TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 16
Number 4
December 2022

DOI: 10.12716/1001.16.04.14

Study of Environmental Efficiency of Ship Operation in Terms of Freight Transportation Effectiveness Provision

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ABSTRACT: Development and implementation of various projects focused on improving standards of energy efficiency and rational use of energy carriers is a priority for numerous enterprises and companies. Modern shipping devotes sufficient attention to improving the environmental performance of the fleet. As part of the strategy to improve environmental safety and energy efficiency, as well as to reduce air and marine pollution in industries, including maritime transport and shipping, a set of steps to improve the ship's energy efficiency is being implemented. This process is carried out in various ways, however, at the same time maintaining the economic indicators of fleet operation. Relevant is the research aimed at analyzing the introduction of energy management systems in the maritime transport and summarizing the experience of operating the ships, which allows to identify a number of proposals, the implementation of which allows to maintain the economic efficiency of transportation. The article offers a review of the main energy efficiency tools and ways to ensure the transport efficiency of existing ships without modernization by operating them at reduced speeds and fuel consumption and thereby minimizing carbon emissions, as well as developing a set of measures to improve the environmental efficiency of cargo transportation.

1 INTRODUCTION

Maritime transport without exaggeration remains the main mode of transport for the vast majority of cargo types, as the cost of its transportation competitive and acceptable to all market participants. With the intensive development of the maritime transport sector, the pressure on the environmental component of the industry increases proportionally. As a result, the unstable level of fuel costs, the increased necessity for environmental management along with a tendency to lower fuel consumption are the main factors that make it necessary to introduce energy-efficient measures on ships. This is due to several reasons, which include ineffective ship design, poor planning, and lack of optimal use of resources. Thus, the concept and necessity of for their application in the shipping industry have been transferred into the realities of the daily operation of the maritime transport. The emissions from the international shipping of more than a hundred thousand ships constitute almost 3% of total greenhouse gas emissions that cause climate change resulting in global warming; therefore, the shipping industry has an important place in the problem of climate change.

International Maritime Organization (IMO), MEPC.203(62) adopted resolution, introduced into The International Convention for Prevention of Marine Pollution for Ships (MARPOL) Annex VI, in particular, a new Chapter 4, which establishing a number of requirements for ships energy efficiency and targeting a step-by-step reduction of carbon dioxide emissions from seagoing ships. It is notable that in general, the environmental efficiency of maritime transport (energy consumption per unit of freight carried) is significant compared to other modes of transport. The adoption of the Resolution has put the international maritime community "in the forefront" of the struggle to improve energy efficiency, as in fact the new rules represent the first industry standard of energy efficiency in the entire global economy. New regulations incorporate a number of measures to improve the ship's energy efficiency, especially by reducing the amount of carbon dioxide emissions into the atmosphere.

The problems of ensuring energy efficiency, along with the improvement of environmental safety of ships, have always received close attention from leading scientists in the field of water transport operation, as well as international institutions and societies. The specifics of alternative fuels consumption and prospects of conversion of ships of sea and river transport to alternative fuels are reviewed in (Volyanskaya et al., 2018; Karpenko & Koptseva, 2017; Bezyukov et al., 2014). Tools and methods of management of ships energy efficiency are studied in (Energy Efficiency Measures, 2011; Hüffmeier & Johanson, 2021; Rajeev, 2018). Revealing of the main principles and measures on increase of energy efficiency on ships is offered in (Maritime Cyprus, 2018). Guidelines for incorporating innovative technologies for improving energy efficiency to compute and validate the achieved performance for ships under severe weather conditions and the regulatory requirements from governing organizations are presented in (Ship Energy Efficiency, 2016; MEPC.1/Circ.684, 2009; MEPC.1/Circ.815, 2013; GloMEEP, 2017). The operational energy efficiency performance of a ship is analysed taking into account the influence of navigational conditions and the optimization of ship time in port (Hannes & Styhre, 2015). Analysis of the operational ship energy efficiency considering navigation environmental impacts (Yuan et al., 2017; Shivam, 2019). Methods for ensuring the safety of navigation and new approaches to assessment for controlling accidents in maritime transport are developed in (Melnyk & Onyshchenko, 2022). Both technical and operational measures for reducing emissions of greenhouse gases and improving the environmental and energy efficiency of ships have been studied in (Onishchenko et al., 2022). Research on measures to prevent ship pollution and emissions from ships has been studied by (Yan, 2011; Rayhan, 2021). Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies (Comer & Osipova, 2021). General issues of shipping safety and methods to ensure the efficiency of cargo transportation in (Chkalova et al., 2022; Gnap et al., 2022). Issues related to ensuring the safety of ship navigation and accident-free operation (Burmaka et al., 2022).

