

Article

Advances in Quantifying the Efficiency of Energy Consumption, Conversion, and Transmission on Merchant Ships

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Abstract

Improving the efficiency of energy consumption, conversion, and transmission on merchant ships has become a critical challenge due to rising fuel costs, increasingly stringent environmental regulations, and the introduction of operational efficiency requirements such as the IMO CII. Existing energy-efficiency metrics are predominantly based on absolute or design-oriented indicators and do not adequately capture the latent reserves of energy savings embedded in ship energy systems. This study addresses this gap by proposing a methodological framework for quantifying energy efficiency through the concept of relative energy-saving potential. The proposed approach integrates ship energy balance analysis with a hierarchical assessment of relative theoretical, technical, and economically feasible energy-saving potentials. The framework is demonstrated using an illustrative numerical example for a representative medium-size product tanker. The presented calculations are intended to demonstrate the applicability of the methodology rather than to provide vessel-specific operational recommendations. The results indicate that a significant share of energy losses can be identified and reduced by technical and economic feasibility considerations. The study concludes that relative energy-saving potentials offer an effective and scalable foundation for ship energy management, supporting SEEMP implementation, CII compliance strategies, and integration into digital twin and AI-based energy management systems.

Keywords: energy efficiency; energy-saving potential; merchant ships; techno-economic assessment; ship energy management; digital twin



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1. Introduction

In today's environment of rapidly growing demands for energy efficiency and environmental safety in maritime transport, the issue of rational energy use on board merchant ships is becoming particularly relevant [1]. Consumption [2], conversion [3], and transmission of energy [4] in ship energy systems is a complex process involving the interaction between ship power plants, auxiliary machinery, and automated control systems [5]. The efficiency of these processes directly affects fuel consumption, pollutant emissions, and overall ship performance [6].

Despite the existence of several methods for evaluating the efficiency of energy systems, simplified or fragmentary criteria are often used in maritime operations [7], which do not consider the complex interaction between the elements of the energy cycle [8].

In view of this, there is a need to develop and substantiate a generalized criterion that would allow for a quantitative and qualitative assessment of the efficiency of energy consumption, conversion, and transmission, considering thermodynamic, operational, and economic parameters.

The energy systems of modern merchant ships operate under complex operating conditions characterized by load variability, multifunctionality of energy consumers, the need to ensure high reliability, and compliance with international environmental standards [9]. At the same time, energy losses associated with the imperfection of conversion devices, irrational distribution of loads between power plants, and losses during energy transmission account for a significant share of the structure of ship energy processes.

An analysis of existing approaches to assessing the efficiency of ship energy systems shows that certain traditional indicators dominate, such as specific fuel consumption, efficiency coefficients, CO₂ emissions, etc., which makes it impossible to cover all aspects of the energy cycle [10]. But these traditional indicators do not capture the internal structure of ship energy losses and are insufficient for adaptive energy management, particularly under variable operating conditions [11,12]. The lack of a single, generalized efficiency criterion makes it impossible to objectively compare the energy efficiency of different systems and technologies, complicating the process of making informed decisions about modernizing or optimizing energy consumption.

This issue is particularly relevant in the context of the digital transformation of the maritime industry [13], where the integration of intelligent energy management systems requires clear, formalized, universal criteria for automated analysis and performance forecasting. Thus, there is an urgent need to develop comprehensive efficiency criteria that would combine technical, economic, and environmental parameters, allowing for a holistic assessment of energy processes on board a ship and decisions to be made regarding their optimization.

The purpose of the study is to substantiate the optimal criterion for the efficiency of energy consumption, conversion, and transmission processes on a merchant ship, which allows for the assessment of energy conservation reserves.

Research objectives:

1. Review current scientific publications and technical sources that assess the efficiency of ship energy systems, with a focus on energy consumption, conversion, and transmission.
2. Identify the most common efficiency indicators used in maritime transport practice and analyze their advantages and limitations.
3. Propose an optimal efficiency criterion combining thermal, economic, and environmental parameters.
4. Apply the proposed criterion to evaluate the efficiency of merchant ship power plants.

1.1. Literature Review

The challenge of improving energy efficiency in maritime transport [14] has recently attracted increasing attention from scientists and practitioners. Research focuses on improving energy consumption, conversion, and transmission processes on ships to reduce fuel consumption [15], minimize harmful emissions [16], and ensure compliance with IMO regulatory requirements [17].

In [18], the authors presented the concept and simulation modeling of a ship energy efficiency management system based on the analysis of operational data. This approach allows energy consumption to be adapted to the dynamic conditions of the voyage. In turn, in [19], the author assessed the energy efficiency of a passenger ship, pointing to the possibility of improving operational performance even in traditionally built ships.

Ref. [20] presents an extended emissions index (EEI) for fishing vessels, which considers not only CO₂, but also SO_x and NO_x, providing a more comprehensive ecological assessment of energy consumption systems. Ref. [21] explores the methodology for assessing greenhouse gas emissions using Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Indicator (EEOI), and Energy Efficiency Navigational Indicator (EENI) indices and monitoring data in time series.

The authors of [22,23] identified barriers to the implementation of energy efficiency measures in shipping, including information asymmetry, the distribution of responsibility among market participants, and economic barriers to investment in new technologies. In [24], scientists investigated the cost–benefit ratio of various ballast water treatment technologies, which is closely related to energy efficiency and electricity consumption on board.

Researchers pay particular attention to innovative technologies such as air cushion systems [25], organic Rankine cycles [26], the use of photovoltaic panels, and the miniaturization of main electrical panels [27]. In [28], the authors systematized approaches to reducing emissions and improving energy efficiency, in particular methods for optimizing speed and navigation planning.

From the perspective of mathematical analysis methods, [29] proposed the use of multivariate regression and artificial neural networks to evaluate energy consumption efficiency based on trip data.

The work of scientists ([30]) demonstrates the possibilities of using energy efficiency management plans (SEEMP) in operational efficiency management. Ref. [31] deepens the analysis of container ships, focusing on the relationship between engine characteristics, energy consumption, and load parameters. Previous studies have demonstrated that detailed subsystem-level modeling of ship power and energy flows provides a more realistic basis for efficiency assessment than aggregated voyage indicators [12,32,33].

The introduction of the Carbon Intensity Indicator (CII) with mandatory ship rating classes from A to E by the International Maritime Organization has further highlighted the limitations of absolute and design-based efficiency indicators [34]. Since the CII rating is highly sensitive to operational conditions and year-to-year performance, there is a growing need for relative, normalized indicators capable of quantifying latent energy-saving reserves and supporting adaptive energy management decisions throughout a vessel's lifecycle.

1.2. The Most Common Energy Efficiency Indicators

Several methods and indices can be used to compare the energy efficiency of merchant ships, each focusing on different aspects of ship operation and design. Table 1 lists the main methods and indices used to date.

Thus, the available scientific literature offers a multi-vector view of the problem, covering:

- Performance indicators (EEDI, EEOI, EEI, EENI) described in Table 2;
- Simulation modeling methods;
- Economic justification of technologies;
- The introduction of digital monitoring systems;
- Technological modernization of energy supply systems.

However, none of the reviewed indicators explicitly quantify the latent energy-saving reserves embedded in ship energy systems. This indicates the need to develop optimal efficiency criteria that would make it possible to assess the energy-saving potential of merchant ships by combining the technical, environmental, and economic aspects of ship energy systems.

Table 1. Classification of key indicators of ship energy efficiency and their application.

Indicator	Purpose	Calculation Method/Approach	Scope of Application
EEDI	Assesses the energy efficiency of new ships at the design stage	Based on CO ₂ emissions per unit of transport work (e.g., ton-mile)	Comparison of the design efficiency of different types of ships [18,19].
EEOI	Assesses the operational energy efficiency of ships during operation	Based on actual fuel consumption and CO ₂ emissions during voyages	Monitoring and improving the operational efficiency of ships [18].
EEI	Considers additional emissions such as SO _x and NO _x , together with CO ₂	Calculation includes CO ₂ , SO _x , and NO _x for a comprehensive assessment of environmental impact	Comprehensive environmental impact assessment, in particular for specialized vessels [20].
EENI	Evaluates energy efficiency based on routes and speed plans	Ship routes and speeds are analyzed to optimize fuel consumption	Optimization of routes and speed to reduce fuel consumption and emissions [21].

Table 2. Equations for calculating key indicators of ship energy efficiency.

