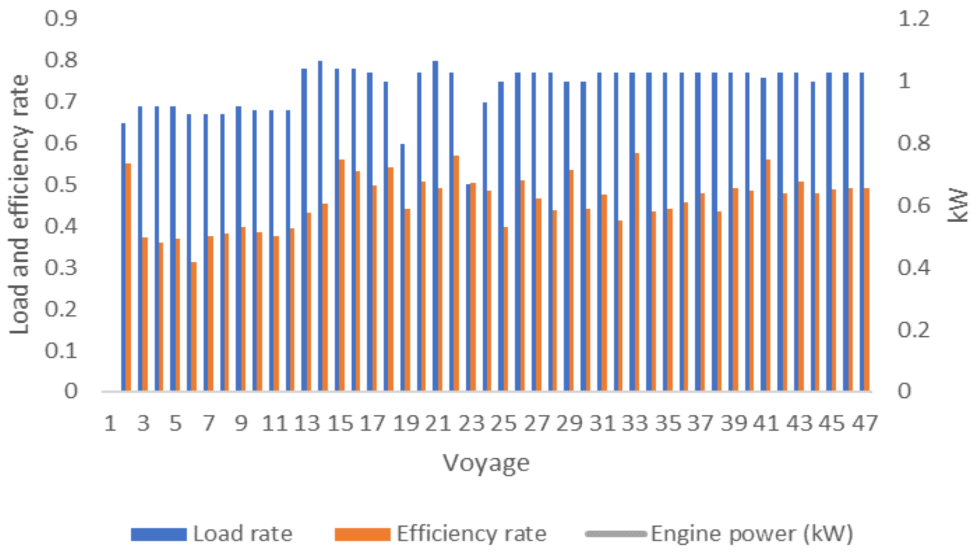


Fig. 7. Relationship between ship load rate and energy efficiency

The analysis shows that the ship's average load analysis is at a value of 73.65%, while its average efficiency is found to be 46.27%. This value has been evaluated alongside the engine's average power output of 4934.7 kW, and it has been observed that the ship's average load is 29,921.65 tons. When examining the ship's efficiency distributions, it is observed that it falls within the range of 31% to 55%. Within this framework, the relationship between the engine's consumption behavior and the load has also been assessed. The ship's total load range varies between 14,000 tons and 35,000 tons. The performance distribution of the engine for this load range has been analyzed and distributions given in Fig. 8.

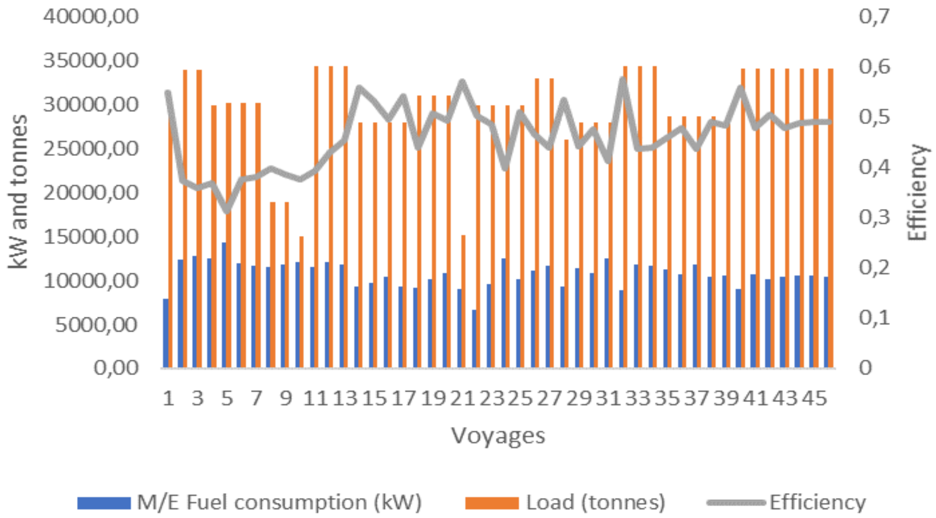
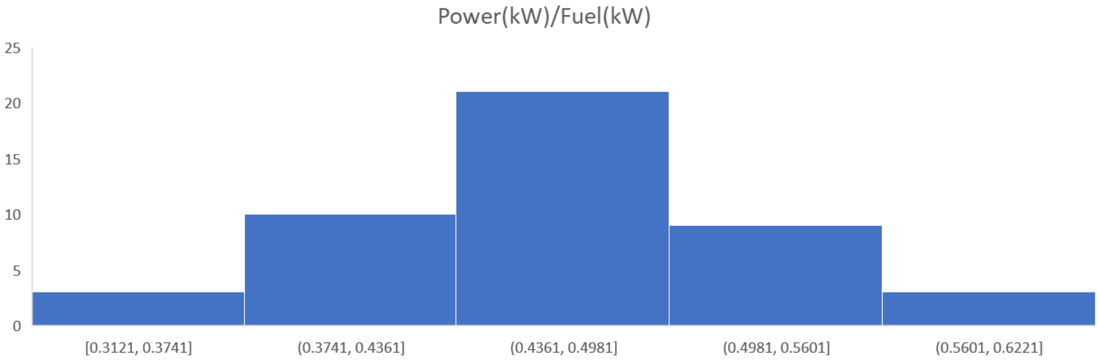
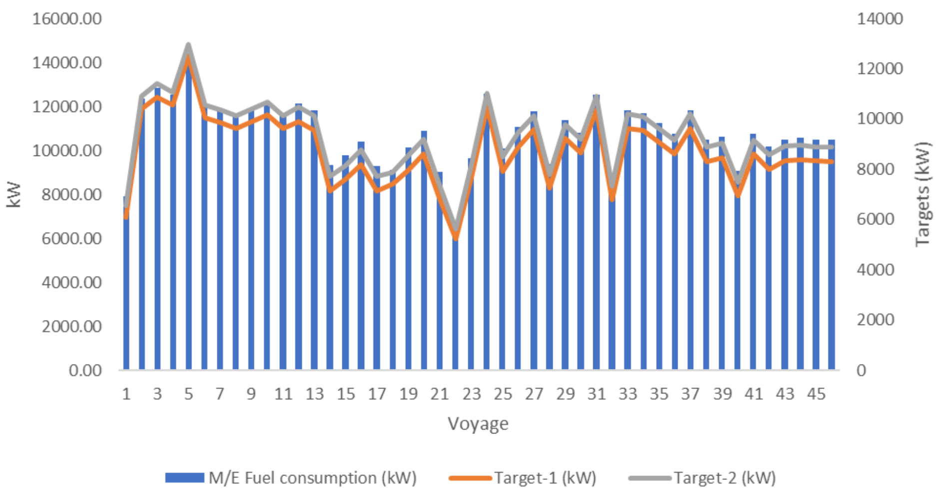