Considering the work of scientists in this field, it should be noted that the task of searching for ways to mitigate emissions of noxious substances resulting from ship operation and the issues of enhancing their level of energy efficiency by implementing various operational methods is highly topical. Therefore, in this paper it is proposed to analyse the main tools of ship energy efficiency management, their interrelation and dependence on the initiatives of the IMO, on energy saving methods on board ships, integrated assessment and prediction of their operational efficiency and reduction of carbon footprint in the environment. In addition, an analysis of the international regulatory framework is necessary to find solutions to the problem of emissions from ships through practical measures both by ship crews to reduce fuel consumption and by personnel working in the maritime sector and dealing with environmental protection and climate change issues.

2 MATERIALS AND METHODS

The energy saving in the transportation sector is increasingly clear-cut and is becoming more and more important in the context of the annual increase in energy consumption, the growing degree of negative impact on the environment, and the number of emissions of harmful substances.

The MARPOL is one of the important conventions that protect the marine environment from shipboard pollution. Along with International Convention for the Safety of Life at Sea (SOLAS), they are regarded as two effective tools in the field of safety and environmental protection of the IMO within the framework of continuous improvement and technical evolution of innovations to enhance the ships energy efficiency. In view of the growing concern about the increase in greenhouse gas emissions and fuel consumption, the maritime industry's regulatory body the Marine Environment Protection Committee (MEPC) of IMO has introduced a number of steps for reducing greenhouse gas emissions from ships. The primary objective was to introduce two compulsory tools - Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). It should be noted that the transportation sector is a leader in atmospheric emissions statistics. Greenhouse gas emissions by sector, where emissions are measured in carbon dioxide equivalents (CO_2). This means non-CO_2 gases are weighted by the amount of warming they cause over a hundred-year timescale (Fig.1).

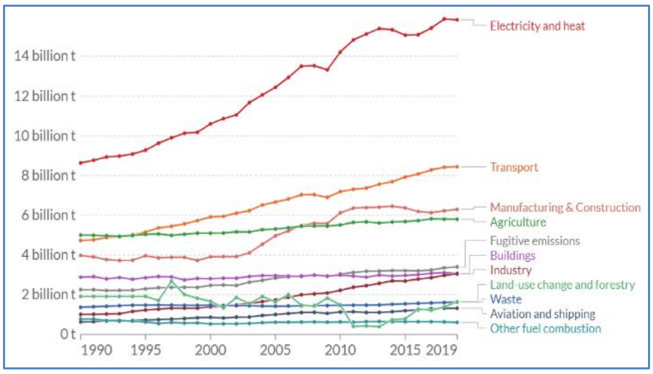

Figure 1. Greenhouse gas emissions by industry sectors
Source: Our World in Data based on Climate Analysis Indicators Tool (CAIT)

As known, EEDI is necessary to monitor the quantity of carbon dioxide and harmful emissions from ships and is a means of supporting and stimulating the development of energy efficiency standards. The idea behind its implementation is to achieve a reduction in carbon dioxide emissions by improving the hull design and optimizing the operation of ship technical systems and equipment, thereby increasing the overall efficiency of the ship. The level of carbon dioxide emissions is calculated on the basis of carbon-based fuel consumption. The fuel consumption level, in turn, is determined by the power used for the propulsion and the auxiliary capacity, which is measured under certain design conditions. The transport performance of the ship is estimated as the design power of its propulsion system times the speed measured at summer draught at maximum loaded condition and at 75 percent of the nominal capacity.