Indicator	Equations
EEDI [18,19]	$EEDI = \frac{CO_2 \text{ emissions (g)}}{\text{transport work (ton-mile)}};$ or $EEDI = \frac{\sum_i (CF_i \cdot SFC_i \cdot P_i)}{\text{Capacity} \cdot \text{Speed}}$ here CF_i—fuel conversion factor for CO₂ emissions; SFC_i—specific fuel consumption (g/kWh); P_i—engine power i; Capacity—deadweight or gross tonnage (depending on the type of vessel); and Speed—design speed of a vessel.
EEOI [18]	$EEOI = \frac{\sum_{j=1}^n FC_j \cdot CF_j}{\sum_{j=1}^n \text{Cargo Carried}_j \cdot \text{Distance}_j}$ here FC_j—amount of fuel consumed for the voyage j; CF_j—fuel conversion factor to CO₂; Cargo Carried—tonnage of cargo or number of passengers; Distance—voyage distance.
EEI [20]	$EEI = \frac{w_1 \cdot CO_2 + w_2 \cdot SO_x + w_3 \cdot NO_x}{\text{transport work}},$ here : w_1, w_2, w_3—weighting factors reflecting the impact of each type of emission.
EENI [21]	$EENI = \frac{\int_0^T P(t) dt}{\text{transport work}},$ here : $P(t)$—current energy consumption at a given moment in time t; T—total voyage time.

While energy audits, SEEMP-based KPIs, energy balance models, exergy analyses, and operational benchmarking provide valuable tools for assessing ship energy performance, they typically report either aggregated indicators or subsystem-specific efficiencies without a unified mechanism for progressively constraining theoretical saving opportunities by technical and economic feasibility (Table 3). The proposed framework contributes a comparable, stepwise indicator hierarchy—relative theoretical, technical, and economically feasible energy-saving potentials—that supports transparent subsystem prioritization and decision-making under retrofit and investment constraints.

The proposed framework complements (rather than replaces) audits and KPIs by providing a consistent feasibility-tiered indicator structure for subsystem-level decision support.

The main added decision capability is the progressive feasibility filtering of loss-based saving opportunities into technically achievable and economically feasible subsets, enabling transparent subsystem ranking and investment prioritization using a unified indicator structure.

Table 3. Comparison of the proposed “relative energy-saving potentials” framework with established approaches.

Approach	Primary Output	Typical Level	Feasibility Filtering (Theoretical— Technical— Economical)	Subsystem Prioritization Support	Key Limitations Addressed by This Study
Energy audit (IMO/SEEMP practice)	List of measures; savings estimates	Ship/subsystem	Partial (often qualitative)	Medium	Often lacks a unified, comparable indicator hierarchy across subsystems
Ship energy balance framework	Energy flow breakdown	Ship/subsystem	No (descriptive)	Medium	Quantifies flow but does not translate them into comparable feasibility-tiered potentials
SEEMP KPI hierarchy (EEDI/EEOI/CIL, etc.)	Aggregated efficiency indices	Ship/voyage/ annual	No	Low	Strong for compliance tracking, weaker for subsystem-level retrofit prioritization
Exergy-based assessment	Exergy destruction and quality losses	Component/ system	No	Medium	Strong thermodynamic insight, but limited direct linkage to practical retrofit feasibility and investment filtering
Operational benchmarking (fleet/voyage)	Relative performance ranking	Fleet/voyage	No	Low–Medium	Highlights “who performs better”, but not “where” savings can be realized with technical/economic constraints
Proposed framework (this study)	Relative potentials: theoretical, technical, and economical	Subsystem–ship	Yes (explicit stepwise constraints)	High	Provides a structured, comparable decision basis for subsystem prioritization under realistic constraints

2. Methodological Framework for Assessing Energy Efficiency and Energy-Saving Potential of Merchant Ships

The numerical calculations presented in this section serve an illustrative purpose and are used to demonstrate the practical application and internal consistency of the proposed methodological framework. The selected vessel characteristics and parameter values represent a typical configuration rather than measured data for a specific ship, and the resulting numerical outputs should not be interpreted as operationally actionable or directly generalizable.

The effectiveness of energy conservation measures on a merchant ship can be assessed by analyzing the dynamics of energy, operational, and financial indicators. In addition to absolute values of fuel and energy consumption, the dynamics of ship operating costs, particularly in terms of fuel and energy resources, are also important. The main result of implementing energy-efficient measures on board is a reduction in costs and, accordingly, an increase in the profitability of shipping activities. One of the key indicators characterizing the impact of energy conservation is the share of energy costs in the total cost of transportation.

Forecasting changes in transportation costs after implementing energy efficiency measures can be done based on an analysis of operational data from similar vessels, using two main approaches: parametric (considering changes in specific characteristics, such as specific fuel consumption, time spent in port, etc.) and structural analogy (based on statistical models for the fleet).

To assess the effectiveness of such measures, it is advisable to use the concept of a ship's energy-saving potential. The concept of energy conservation in the fleet proposed by the authors of the article treats this potential as a strategic resource that ensures sustainable and cost-effective operation of the vessel even in conditions of an unstable external environment. The concept of energy-saving potential as a structured reserve of efficiency improvement has previously been explored in transport and energy systems research, emphasizing its suitability for strategic and operational decision-making [32,35].

The case study considered in the present study corresponds to a representative medium-size product tanker and is employed for illustrative purposes only, with the primary objective of demonstrating the practical implementation of the proposed energy efficiency assessment methodology.

Figure 1 illustrates the integrated methodological framework used in this study to quantify the efficiency of energy consumption, conversion, and transmission on merchant ships. The framework is designed to combine methodological development with illustrative numerical evaluation, where calculated values serve to demonstrate the applicability of the proposed approach rather than to represent standalone experimental results.

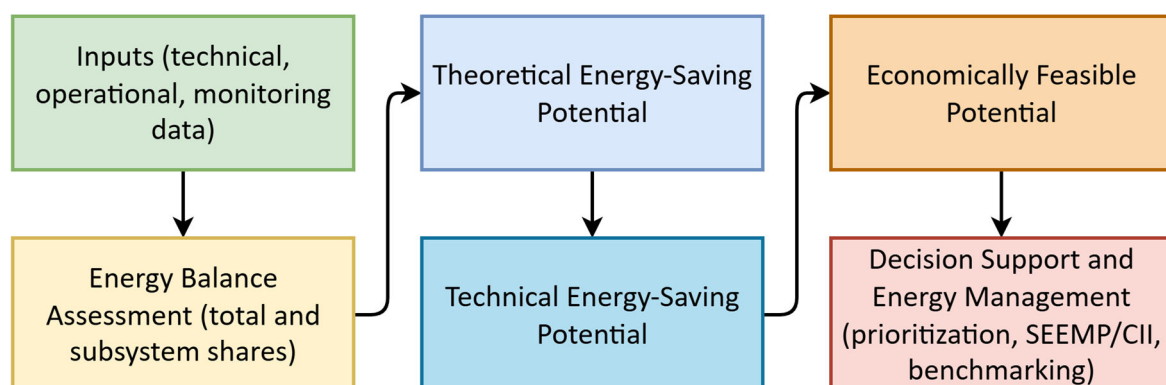


Figure 1. Methodological framework for quantifying theoretical, technical, and economically feasible energy-saving potentials of merchant ships.

The methodology begins with the collection of technical, operational, and energy monitoring data, which are used to construct the ship energy balance and identify the structure of onboard energy consumption. Based on this baseline, the relative theoretical energy-saving potential (defined as a loss-based upper-bound indicator derived from the ship energy balance) is determined, representing the maximum share of energy that can be saved under idealized conditions. This indicator establishes an upper bound for further analysis.

Subsequently, the theoretical potential is progressively constrained through the introduction of technical and economic feasibility criteria. The relative technical energy-saving potential reflects the portion of theoretical savings that can be realized using presently available technologies without fundamental modifications to the vessel configuration. The relative economically feasible potential further refines this estimate by accounting for investment costs, fuel prices, and payback criteria.

The numerical calculations presented in the subsequent subsections are therefore embedded within the methodological framework and serve to illustrate the practical

implementation of the proposed indicators. This integrated structure ensures consistency between the analytical formulations and their application to a representative merchant vessel, while maintaining the primary focus on methodological advancement.

According to the approaches developed by the authors of the article, the economic potential of a vehicle can be considered as the maximum possible efficiency of the use of technical and organizational resources. In shipping, this means achieving the minimum level of energy consumption per unit of cargo transported for a given route, speed, and schedule.

The energy-saving potential of a ship encompasses not only the technical parameters of its power plant, but also the organizational capabilities of energy consumption management (e.g., optimization of speed, schedule of voyages, and use of digital data-based decision support systems). Unrealized but potentially useful resources include, in particular:

- Heat from ship engine exhaust gases;
- Heat from ship engine cooling systems;
- Heat from auxiliary ship equipment exhaust gases;
- Energy from sea waves or solar radiation (as part of hybrid ship systems).