Fig. 8. The relationship between the ship's load rate and energy efficiency

The average consumption value based on the ship's energy efficiency rate and load distribution has been found to be 0.38 kW/ton. This value varies within the range of 0.26 kW/ton to 0.63 kW/ton. For these consumption behaviors, regression analyses were performed based on the defined criteria for the ship's energy efficiency analyses. However, the R^2 value did not show any compatibility with the variables. In this context, the best consumption behavior was examined, and a histogram based on the Power/Fuel rate was created, with distributions presented in Fig. 9.



a. Power/Fuel histogram



b. Energy efficiency potential

Fig. 9. CUSUM graph of histogram and target energy efficiency study

The CUSUM chart produces results that are directly formed by the differences between actual consumption and the target-based consumption expectationas given in Fig. 9(b), and are shaped by the least squares approach. This expectation is actually made for the cumulative total. However, it should be noted that in certain instances, the ship's consumption may fall short of initial expectations. In this study, a two-stage target was developed for the ship. The mean of the initial target unit power production was accepted as 0.422 kW according to the histogram given in Fig. 9(a), and the total fuel energy was calculated for each voyage accordingly. For the second target study, the unit consumption was taken as 0.312. In this efficiency evaluation, the average energy efficiency potential for target one was found to be 19.24%, and for target two, it was found to be 14.22%. These figures are contingent upon the operational capabilities. Based on this, the action steps for the ship's operational processes can be assessed gradually within the energy management framework. The environmental impact of the ship, according to these data, can be evaluated using exergy analysis, in equations (5-9) and a target for environmental pollution rate can be proposed. In this context, the ship's exergy efficiency has been first addressed, and the distributions are presented in Fig. 10.

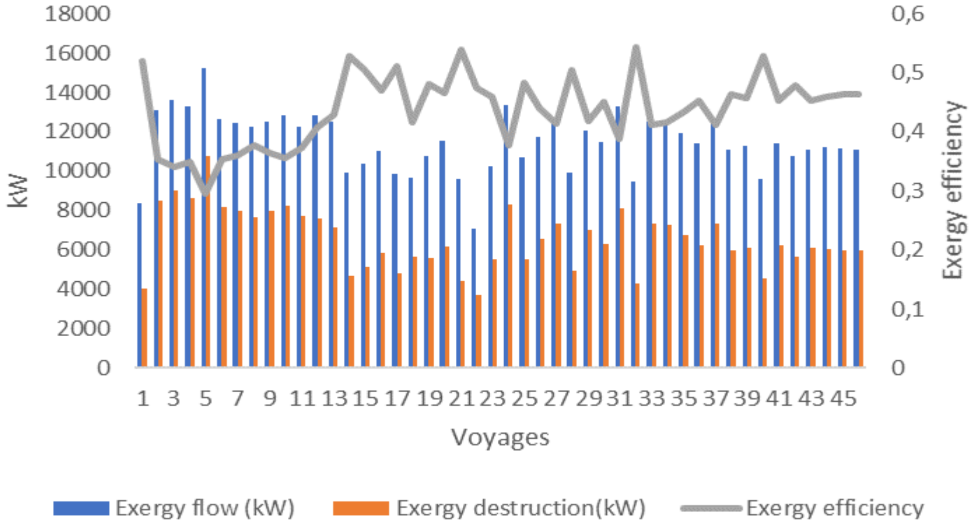


Fig. 10. Exergetic parameters

The ship's average exergy efficiency indicates a potential of 43.65%, while the development rate based on exergy destruction has been calculated according to the generated exergy destruction. Based on the referenced voyages, the ship's improvement potential shows a potential of 31.75%. According to this value, the ship's environmental efficiency potential has been evaluated, and the distributions are presented in Fig. 11.