Ship Energy Efficiency Management Plan is a special instrument developed by IMO for measuring and controlling the level of greenhouse gas emissions (GHG) from ships. The SEEMP main objective is not only to reduce the number of harmful emissions from ships, but also to increase their operational efficiency and reduce fuel consumption. Implementation of SEEMP and EEDI tools for proper control of pollution from ships takes place on all new ships built after 2013. However, a SEEMP plan should be developed and implemented by the shipowner or operator of the vessel to potentially reduce the operating costs of the vessel, which ultimately aims to reduce overall fuel consumption, including emissions in the long term.

Ship energy efficiency best practices are planned and implemented through a SEEMP, which should describe optimal energy efficiency management techniques to be applied on board the ship and at the ship owner's office to ensure highest effectiveness of the ship's voyage. Main tools for ship energy efficiency management presented on Fig.2.

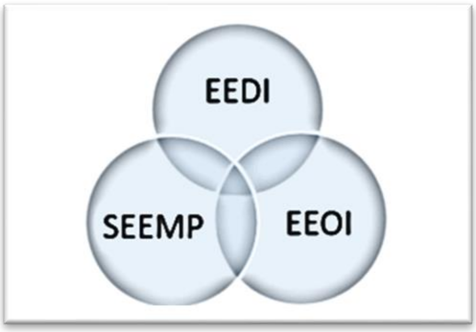

Figure 2. Main tools for ship energy efficiency management

The IMO regulatory framework states that the Energy Efficiency Operational Indicator (EEOI) refers to one of the elements intended to be used as the ship's "energy efficiency measurement" in the operational stage to monitor the ship's overall energy efficiency performance.

According to IMO guidance, the purpose of the EEOI is to establish a coherent approach to measuring a ship's energy efficiency per voyage or over a period of time. The EEOI is anticipated to provide assistance to ship owners and operators in evaluating the efficiency of their fleets. It would also track individual ships in operation and thus monitor the results of any changes done to the ship or its operation. Actually, EEOI is recommended as a monitoring instrument in SEEMP. Same as EEDI, EEOI is the quantity of carbon dioxide emitted by a ship on a unit of transportation service per cargo mile.

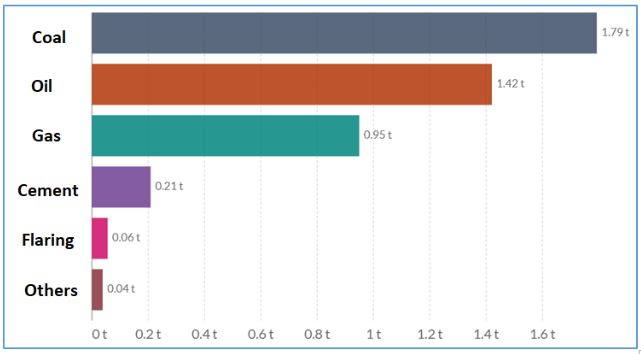

Figure 3. Carbon dioxide emission by fuel type, 2020

EEOI guidelines are of a recommendatory nature and represent a use of operational indicator as applicable. Nevertheless, ship owners, ship operators and stakeholders can use either the EEOI Guidelines or an alternative method within their own environmental management systems and consider adoption of the principles contained therein in the development of performance monitoring plans.

To assist in the consistent assessment of EEOI, the guidance provides definitions such as:
– consumption of fuel defined as all types of fuel consumed at sea and in port, or during the voyage or time period concerned (days) by main engines, auxiliary engines, boilers etc.
– distance travelled means actual distance made good in nautical miles for the voyage or time period.

Guidelines EEOI applies to all vessels performing transportation work. Types of cargoes are general and include, but are not limited to: bulk and liquid cargoes, general cargoes, containers, overweight cargoes, frozen and refrigerated cargoes, lumber and log products, freight carried on freighters, cars and trucks, vehicles on Ro-Ro ferries and passenger ships.

The weight of the transported cargo or transport work is the tonnage of the transported cargo or transport work, expressed as follows:
– the metric tons of cargo to be carried should be used for dry bulk carriers, liquid bulk carriers, gas carriers, ro-ro ships, and general cargo ships;
– the number of TEUs or metric tons of total cargo and containers should be used for container ships carrying only containers;
– weight may be used for ships carrying a combination of containers and other cargo for laden TEUs of 10 tons and for empty TEUs of 2 tons;
– the number of passengers or the gross tonnage of the ship should be used for passenger ships, taking into account Ro-Ro passenger ships.