Studying the energy-saving potential of a specific vessel allows for:

- Identifying available reserves for reducing energy costs;
- Justifying the investment feasibility of modernizing ship systems;
- Building a model of the technical and economic effect of implementing relevant measures;
- Organizing monitoring of the dynamics of energy costs.

Compared to the traditional method of assessing efficiency based on specific fuel consumption, assessing the dynamics of energy saving potential allows for a comprehensive consideration of the technical, operational, and organizational aspects of a ship's operation.

According to Figure 2, it is advisable to classify the energy saving potential of a merchant ship according to its participation in the energy process (main/auxiliary mechanisms), by type of resource (fuel, heat, electricity, and renewable energy), by calculation method (actual/estimated values), and by management level (engine room, bridge, and shore services).

The proposed scheme classifies a ship's energy-saving potential according to five key criteria covering the technical, organizational, resource, and methodological aspects of its formation and implementation.

In the production process, capacity is distributed among components related to the main power plants (main engines), auxiliary mechanisms (pumps, compressors, and generators), and ship life support systems (lighting, ventilation, air conditioning, etc.).

The structure of energy consumption is considered by type of resource: traditional fuels, electricity, thermal energy, and renewable energy sources (solar, wind, wave energy, etc.), which can be used as alternative or additional sources of energy.

Based on the calculation method, potential is divided into actual (measured based on operational data) and estimated (calculated using models, simulations, or analytical methods). Both types are associated with an in-depth classification according to the degree of potential realization: theoretical, technically achievable, economically feasible, and essentially obtained.

In terms of management hierarchy, potential is classified according to where it is implemented or managed: the engine room (operational implementation of measures), the navigation bridge (optimization of speed, routes, and ballasting), and the shore-based technical service (analytics, planning of measures, and coordination).

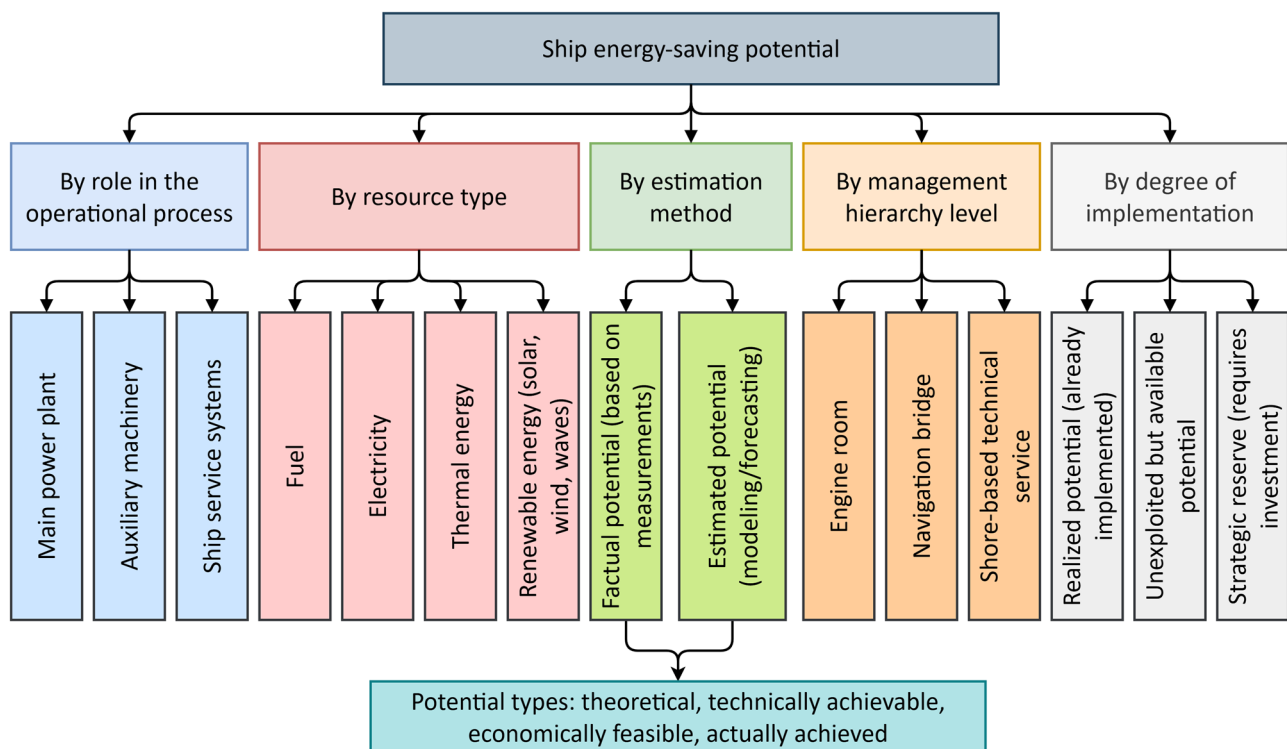


Figure 2. Classification of the energy saving potential of a merchant ship.

In terms of implementation, potential can be:

- Engaged (energy efficiency measures already implemented);
- Unengaged but available (can be implemented without significant capital investment);
- Strategic reserve (implementation requires investment or technological change).

This multidimensional classification allows for the systematic analysis of a ship's energy efficiency, assessment of potential fuel and energy savings, and development of scientifically sound programs for implementing energy efficiency measures in shipping.

It is advisable to begin researching the energy-saving potential of a merchant ship by looking at individual subsystems and energy consumption elements. For example, it is worth separately analyzing the fuel consumption of the main power plant, auxiliary diesel engines, life support systems (HVAC), ballast pumps, inertial navigation systems, etc. If it is necessary to assess the potential of the entire ship's power plant or the energy efficiency of individual voyages, it is advisable to consider the load factors of mechanisms, the simultaneity factors of consumption, and other analytical indicators that allow for the accumulation of data on individual consumers within a single operational structure of the ship.

The economically viable potential for technical energy savings in the fleet is also significant. Like mechanical engineering, its implementation on modern ships can significantly reduce fuel and electricity consumption, which directly affects the cost of transportation and environmental performance in accordance with the requirements of MARPOL Annex VI and SEEMP.

According to the authors of the article, the use of specific fuel consumption indicators on marine vessels has several limitations. In conditions of variable routes, different loads, unstable weather conditions, and various operating modes, specific fuel consumption (e.g., g/ton-mile or g/mile) does not always reflect the actual energy efficiency [36]. Such indicators do not allow for a full assessment of the energy efficiency dynamics of a particular

vessel, comparison of different types of vessels, or even comparison of the same vessel under different operating conditions.

Each vessel has its own unique energy configuration, loading regime, and routes. Even vessels of the same type can demonstrate different levels of energy efficiency depending on operating conditions (ballast or loaded voyages, speed regimes, frequency of port calls, etc.). Therefore, a direct comparison of ships based on specific indicators (e.g., fuel consumption per ton-mile) without considering the operational context is methodologically incorrect and does not allow for the accurate systematization of ship energy efficiency.

2.1. Relative Theoretical Energy-Saving Potential

The relative theoretical energy-saving-potential indicator is the optimal criterion for assessing the efficiency of energy consumption, conversion, and transfer on a merchant ship. This indicator allows for assessing the share of the ship's total energy consumption that could theoretically be saved by implementing energy-efficient technical, organizational, or operational measures.

The energy savings potential calculation should be performed over the course of an annual operating cycle. This allows for the consideration of seasonal and route-related fluctuations in ship load.

Comparing the energy efficiency of different ships or the same ship in different years, it is advisable to use the relative value of theoretical energy saving potential, i.e., the share of energy that can be extracted from the loss structure and used efficiently.

Total energy consumption (e.g., in tons of fuel equivalent or kWh) is not representative in terms of energy savings. Instead, it is critically important to assess the number of potential losses that can be avoided—that is, the portion of energy that can theoretically be saved without compromising the functionality or safety of the vessel.

The share of theoretically saved energy in total consumption is, in the authors' opinion, one of the most objective indicators of a ship's energy efficiency. It reflects not only the technical condition of the power plant, but also the effectiveness of energy management, the level of automation, the optimality of operational decisions (speed, route, and ballasting), and the degree of implementation of innovative technologies (e.g., heat recovery systems or auxiliary sails).

Upon receiving the results of an energy audit with a calculation of relative theoretical potential, the management of a shipowner or ship operator can:

- Assess the efficiency of fuel and energy use on a specific ship;
- Compare vessels within the fleet using a unified indicator;
- Identify areas for concentration of efforts (e.g., modernization of the main engine, optimization of auxiliary mechanisms, revision of the operating strategy, etc.).