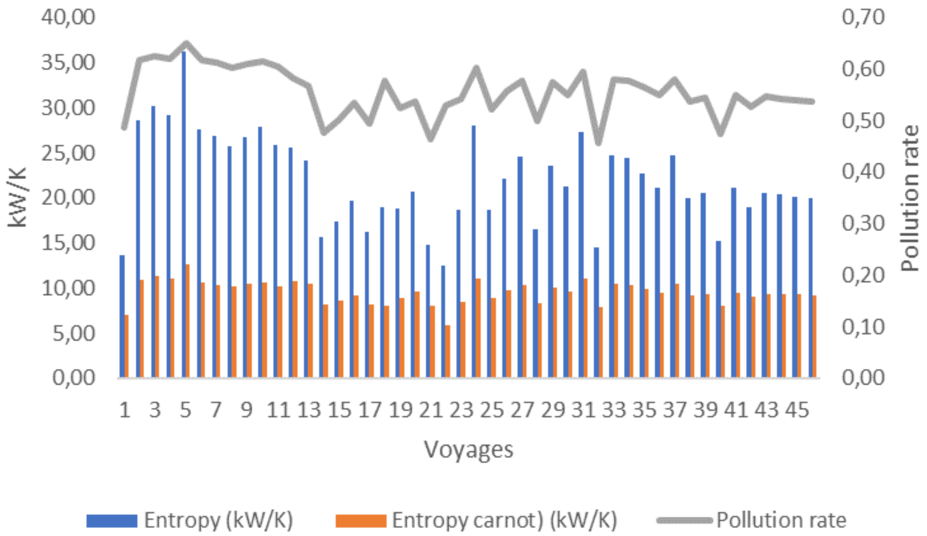


Fig. 11. Ship Entropy production and distributions

Based on the ship's consumption data, the produced entropy value is found to be an average of 1013.03 kW/K, while the thermal entropy potential (Carnot) of the ship's engine is 439.89 kW/K. According to the ship's overall consumption behavior, the pollution potential is found to be an average of 57%. Considering the improvement potential, the average efficiency potential in terms of total environmental pollution is 17.96%. Energy management, depending on the operational conditions of the ship, should consider developing an energy efficiency target based on either fuel-related consumption or environmental impact, alongside field studies. However, a stepped target has been proposed for the consumption histogram, reflecting the actual consumption values.

5. Conclusions

In this study, the performance and environmental efficiency of energy management for the reference chemical tanker were examined. The analysis revealed the relationship between the ship's speed, distance, and energy consumption, showing uncontrolled values and high consumption levels, particularly in terms of energy consumption per mile. This situation indicates that better management and optimization processes are required to meet the ship's energy efficiency goals. Additionally, the energy efficiency rate was defined in conjunction with the ship's load rate and consumption behavior. The environmental impact, based on entropy production, was also evaluated using an entropy-based approach. Moreover, the ship's energy efficiency rate was shaped according to its improvement rate.

The energy efficiency targets based on the histogram approach were found to be 8.80% for the first target and 32.58% for the second target. The energy efficiency analysis showed that the ship's improvement potential is 31.75%, while the average environmental pollution was found to be around 57%. Using the entropy approach, the energy efficiency rate of the ship was determined to be 17.96%.

To improve energy efficiency on ships, first of all, the operational operating data of important energy users should be reviewed together with the defined efficiency ratio. Especially in main engine consumption, air fuel ratio and air temperature are manageable tools. In addition, trainings based on the development of energy efficiency behavior culture on ships are also important. In addition, especially energy efficient technology change is also a process that needs to be planned.

The approaches set to optimize the ship's energy efficiency and environmental impact can be viewed as a new consumption-oriented approach for energy management on ships. This study suggests new areas for further research, such as making improvements in operational processes by focusing directly on the ship's targets. Evaluating the targets defined through operational processes is also proposed as a separate study. In addition, technology management and financial analyses are another suggested study for the development of investment priorities. In particular, a forecasting approach with artificial intelligence and time series for consumption management can be an effective study for energy management.

Abbreviations

SEEMP	: Ship Energy Efficiency Management Plan
EEXI	: Energy Efficiency Existing Ship Index
IMO	: International Maritime Organization
ECAs	: Emission Control Areas
EEDI	: Energy Efficiency Design Index
CII	: Carbon Intensity Index
LNG	: Liquefied Natural Gas
MEPC 62	: 62nd session of the Marine Environment Protection Committee

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