For some particular cases, the work performed may be expressed as follows:
– the number of transport units or meters of occupied lanes for car ferries and car carriers;
– number of TEUs empty or full for container carriers, etc.

One must note that, for particular cases, the type of cargo must selected accordingly to the objectives of energy management and may differ between companies. Voyage usually refers to the period between departure from the present port and departure from the subsequent port. Other alternative definitions of voyage may also be acceptable. Coherent application of the foregoing definitions within each company is important for further comparisons of energy efficiency indicators, in particular EEOI, across the entire fleet.

The basic EEOI expression for a voyage is defined as:

$$EEOI = \frac{\sum_i FC_i \times C_{carbon}}{\sum_i m_{cargo,i} \times D_i} \quad (1)$$

The management method allows EEOI to be averaged over a number of voyages. If the average for the given period or number of trips is obtained, the EEOI is calculated as:

$$Average\,EEOI = \frac{\sum_i \sum_j \left(FC_{ij} \times C_{Fj} \right)}{\sum_i \left(m_{cargo,i} \times D_i \right)} \quad (2)$$

where: j – type of fuel; i – number of voyages; FC_{ij} – quantity consumed j- fuel quantity during the i-voyage; C_{Fj} – the coefficient of fuel mass conversion to CO_2 (j-fuel); m_{cargo} – cargo carried (tons) or work performed (gross tonnage) for passenger ships; D – distance made good in nautical miles, respectively, for transported cargo or work performed.

Units of EEOI vary depending on the measurement of the cargo or work performed, e.g., tons CO_2/(ton-miles), tons CO_2/(TEU-miles), tons CO_2/(man-miles), etc. It is worth noting that equation (2) gives no simple average EEOI value for the number of trips. Consequently, a simple average of EEOI per voyage should be avoided. The moving average calculation is used instead to utilize the average value as a performance measure.

The moving average, if used, can be calculated for an appropriate period of time, for example, calendar year or number of trips, which is assumed to be statistically significant for the initial averaging period. A moving average EEOI for this period or number of trips is then calculated using equation (2), with the following methodology. For a series of trips, e.g. 20 trips, the first moving average element, e.g. for a 4-trip subset, comes by averaging the initial number of trips, e.g. the initial 4 trips. Then, the subset is modified by "shifting forward," i.e., the first trip from the previous subset, e.g., trip 1, is excluded and the next trip, e.g., trip 5, is included. That new subset will give the second element of the moving average. This process continues until all trips are covered.

Ship's logs can be selected as primary data sources: ship's deck log and other similar official records. It is essential that there is enough information collected on board about fuel type and quantity, travelled distance, and cargo type to make a realistic estimate.

Quantity and type of fuel used, as well as the distance travelled, should be constantly recorded by the ship. If possible, the entire process must be computerized. The coefficient CF used in the EEOI equation (see (1) and (2)) is a dimensionless factor of conversion between fuel consumption and carbon dioxide emissions generated.

In addition, the EEOI must be a representational value of the ship's operational energy efficiency over a specific period that reflects the ship's overall trading model. The following basic steps are usually required to establish an EEOI:
- define the period covered by the EEOI;
- identify sources for data collection;
- collect the information;
- convert data into the corresponding format;
- calculate value of EEOI.

Data recording method should be consistent to ensure that information can be readily compared and analysed to assist in the retrieval of necessary information. The data collected from ships must contain the mileage travelled, fuel quantity and type used, and any relevant information about the fuel that may affect the quantity of carbon dioxide produced.

3 RESULTS AND DISCUSSION

The EEDI (Energy Efficiency Design Index) is an optional tool but it allows the shipbuilding sector to utilize the latest technologies for commercial ship design if they meet the required energy efficiency levels and parameters. EEDI establishes a minimum level of energy efficiency per tonnage mile for various ship types and sizes. Calculation of energy efficiency parameters for existing ships is part of the plan to implement environmental efficiency improvement measures. For the standard configuration of the vessel, the propulsion system (diesel engine) is directly connected to the fixed pitch propeller and the power plant consists of four auxiliary diesel generators. The energy-saving equipment installed on board, which should have been taken into account in the EEDI calculations, includes a waste heat steam boiler. The algorithm for calculating the environmental energy efficiency of a container ship is given below.