The authors of the article propose determining the relative theoretical energy-saving potential using Equation (1):

$$P_{RES}^{theor} = \frac{E_{pot}^{theor}}{E_{total}} \cdot 100\%, \quad (1)$$

here $E_{pot}^{theor} = E_{total} \cdot (1 - \eta_e)$ —theoretically possible amount of energy that can be saved on a ship by implementing energy-saving measures (kWh or tons of fuel equivalent); η_e —fuel efficiency of an engine, defined as a function $f(\text{Engine power})$, an example of the function is shown in Figure 3; $E_{total} = F_c \cdot F_{lcv}$ —total energy consumption by the ship during the relevant period (year, voyage, etc.), including all types of fuel and electricity (kWh or tons of fuel equivalent); F_c —fuel consumption by the vessel for the relevant period (year, voyage, etc.), kg; and F_{lcv} —lowest calorific value, kJ/kg.

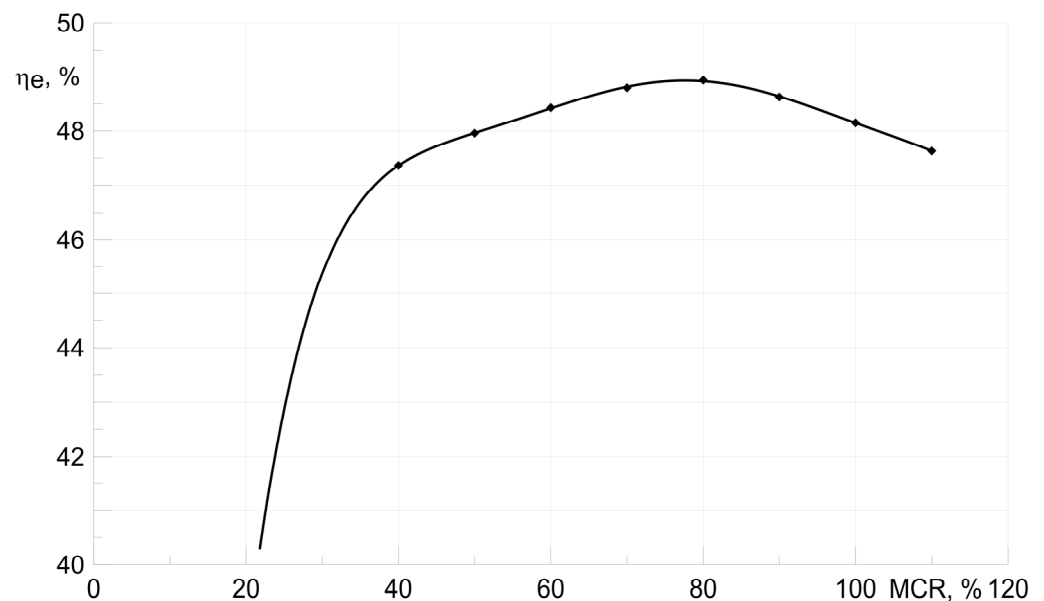


Figure 3. Dependence of fuel efficiency of the MAN 6S46MC-C7 engine on its load level (% MCR). The curve is constructed by the authors based on digitized manufacturer performance data and published technical documentation and represents a typical efficiency characteristic rather than measured operational data for a specific engine installation.

From an energy balance perspective, the term $1 - \eta_e$ represents the aggregate share of energy that is not converted into useful mechanical work and is dissipated through various loss mechanisms, including exhaust gas heat, cooling system losses, friction, and conversion inefficiencies. At the theoretical level, all such losses are considered as a single upper-bound reserve for potential energy saving. This definition does not imply that all losses are practically recoverable, nor does it assign recoverability to specific subsystems or energy forms.

The distinction between total theoretical losses and practically recoverable energy is introduced in subsequent stages of the methodology. Technical feasibility constraints (Section 2.2) and economic feasibility criteria (Section 2.3) progressively limit the theoretical potential to realistically achievable and economically justified subsets.

The resulting value P_{RES}^{theor} is expressed as a percentage and allows for estimating the share of irrational energy consumption that can be optimized; conducting a comparative analysis of the energy efficiency of ships regardless of type, tonnage, or voyage duration; and justifying the economic feasibility of investments in energy-saving measures, in particular in the modernization of equipment, the introduction of automated energy consumption management systems, the transition to alternative energy sources, etc.

In the future, this indicator may become a key indicator in the structure of digital energy management of the fleet, forming the basis for scenario modeling, rating ships for energy efficiency, and building adaptive ship operation strategies in accordance with IMO requirements (SEEMP, EEOI, CII).

Figure 3 illustrates the fuel efficiency of the MAN 6S46MC-C7 main engine as a function of its load level (% MCR). The graph shows the change in specific efficiency (effective efficiency) of the engine within the range from 20% to 110% of the rated power (Maximum Continuous Rating, MCR). The curve has a clearly defined maximum in the range of 80% MCR, where the highest level of fuel efficiency is achieved—about 49%.

When the load decreases or increases, efficiency decreases due to an increase in relative heat losses and the inefficiency of combustion processes. A particularly noticeable decrease in efficiency is observed when the engine is operating at low loads (less than 40% MCR),

where the efficiency can drop to 42% and below. This characteristic is critically important for justifying ship operating modes and calculating energy saving potential, since operating in the 70–85% MCR range provides the optimal balance between performance and fuel consumption.

The efficiency curve shown in Figure 3 is derived from manufacturer performance data (Table A1) for the MAN 6S46MC-C7 engine [37]. Discrete efficiency values at representative load points were digitized from published technical documentation and interpolated to obtain a continuous efficiency function $\eta_e = f(\text{MCR})$. The curve represents a typical engine performance envelope and is used in this study for illustrative and methodological purposes. The sensitivity of engine efficiency to load variations and operating modes has been previously demonstrated for marine diesel engines, confirming the importance of relative, loss-based indicators.

Figure 4 shows the typical distribution of the operating time of the main engine of a Chemical/Oil Product Carrier (deadweight tonnage 37,600 tons, with a MAN 6S46MC-C7 main engine) for the main operating modes with the corresponding engine load (% MCR), the parameters of whose propulsion system are given in Table 4. During a typical voyage, the ship spends most of its time in full sea speed mode, which is characterized by an engine load of about 85% of its rated power and accounts for about 75% of the total voyage time. Slow steaming mode with an engine load of about 60% accounts for 10% of the time. Maneuvering (40% MCR), idling (0% MCR), anchoring/drift (0% MCR), and port operations (0% MCR) account for 5%, 3%, 4%, and 3% of the time, respectively. This distribution of engine operating time is the basis for assessing a ship's energy efficiency, allowing for the clear identification of modes with the greatest energy-saving potential and the development of optimal strategies for reducing fuel and energy costs.

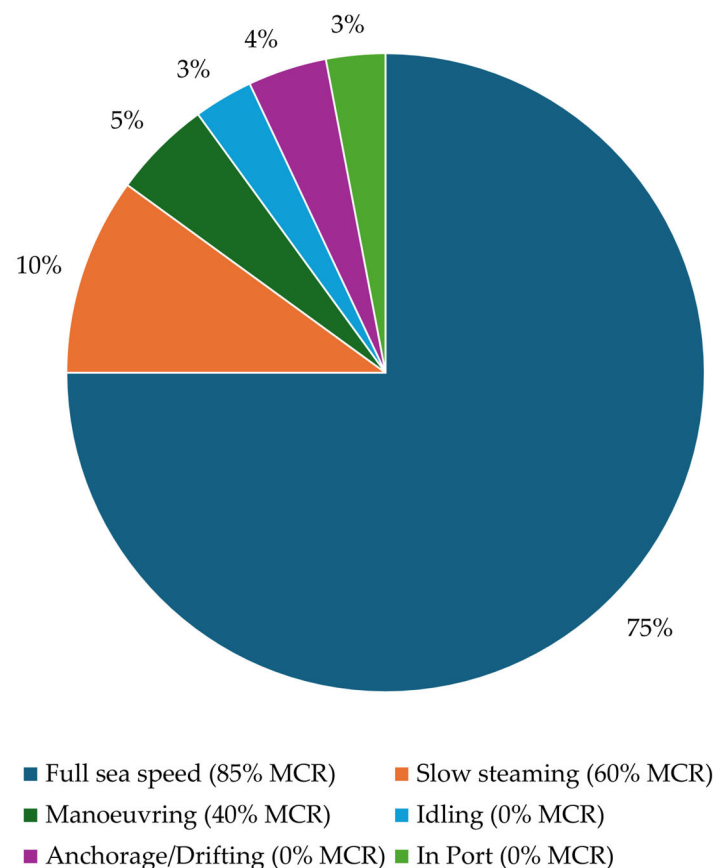


Figure 4. Typical distribution of operating time of the main engine of a merchant ship, using a Chemical/Oil Product Carrier as an example.

Table 4. Parameters of the ship's propulsion system.

Parameter	Value	Dimension
Vessel type	Chemical/Oil Product Carrier	-
Deadweight	37,000	metric tones
Body length	185	m
Board height	27.5	m
Depth	17	m
Draft (design)	9.9	m
Water displacement	39,200	metric tones
Engine type	MAN 6S46MC-C7	-
Number of cylinders	6	-
Cylinder diameter	460	mm
Piston stroke	1932	mm
Effective power (at MCR point)	7860	kW
Engine speed (at MCR point)	129	rpm
Mean effective pressure (at MCR point)	19	Bar
Turbocharger	1 × ABB TPL73	-
Propeller type	Fixed pitch propeller	-
Propeller series	Japanese MAU	-
Diameter	5.6	m
Number of blades	4	-
Propeller pitch 70% of the radius	4.2	m
Diesel generators	3 × 1000	kW
Emergency diesel generator	118	kW

Table 4 presents the main parameters of the propulsion system of a Chemical/Oil Product Carrier with a deadweight of 37,000 metric tons. The table contains summary information on the geometric characteristics of the hull, the main technical parameters of the main engine, and the design of the propeller. The power plant is a two-stroke low-speed MAN 6S46MC-C7 diesel engine with six cylinders, an effective power of 7860 kW, and a rotation speed of 129 rpm at Maximum Continuous Rating (MCR). The average effective pressure is 19 bar, and supercharging is provided by an ABB TPL73 gas turbine supercharger. The Japanese MAU fixed-pitch propeller has four blades, a diameter of 5.6 m, and a pitch of 4.2 m at 70% of the radius. A comprehensive assessment of these characteristics allows for modeling the efficiency of the ship's power plant, calculating fuel consumption, analyzing the energy balance, and justifying measures to improve the energy efficiency of ship operation.

Table 4 contains the results of calculating the theoretical energy saving potential of a merchant ship for a conditional voyage lasting 21 days, considering the main operating modes of the main engine. For each mode, the share of engine operating time, its duration in hours, the corresponding power (defined as a fraction of the nominal power—7860 kW), and the effective efficiency value according to the dependence shown in Figure 3 are given.

The calculation of theoretical energy saving potential (Table 5) assumes that energy losses that are not converted into useful work can be partially recovered (e.g., in the form of heat from exhaust gases or cooling). The values obtained show that the bulk of the potential (~2.68 GWh) is attributable to full-speed operation due to its duration (75% of total time) and high load. Slow steaming and maneuvering provide relatively smaller amounts of potential energy, but together they provide additional reserves for energy saving (≈340 MWh).

Table 5. Results of calculating the theoretical energy saving potential of a merchant ship's main engine for a conditional voyage lasting 21 days.

Operating Mode (Load)	Part of Voyage Time, %	η_{er} , %	Working Time, Hours	Engine Power, kW
Full speed ahead (85% MCR)	75	48.75	378.0	6681
Slow steaming (60% MCR)	10	48.43	50.4	4716
Maneuvering (40% MCR)	5	47.37	25.2	3144

Table 6 contains the results of calculating the theoretical energy saving potential of commercial ship diesel generators. During a real 21-day voyage, the ship's diesel generators operate during periods when the main engine is either stopped or does not generate electricity through the shaft generator. This applies to maneuvering, idling, anchoring/drifted, and port operations, which in total amount to 75.6 h, or 15% of the voyage duration. The remaining 85% of the time, power is supplied by a shaft generator driven by the main engine.

Table 6. Results of calculating the theoretical energy saving potential of commercial vessel diesel generators for a conditional voyage lasting 21 days.

Operating Mode of Ship Diesel Generators	Part of Voyage Time, %	η_{er} , %	Working Time, Hours	Engine Power, kW	E_{pot}^{theor} , kWh
Maneuvering	5	40	25.2	1200	46,915
Idling	3	40	15.1	1200	28,149
Anchoring/drifted	4	37	20.2	1000	34,648
Port operations	3	42	15.1	1400	30,581

The table considers periods when the main engine does not provide power through the shaft generator and the onboard power supply is provided by diesel generators. For each mode, the duration of operation of the auxiliary engines and the typical value of the brake efficiency depending on the load are determined, and the theoretical energy saving potential corresponding to the proportion of lost heat energy that can be recovered or reduced as a result of optimization is calculated.

The greatest energy saving potential is recorded in maneuvering mode (46.9 MWh), as generators operate at an average load for 25 h. At the same time, significant energy losses are observed during anchoring/drifted and port operations, where the efficiency of diesel generators varies between 37% and 42%, reflecting a decrease in efficiency when operating in unstable and low-load modes. The total theoretical energy saving potential of auxiliary engines per voyage is approximately 140.3 MWh, which can be used as a benchmark for implementing measures to reduce fuel consumption of the auxiliary power system.

In summary, the total theoretical energy saving potential for a conditional voyage lasting 21 days is approximately 3.15 GWh, which indicates significant reserves for reducing energy consumption even while maintaining the existing operating modes of the vessel.

These results form the basis for further analysis of the technical and economic potential of implementing energy recovery measures, as well as for justifying investments in energy efficiency improvement systems.

2.2. Relative Technical Energy-Saving Potential

Relative technical energy saving potential (P_{RES}^{tech}) is the share of total energy consumption that can be technically saved by implementing achievable energy-saving technologies without changing the purpose or basic configuration of the vessel.

The purpose of introducing a methodology for calculating the relative technical energy saving potential is to assess the amount of energy that can be saved on board a specific vessel, considering:

- The latest technology level;
- The existing design features of the vessel;
- The possibilities for the technical integration of energy-efficient solutions without complete reconstruction of the systems.

This indicator allows for moving from ideal (theoretical) conditions to technically achievable results.

Contrary to theoretical potential (Section 2.1), which considers all possible energy savings without restrictions, technical potential considers the current state of the ship, the technical feasibility of measures, and existing technical barriers: structural, dimensional, energy, etc. Therefore, the relative technical potential for energy saving is determined by Formula (2):

$$P_{RES}^{tech} = \frac{E_{pot}^{tech}}{E_{total}} \cdot 100\% = P_{RES}^{theor} \cdot k_{tech}, \quad (2)$$

here E_{pot}^{tech} —technically achievable energy saving potential, i.e., the amount of energy that can be saved using modern available technologies without changing the basic technical parameters or intended purpose of the vessel (kWh or tons of fuel equivalent); E_{total} —total energy consumption by the ship during the relevant period (year, voyage, etc.), including all types of fuel and electricity (kWh or tons of fuel equivalent); and k_{tech} —technical availability coefficient.

The technical availability coefficient of energy saving potential (3) reflects the share of the total (theoretical) energy saving potential that can be technically implemented given the current level of scientific and technical progress. It is defined as the ratio of relative technical potential to relative theoretical potential, i.e.,

$$k_{tech} = \frac{P_{RES}^{tech}}{P_{RES}^{theor}} = \frac{E_{pot}^{tech}}{E_{pot}^{theor}}. \quad (3)$$

To calculate the technically achievable energy saving potential of a ship (Equation (4)) using the algorithm shown in Figure 5, it is necessary to conduct a sequential analysis of energy consumption on board the ship, considering:

- The quantitative share of each subsystem in total consumption;
- The technical efficiency coefficient of the measures implemented;
- The achievability coefficient (the actual possibility of implementing a technical measure).

$$E_{pot}^{tech} = \sum_{i=1}^n (E_i \cdot L_i \cdot \gamma_i), \quad (4)$$

here E_i —energy consumption by i -th consumer or subsystem (main engine, auxiliary diesel generators, pumps, HVAC, etc.) over a period of time; L_i —estimated share of energy losses for the i -th subsystem (e.g., 1—engine efficiency); and γ_i —technically achievable loss reduction factor ($0 < \gamma_i < 1$), which shows what proportion of losses can be offset by implementing achievable technical solutions.

E_i determined based on the results of an energy audit, ship records, modeling, or, as in the case of the authors, using the shipmonitoring.org energy parameter monitoring system (in kWh/year).