The procedure as follows:

6. Determine the maximum value - $EEDI_{(max)}$:

$$EEDI_{(max)} = a_i \cdot D_{w(i)}^{-c_j} \quad (3)$$

where: a_i, c_j – dimensionless empirical coefficients of the i-th ship's type, $D_{w(i)}$ – vsl's deadweight, tons.

7. Determine the subject ship's operational $EEDI_{(OPS)}$:

$$EEDI_{(OPS)} = (1 - 0.01 \cdot E) \cdot EEDI_{(max)} \quad (4)$$

where: $EEDI_{(max)}$ – maximum EEDI of $D_{w(i)}$ of given ship. The value of E is a piecewise continuous function of three variables: ship's type i = 4; ship's deadweight $D_{w(i)}$; certain time period.

8. Determining the estimated greenhouse gas emission rate $EEDI_{(GHG)}$:

$$EEDI_{(GHG)} = \left(\prod_{q=1}^{M} f_{hq} \sum_{k=1}^{nME} \left(P_{ME(k)} C_{FME(k)} SFC_{ME(k)} \right) + \left(P_{AE} C_{F(AE)} SFC_{AE} \right) \right) + \prod_{q=1}^{M} f_{hq} \sum_{k=1}^{nPG} P_{PG(k)} + -\sum_{k=1}^{nr} \left(f_{r(k)} P_{AEr(k)} \right) C_{FAE} S_{AE} + \sum_{k=1}^{nr} \left(\left(f_{r(k)} P_{MEr(k)} \right) C_{FME} S_{ME} \right) \left(f_{Dw} D_w V_{ref} f_w \right) \quad (5)$$

where: CF – specific (mass) CO_2 content at complete combustion of carbon in fuel (Table 1).

Table 1. Types of fuel used on ships

№	Type	Notes	Carbon content g/l	CF relative units
1	Diesel/Gas Oil	ISO 8217	0,875	3,2060
2	Light Fuel Oil (LFQ)	ISO 8217	0,860	3,1510
3	Heavy Fuel Oil (HFO)	ISO 8217	0,850	3,1144
4	Liquefied Petroleum Gas (LPG)	Propane Butane	0,82 – 0,83	3,00 – 3,030

V_{ref} = 19,0 – ship's speed, kn;
$D_{w(i)}$ – for given ship's type (container) is ratio 65% from deadweight;
$D_{w(i)}$ = 113000 x 0,65 = 73430 tons;
$P_{(x)}$ – aggregate power of main and auxiliary engines (respectively (PME) and (PAE), kW;

$$PME_{(i)} = 0,75 \cdot MCRME_{(i)} - PPS_{(i)} = 0,75 \cdot 51000 = 38250 \quad (6)$$

where:
PPS(i) – The output power of each installed shaft generator divided by the performance factor of the shaft generator, 0.75, kW;
MCRME(i) – maximum continuous output of the i-th engine, kW;
PPG(i) – A part of the nominal output of each generator engine divided by the weighted average efficiency of the electric generator, 0.75, kW, (in case of joint operation of shaft and electric generators) *PPS(i)* + *PPG(i)*, provided in the ship's running mode, this scheme should be included in the calculations;
Pmer(i) – A part of the main engine output reduced due to the implementation of innovative energy-efficient mechanisms and technologies, 0.75, kW;
PAEr(i) – is the output of auxiliary engines, reduced due to innovative technologies in the field of electricity and energy efficiency field, kW;
PAE – Auxiliary engine power needed to support the continuous maximum running load, which includes the required propulsion and service load, but excludes the propulsion system load: steering gear, cargo and ballast pumps, and cargo handling equipment of a fully laden ship at *Vref*;

$$P_{AE} = 0,025 \sum_{i=1}^{n(ME)} MCR_{ME(i)} + 250 = 0,025 \cdot 51000 + 250 = 152\,kW \quad (7)$$