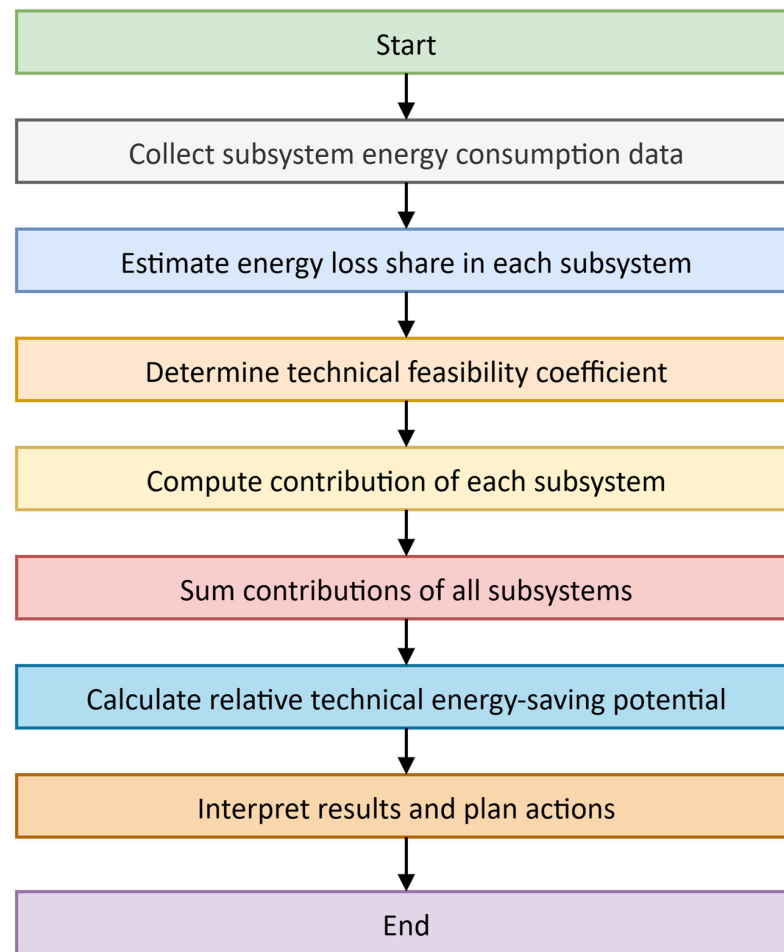


Figure 5. Algorithm for calculating technically achievable energy saving potential.

L_i depends on the type of subsystem:

- Main engine: $1 - \eta_e$, here $\eta_e \approx 0.42\text{--}0.49$;
- Generators: $1 - \eta_g$, here $\eta_g \approx 0.2\text{--}0.31$;
- HVAC: Depends on the system, approximately 0.3–0.5;
- Pumps: $1 - \eta_m$, here $\eta_m \approx 0.25\text{--}0.4$.

γ_i statistical values:

- For engine heat recovery systems—0.2–0.4;
- For optimizing frequency control of pumps—0.3–0.6;
- For lighting modernization (LED)—up to 0.8;
- For propeller devices—0.1–0.25.

To enable the analytical estimation of the relative technical energy-saving potential, the proposed methodology requires a set of representative parameters characterizing energy losses and the technical feasibility of their reduction for major onboard subsystems. These parameters include the estimated share of energy losses associated with each subsystem and the technically achievable fraction of loss reduction based on currently available technologies and retrofit practices. The use of technical availability coefficients reflects practical retrofit constraints and aligns with approaches applied in digital monitoring-based ship energy assessments [12,33].

Table 7 summarizes typical ranges of these parameters for the main engine, auxiliary diesel generators, pumping systems, HVAC systems, and lighting. The presented values are derived from published technical data, engineering practice, and results of ship energy

audits, and are intended to provide a consistent and transparent basis for the illustrative calculations presented in the subsequent analysis.

Table 7. Typical values of estimated energy losses and technically achievable reduction in losses.

Subsystem	L_i	γ_i
Main engine	0.50–0.58	0.20–0.35
Auxiliary engines	0.30–0.40	0.30–0.50
Pumping equipment	0.25–0.35	0.40–0.60
HVAC systems	0.40–0.60	0.30–0.50
Lighting	0.20–0.30	up to 0.80

The coefficients L_i and γ_i used in the case study are empirical, experience-based parameters derived from the authors' direct onboard engineering practice and energy audits conducted on merchant ships of comparable size and configuration. These values reflect realistic retrofit constraints, including spatial limitations, system integration feasibility, and operational reliability requirements, rather than idealized theoretical maxima. Therefore, the selected coefficients should be interpreted as conservative and practically achievable estimates intended to demonstrate the applicability of the proposed methodological framework. These coefficients are therefore vessel- and context-dependent and should not be interpreted as universal constants.

For clarity, technical energy-saving potentials are reported in kWh or MWh, as they represent subsystem-level fractions of the total theoretical potential expressed in GWh. Using the parameter ranges defined above, the relative technical energy-saving potential is calculated for the representative merchant vessel considered in this study. The calculation follows the subsystem-based approach introduced in the methodological framework and accounts for the contribution of each major energy consumer to the overall technical potential.

Table 8 presents the results of the technical energy-saving potential assessment for a typical voyage scenario. The values reported in the table illustrate how the theoretical energy-saving potential is progressively constrained by technical feasibility factors, thereby providing a realistic estimate of the portion of energy savings that can be achieved without fundamental modifications to the vessel configuration.

Table 8. Results of calculating the technical energy-saving potential of a merchant ship for a real voyage lasting 21 days.

Subsystem	E_i	L_i	γ_i	E_{pot}^{tech} , kWh
Main engine	3,016,165	0.53	0.25	399,642
Auxiliary engines	140,300	0.3	0.4	16,836
Pumping equipment	100,000	0.35	0.5	17,500
HVAC systems	50,000	0.5	0.3	7500
Total	—	—	—	441,478

The subsystem energy consumption values E_i used in the illustrative calculations represent aggregated energy consumption over a representative 21-day voyage. The values are derived by combining assumed operating modes, typical load factors, and subsystem duty cycles for a medium-size product tanker, rather than from measured ship-specific datasets. The calculations are intended to demonstrate the application of the proposed framework and are not annualized or normalized benchmarks.

The assumed operational profile consists of full-sea operation, slow steaming, maneuvering, anchoring, and port stays, with time shares consistent with typical product tanker

voyages of similar duration. Energy consumption for each subsystem is calculated by integrating rated or representative power levels over the corresponding operating periods.

The system boundaries adopted for the illustrative energy aggregation are as follows: main engine—propulsion power only; auxiliary generators—ship service electricity during non-shaft-generator operation; pumping systems—cargo and ballast pumping during relevant operational phases; and HVAC—accommodation and service space conditioning. Losses external to onboard energy generation (e.g., shore-side infrastructure) are not considered.

For each subsystem, energy consumption is calculated as the time-integral of the representative power demand over the defined operating periods, ensuring consistency between the assumed voyage profile and the reported energy totals.

References to energy monitoring platforms and audit data indicate typical sources that can be used to populate the framework in practical applications; however, the numerical values used in this study are illustrative and based on representative assumptions.

For the main engine, a technical feasibility factor of $\gamma_{ME} = 0.25$ was adopted based on onboard experience, reflecting the realistically recoverable fraction of conversion losses through measures such as waste heat recovery, load optimization, and control-system improvements, without fundamental redesign of the propulsion system.

Values are provided for illustrative purposes only to demonstrate the application of the proposed framework. For the illustrative vessel, representative point values of L_i and γ_i were selected within the reported ranges based on a conservative selection rule, prioritizing technical feasibility and minimal system modification. Mid-range or lower-bound values were adopted to avoid overestimation of technically achievable energy savings.

Thus, for this example $E_{pot}^{tech} = 441.5$ MWh

Pros of this approach:

- Ability to adapt to the configuration of a specific vessel;
- Suitability for implementation within digital energy management systems;
- Consideration of both the technical structure and the realities of implementation.

Cons:

- Does not take economic factors into account;
- Requires expert assessment of technical feasibility and loss rates;
- Requires accurate data from energy audits or digital monitoring.

A systematic sensitivity analysis of the adopted coefficients represents a valuable direction for future research, particularly for fleet-level studies and comparative assessments across different vessel classes.

Throughout the manuscript, power quantities (kW) are used exclusively to describe instantaneous or rated capacities of machinery, while all energy-saving potentials are expressed as accumulated energy values (kWh, MWh, or GWh) over a defined operating period. This convention is applied consistently across equations, tables, and text to avoid ambiguity between power and energy.

2.3. Economically Feasible Energy-Saving Potential

The purpose of this calculation is to estimate the share of energy savings that are not only technically possible but also economically feasible under current conditions, including fuel prices, implementation costs, payback periods, and investment accessibility.

The relative economic potential of energy saving should be determined using Equation (5):

$$P_{RES}^{econ} = \frac{E_{pot}^{econ}}{E_{total}} \cdot 100\% = P_{RES}^{tech} \cdot k_{econ} = P_{RES}^{theor} \cdot k_{tech} \cdot k_{econ}, \quad (5)$$

here E_{pot}^{econ} —economically feasible energy saving potential, i.e., the amount of energy that can be saved in a technically feasible and economically justified manner under current conditions (cost of energy carriers, cost of measures, and payback period) (kWh or tons of fuel equivalent); E_{total} —total energy consumption by the ship during the relevant period (year, voyage, etc.), including all types of fuel and electricity (kWh or tons of fuel equivalent); and k_{econ} —technical availability coefficient.

The economic feasibility coefficient of energy saving potential (Equation (6)) is an important indicator that characterizes the share of technical energy saving potential that can be economically justified on a specific vessel, considering limited investment resources, market fuel prices, the cost of implementing measures, and the expected payback period.

$$k_{econ} = \frac{p_{RES}^{econ}}{p_{RES}^{tech}} = \frac{E_{pot}^{econ}}{E_{pot}^{tech}}, \quad (6)$$

Assessing the economically feasible potential for energy saving (Equation (7)) allows for determining what proportion of technically feasible energy conservation measures should be implemented under current economic conditions. The methodology is based on calculating, using the algorithm shown in Figure 6, the net present value (NPV), payback period, or ratio of capital expenditures to expected savings.

$$E_{pot}^{econ} = \sum_{i=1}^n (E_i \cdot L_i \cdot \gamma_i \cdot \delta_i), \quad (7)$$

here δ_i —economic feasibility coefficient—a share of technically achievable potential, the implementation of which is justified by NPV, payback period, or IRR criteria.

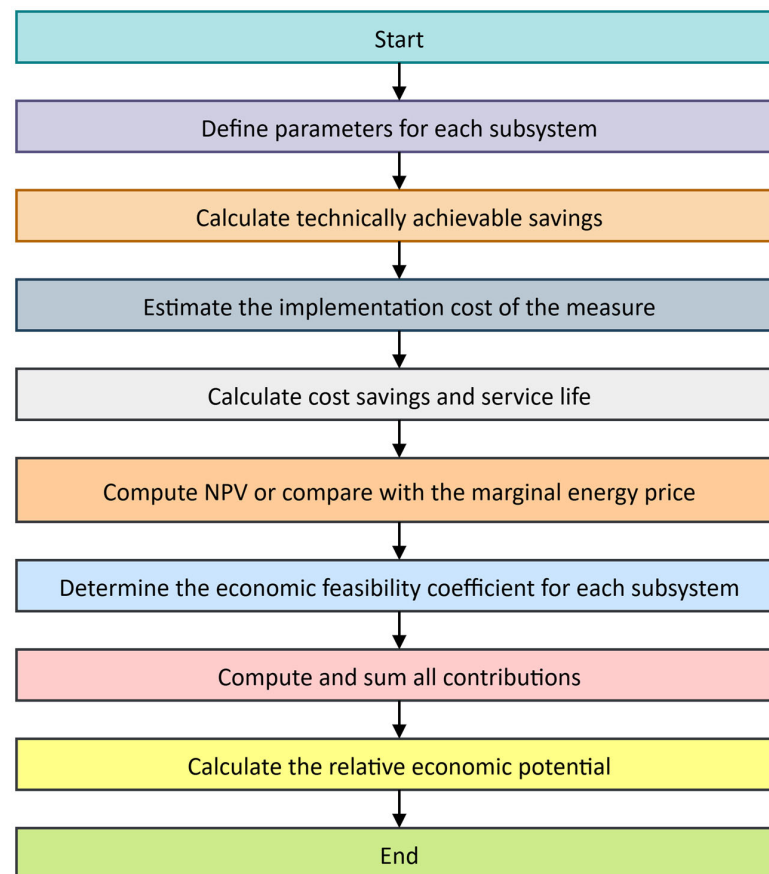


Figure 6. Algorithm for calculating economically feasible energy saving potential.

Calculation of the Economic Feasibility Coefficient

For the illustrative techno-economic assessment, the following assumptions are adopted: (i) evaluation horizon of 10 years; (ii) real discount rate of 8%; (iii) onboard energy generation based primarily on MGO-fueled auxiliary engines; (iv) lower heating value of MGO of 42.7 MJ/kg for conversion to kWh; (v) indicative implementation costs excluding class approval fees and major system integration works; and (vi) maintenance, lubricating oil, and depreciation costs included in the equivalent energy price.

Each technical measure must be assessed for economic feasibility. To do this, the following calculations are made:

Option 1: Net Present Value (NPV)

$$NPV_i = \sum_{t=1}^T \frac{S_i(t)}{(1+r)^t} - C_i, \quad (8)$$

here $S_i(t)$ —annual fuel cost savings (in USD); C_i —cost of implementing the measure; r —discount rate; and T —measurement period.

Option 2: Marginal energy price

$$C_i \leq E_{tech,i} \cdot P_e \quad (9)$$

here P_e —average cost of 1 kWh (or 1 ton of fuel equivalent); and $E_{tech,i}$ —technically achievable savings for the subsystem i .

Determining the economic feasibility coefficient:

$$\delta_i = \begin{cases} 1, & \text{if } NPV_i > 0; \\ 0, & \text{if } NPV_i \leq 0; \\ 0 \dots 1, & \text{for partial implementation or uncertainty.} \end{cases} \quad (10)$$

The results of calculating the economically feasible energy saving potential using the example of a merchant ship are summarized in Table 9.

Table 9. Results of calculating the economically feasible energy saving potential of a merchant ship for a conditional voyage lasting 21 days.

Subsystem	E_i	L_i	γ_i	δ_i	E_{pot}^{econ} , kWh
Main engine	3,016,165	0.53	0.25	0.7	279,749
Auxiliary engines	140,300	0.3	0.4	0.6	10,102
Pumping equipment	100,000	0.35	0.5	0.5	8750
HVAC systems	50,000	0.5	0.3	0.2	1500
Total	—	—	—	—	300,101

Pros of this approach:

- Ensures the link between technical capabilities and economic reality;
- Allows for the formation of priority investment programs;
- Supports decisions within SEEMP, CII, and EEOI through economic optimization.

Cons:

- Requires reliable information about investment costs;
- Does not consider external benefits (social, environmental, and image);
- Requires assessment of risks and scenarios (fuel, tariffs, depreciation).

Integrating economic feasibility criteria into energy efficiency assessment is essential for realistic implementation planning and has been applied in previous techno-economic studies of transport systems [38].

2.4. Techno-Economic Assessment and Prioritization of Energy-Saving Measures

Table 10 contains a systematic list of energy-efficient technologies that can be implemented for each of the ship's key subsystems with an indicative implementation cost (in USD), based on data from marine engineering practice, SEEMP recommendations, and commercial ship energy modernization projects.

Table 10. Energy-saving technologies for ship systems with indicative implementation costs and expected effects.

Subsystem	Technology	Estimated Cost (USD)	Expected Effect ¹ (%)
Main engine	Heat recovery unit	40,000–100,000	2–5
	Fuel system optimization	10,000–20,000	1–2
	Load optimization	20,000–35,000	2–4
	Performance monitoring	15,000–40,000	1–3
	Turbocharging modernization	30,000–60,000	2–3
	AI combustion control	40,000–80,000	2–5
Generators	Automatic generator loading	15,000–25,000	2–4
	Frequency converters	25,000–40,000	3–5
	Auto-shutdown at-port	5000–15,000	up to 2
	Heat recovery	30,000–50,000	1–3
	Phase monitoring	10,000–20,000	up to 1.5
Pumps	Frequency converters	10,000–30,000	5–15
	Automatic pump control	15,000–25,000	10–20
	Energy-efficient electric motors	20,000–40,000	5–10
	Hydraulic optimization	10,000–20,000	up to 5
HVAC	Inverter air conditioners	20,000–50,000	10–30
	VSD for fans	10,000–25,000	10–20
	Climate control automation	10,000–20,000	up to 15
	Air recuperators	15,000–30,000	up to 10
Lighting	LED lighting	5000–15,000	50–80
	Motion sensors	3000–10,000	up to 5
	Automatic light control	3000–8000	up to 3
Renewable sources	Photoelectric panels	30,000–80,000	up to 2
	Wind turbines	15,000–40,000	up to 1
	Thermal solar collectors	20,000–35,000	up to 3
Energy management	Digital energy profile	20,000–60,000	3–5
	AI/ML forecasting	30,000–70,000	2–4
	SEEMP integration	20,000–40,000	1–3

¹ Reported effects are non-cumulative and are evaluated sequentially within the prioritization procedure described in Section 2.4.

The costs shown in Table 10 are indicative for medium-tonnage vessels (30–60 thousand DWT, e.g., as in Table 4), excluding VAT, logistics, and installation. Complex measures may require electrical wiring upgrades and additional approvals from the classification society (e.g., when installing heat recovery systems). Energy savings are not cumulative, as some measures overlap.