S(x) – specific fuel consumption of the engine, g/kWh, satisfying requirements of E2 or E3 NOx test cycle (Technical Code, 2008);
$S_{ME(i)}$ - specific fuel consumption which is recorded in engine international air pollution prevention certificate (EIAPP) for 75% of the power of a particular MCR engine, or by torque indicator (for engines belonging to the D2 or C1 NOx test cycle);
$S_{AE(i)}$ - specific fuel consumption is recorded in the EIAPP certificate for 50% of the MCR power, or by the torque value, for engines without EIAPP certificate and its power is below 130 kW. Value to be determined by the manufacturer and to be used by the competent body to validate the International Energy Efficiency Certificate;
f_h – correction factor which considering the ship structural elements (for ships with ice class to be selected from MERC.1/Circ.681 ANNEX VI, for the other types of ships assumed to be equal 1, if there are no additional elements that increase the resistance to motion);
f_w – dimensionless coefficient indicating the ship speed decreasing in case of heaving and pitching (determined on sea trials, by calculation, or taken equal to 1 until specified);
$f_{r(i)}$ – coefficient of the availability of energy efficiency innovative technology (assumed to be 1 for heat recovery systems);
f_{dw} – cargo capacity coefficient (for ships without ice class to be equal to 1).

9. $EEDI_{(GHG)} < EEDO_{(OPS)} = 14,98 < 16,8$ which mans that vessel is energy efficient in terms of environmental friendliness and its modernization is not required.

4 CONCLUSION

The research and calculations show that the considered vessel can be operated without appropriate modernization. To reduce fuel consumption and, accordingly, emissions of carbon dioxide, recommended to use the main engine in part-load mode. In this case, the main engine capacity will not exceed 50-60% of the nominal and the vessel will be mainly operated at speeds corresponding to slow steaming mode. The development and application of the environmental efficiency management plan enables the ship to fully meet the requirements of IMO Resolution No. 684 for the reduction of emissions of harmful gases that cause the greenhouse effect. Thus, the energy intensity of the transport sector must be significantly reduced in order to achieve energy efficiency goals. It is also necessary to develop and maintain documented monitoring methodologies and measuring equipment on a regular basis. Importantly, the source of the assigned values must be properly registered. This will help in areas requiring improvement and will be useful for any subsequent analysis. On the basis of IMO policy and with the objective of avoiding excessive administration burdens on shipboard personnel, is it advisable that EEOI monitoring should be carried out by shore-based personnel based on information collected from relevant records, such as logbooks, service and technical logs, etc. Necessary data can be obtained during internal audits as required by the ISM Code. Other issues of increasing energy efficiency of ships, such as replacement of atmospheric air by synthetic oxygen, resulting in a significant decrease in conversion of hydrocarbon carrier and, consequently, to lower carbon dioxide emissions and issues of implementation and efficiency improvement of ballastless ship passages can be further explored.

Measures to improve the ship transportation effectiveness of ship and provide the efficient use of energy resources on board are presented in Table 2.

Table 2. Measures to increase ship environmental efficiency and transportation effectiveness

Measures to ensure efficient and environmentally friendly energy consumption	Methods of implementation
Passage planning and weather routing service	Contracting with services that provide weather forecasting and optimal routing services.
Optimal ship speed selection	Since the given ship, design speed is 19 knots at 75% of the propulsion load, the shipping company should recommend for the vessel to switch to a propulsion capacity that should not exceed 50-60% of the nominal and the vessel will be mainly operated at speeds corresponding to "Slow Steaming".
Up-to-date navigational charts, nautical publications and guides	Use corrected navigation charts and nautical publications to plan upcoming voyage and route selection.
Optimal ship's ballast plan and trimming	To increase the ship's speed during ballast passages, arrange optimum trim and heel, propeller and bulb immersion.
Technical condition of the ship's hull	To increase the ship's speed during sea passages, it is necessary to observe the technical condition of the underwater part of the ship's hull, especially after long stays in tropical waters
Technical condition of the propeller	In order to achieve the optimal speed of the vessel, it is necessary to monitor the technical condition of the propeller and perform its polishing in a timely manner
Main engine, auxiliary engines, boiler plant and other equipment technical condition	Proper and up to date maintenance of the main engine, auxiliary engines, boiler plant and other equipment should be performed in a timely and qualitative manner according to the approved schedule in order to decrease the fuel consumption and lubricating oil, etc.

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