To synthesize the results of the technical and economic assessments and to ensure consistency between the proposed energy-saving indicators and their practical implemen-

tation, a consolidated techno-economic model is developed. This model integrates the relative theoretical, technical, and economically feasible energy-saving potentials with subsystem-specific energy consumption, technical availability coefficients, and economic feasibility factors.

Table 11 summarizes the key parameters of this integrated model for the representative merchant vessel considered in the study. The table provides a structured comparison of major onboard subsystems, linking their energy consumption levels with corresponding energy-saving potentials, investment costs, and expected economic benefits. This consolidated representation enables a transparent evaluation of trade-offs between technical feasibility and economic effectiveness and supports the prioritization of energy efficiency measures within the framework of ship energy management and compliance with operational efficiency requirements.

Table 11. Consolidated technical and economic model for the implementation of energy-efficient technologies on a merchant ship.

Parameter	Main Engine	Generators	Pumps	HVAC
E_i (kWh)	3,016,165	140,300	100,000	50,000
L_i	0.53	0.30	0.35	0.50
γ_i (tech)	0.25	0.40	0.50	0.30
δ_i (econ)	0.70	0.60	0.50	0.20
E_{pot}^{tech} , kWh	399,642	16,836	17,500	7500
E_{pot}^{econ} , kWh	279,749	10,102	8750	1500
Estimated cost of implementing energy-efficient technologies, USD	60,000	20,000	15,000	10,000
Average energy price ¹ (USD/kWh)	0.25	0.25	0.25	0.25
Annual savings (USD)	69,937	2525	2188	375

¹ The assumed average energy price (0.25 USD/kWh) reflects an aggregated onboard energy cost based on MGO-fueled auxiliary power generation, including fuel, lubricants, maintenance, and depreciation, rather than the market price of propulsion fuel alone.

Prioritization of energy-saving measures is performed using a stepwise decision rule designed for illustrative techno-economic comparison. Each measure j is evaluated using a ranking indicator defined as the ratio of economic benefit to energy impact, expressed as:

$$R_j = \frac{NPV_j}{\Delta E_j} \quad (11)$$

here ΔE_j is the expected energy saving of measure j . Measures are initially ranked in descending order of R_j , representing economic efficiency per unit of energy saved.

A cumulative investment budget constraint is applied during the selection process. Measures are selected sequentially according to their ranking until the available investment budget is exhausted. This approach reflects typical shipowner decision-making, where measures are implemented incrementally rather than simultaneously.

To avoid the double-counting of energy savings, overlapping measures targeting the same subsystem are not applied cumulatively. After the selection of a measure, the remaining energy-saving potential of the affected subsystem is updated, and subsequent measures are evaluated against the reduced residual potential. This sequential updating ensures consistency of the consolidated techno-economic model.

The proposed prioritization method provides a transparent and reproducible mechanism for ranking and selecting energy-saving measures under budget constraints. While

simplified, it establishes a practical foundation for future extensions toward formal constrained optimization or fleet-level decision support systems.

The average energy price of 0.25 USD/kWh used in Table 11 represents an equivalent onboard energy cost derived from aggregated fuel and non-fuel components, rather than the market price of propulsion fuel. This value is applied uniformly across subsystems to enable a consistent comparative assessment of economic feasibility.

Table 12 shows the break-even points for each energy efficiency measure by subsystem. The fastest return on investment is for the main engine upgrade (1 year), while the payback period for the HVAC system is 27 years.

Table 12. Break-even points for subsystems.

Subsystem	Year of Reaching the Break-Even Point
Main engine	1
Generators	8
Pumps	7
HVAC	27

The conducted techno-economic assessment demonstrates that, for the considered Chemical/Oil Product Carrier, a limited investment budget on the order of 60,000 USD is sufficient to implement a selected set of technically feasible energy efficiency measures targeting the main engine subsystem. As shown in Table 10, such measures belong to the category of medium-scale retrofitting solutions and are characterized by a favorable balance between expected energy savings and capital expenditures. This finding confirms that a substantial portion of the economically feasible energy-saving potential can be realized without extensive modifications to the vessel configuration, thereby supporting incremental and risk-controlled improvement of operational energy efficiency.

To avoid ambiguity, different energy scales are used consistently throughout the paper. Total and theoretical energy-saving potentials for the vessel or voyage are expressed in GWh, reflecting the system-level energy balance. Technical and economically feasible potentials are reported in MWh or kWh, as they represent subsystem-level and implementation-constrained fractions of the theoretical potential. This hierarchy ensures physical consistency between the proposed indicators and prevents misinterpretation of their relative magnitudes.

A qualitative scenario assessment indicates that lower fuel prices or higher discount rates increase the payback periods of individual measures, while higher fuel prices or lower discount rates improve economic feasibility. Within realistic ranges of fuel price variation ($\pm 20\%$) and discount rates (6–10%), the relative prioritization of subsystems remains unchanged, confirming the robustness of the comparative conclusions.

2.5. Limitations

The numerical results presented in this study are illustrative and based on representative assumptions rather than measured ship-specific datasets. Therefore, the absolute values of the calculated energy-saving potential should not be interpreted as universal benchmarks. Future work will focus on applying the proposed framework to measure operational data from multiple vessels to support empirical validation and comparative fleet-level analysis.

A qualitative sensitivity assessment indicates that increasing or decreasing the coefficients L_i and γ_i within the ranges reported in Table 7 leads to proportional changes in the calculated technical and economic potentials, without altering the relative prioritization of

subsystems. A full quantitative sensitivity analysis is identified as a direction for future research, particularly for fleet-level applications.

The presented economic results are indicative and intended to support methodological comparison; detailed investment decisions require vessel-specific cost data, contractual fuel prices, and class-approved integration assessments.

3. Conclusions

Calculating the relative theoretical energy saving potential makes it possible to objectively assess the energy efficiency of a merchant ship's operation. It is advisable to use this indicator as a baseline, since it is the maximum possible among all types of potential (technical, economic, and actual), and allows for the assessment of the total reserve for reducing energy consumption without considering current limitations.

The relative technical potential for energy saving (P_{RES}^{tech}) is defined as a value calculated by multiplying the relative theoretical energy-saving potential (P_{RES}^{theor}) by the reduction factor for technical availability (k_{tech}). The value of this factor depends on:

- Availability of modern energy-saving technologies for the vessel (e.g., heat recovery systems, energy-saving propeller devices, and frequency converters);
- Technical feasibility of implementing these measures without radical reconstruction of the power plant;
- Level of technical qualification of the crew and shore-based engineering personnel responsible for the ship's energy management.

The relative economic potential of energy saving (P_{RES}^{econ}), in turn, significantly depends on:

- The volume and cost of the shipowner's available investment resources;
- Approaches adopted for the economic assessment of energy efficiency projects (NPV, IRR, and payback period);
- The current market price of fuel, the costs of maintaining and modernizing equipment, and the expected service life of the vessel.

All relative energy saving potentials are directly related to the current structure of energy consumption on board. The higher the share of energy-intensive systems (e.g., main engine, auxiliary generators, compressors, air conditioning systems, etc.), the more likely significant losses are at the stages of energy generation, transmission, and consumption, and the higher the calculated energy saving potential in a specific functional segment may be.

Thus, segment analysis of a ship's energy consumption (distribution by installations and systems) is an important prerequisite for accurately determining the technical and economic reserves of energy efficiency, and relative potential plays a key role in developing a priority program for the implementation of energy-saving measures.

In a broader perspective, the proposed system of relative energy-saving potentials can be directly integrated into digital twin architectures and AI-based energy management systems, enabling continuous performance monitoring, scenario-based optimization, and adaptive compliance with evolving operational and regulatory requirements.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
CII	Carbon intensity indicator
DT	Digital twin
EEDI	Energy Efficiency Design Index
EEI	Extended Emission Index
EENI	Energy Efficiency Navigational Indicator
EEOI	Energy Efficiency Operational Indicator
EMS	Energy management system
HVAC	Heating, ventilation, and air-conditioning
IMO	International Maritime Organization
IRR	Investment return rate
LED	Light-emitting diode
ME	Main engine
MCR	Maximum continuous rating
ML	Machine learning
NPV	Net present value
SEEMP	Ship Energy Efficiency Management Plan
VSD	Variable speed drive

Appendix A

Table A1 contains the data shown in Figure 3, which was digitized from the manufacturer's curves [37].

Table A1. Digitized load-efficiency points.

MCR, %	η_e , %
20	38.37
40	47.36
50	47.96
60	48.43
70	48.79
80	48.93
90	48.62
100	48.15
110	47.63

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