Volume XXV 2022
ISSUE no.2
MBNA Publishing House Constanta 2022

Scientific Bulletin of Naval Academy

SBNA PAPER • OPEN ACCESS

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To cite this article: L. Rauca, F. Nicolae, Scientific Bulletin of Naval Academy, Vol. XXV 2022, pg. 21-36.

Submitted: 04.04.2022
Revised: 28.07.2022
Accepted: 26.08.2022

Available online at www.anmb.ro

ISSN: 2392-8956; ISSN-L: 1454-864X

doi: 10.21279/1454-864X-22-I2-002

ASSESSMENT OF THE ENVIRONMENTAL IMPACT BY MERCHANT VESSELS' VOYAGE MONITORING

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Abstract: Maritime or inland transportation is one of the essential elements of the global supply chain, contributing to over 85-90% of international trade. Although sea transportation remains one of the most important and feasible choices of goods transportation for most international trade routes, the impact on the environment is one of the major issues that need to be addressed. The maritime industry is facing high demands to find solutions to operate in a more sustainable way, to find feasible and viable decarbonization solutions. To comply with IMO regulations, the shipping industry must develop and invest in future technologies. The paper proposes a method of monitoring the voyage of a container ship, having different characteristics, to determine the impact of vessel's activity on the environment. The research method was applied to various means of operation, such as vessel's speed, the constructive characteristics of the ship (including those of the propulsion system), or the type of fuel used. For each case, the following are performed: monitoring of fuel consumption, calculation of emissions from ships (with an emphasis on greenhouse gases), evaluation of energy efficiency indicators. From this perspective, the article offers an environmental impact assessment solution for merchant ships, to support the management of companies in the decision-making process, to promote environmentally friendly maritime transport and sustainable development of maritime transportation.

Keywords: maritime transportation, air pollution, monitoring, environmental impact, emissions.

Abbreviations

The below abbreviations will be used in this article:

AIS	Automatic Identification System
Bf	Beauford
CII	Carbon Intensity Indicator
CO	Carbon Monoxide
CO2	Carbon Dioxide
DTU	Denmark Technical University
DWT	Deadweight

EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operațional Indicator
EEXI	Energy Efficiency for Existing Ships
EGCS	Exhaust Gas Cleaning System
EPL	Engine Power Limitation
GHG	Greenhouse Gases
GRT	Gross Tonnage
FOC	Fuel Oil Consumption
HC	Hydrocarbons
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LSFO	Low Sulphur Fuel Oil
MCR	Maximum Continous Rating
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NO_x	Nitrogen Oxides
PM	Particulate Matter
SEEMP	Ship Energy Efficiency Plan
SFOC	Specific Fuel Oil Consumption
SO_x	Sulphur Oxides
TEU	Twenty-foot Equivalent Unit
VOC	Volatile Organic Compounds

1. Introduction and literature review

Maritime transportation is one the essential element of the global supply chain, with over 11 billion tonnes of freight in 2020, compared with 4.3 billion tonnes in 1990 [1]. For the past 20 years, the International Maritime Organization's (IMO) annual reports show that shipping is a major contributor to global greenhouse gas pollution. Therefore, the post-pandemic analysis of international shipping by Simpson Spence Young [2] shows that CO2 emissions from maritime transport are at alarming levels, accounting for over 3% of global CO2 emissions: 800 million tonnes in 2019, 794 million tonnes in 2020, and 833 million tonnes in 2021. The International Maritime Organization states that in 2020, 27 723 ships were in operation compared to 27 221 ships in 2019. Over 99.91% of the fuel used was represented by Heavy Fuel Oil (HFO), Low Sulphur Fuel Oil (LSFO), Marine Diesel / Gas Oil (MD/GO), or Liquefied Natural Gas (LNG). Maritime transportation is also responsible for the emission of 13% of all greenhouse gases in the entire transport area. Likewise, the CO2 emissions increased by 4.9% from 2020 [3]. The IMO report states that in 2020 the total amount of fuel used was over 203 million tons compared to 213 million tons consumed in 2019 and LNG consumption increased in 2020 to 11 974 761 tons compared to 10 482 472 tons in 2019. In the same context, studies show that specialized vessels (containers, bulk carriers, Roll-on Roll-offs, oil tankers, and passenger ships) are the main contributors to air pollution, with a share of 71% of total emissions [4]. Based on the existing situation, the IMO has set itself the objective of reducing the environmental impact of maritime transportation by reducing greenhouse gas emissions by more than 50% by 2050 compared to 2008 [5].

The maritime industry is facing high demands to find solutions to operate in a more sustainable way, to find feasible and viable decarbonization solutions. The maritime industry will have to examine alternative fuels, retrofit solutions, invest in new technologies, adapt shipyards, train specialists and ship personnel, etc. In the current climate change conditions as well as the growing awareness of the need for change in the maritime industry, energy-efficient vessels can contribute substantially to decreasing greenhouse gas (GHG) emissions. To this are added the determined limits of the IMO and the general interest of shipowners, charters, and ship operators to reduce costs. Shipping can slightly decrease GHG emissions using current and improved operational and technical solutions, but to achieve the tough IMO restriction and full decarbonization, the shipping industry must develop and invest in future technologies.

The technical solutions that can lead to this goal (changing the type of fuel, retrofitting the propulsion system, more energy-efficient engines, systems that use energy from renewable sources, etc.) are already available on the market and classified by IMO as viable means to decrease the greenhouse gas emissions from ships [6], [7], [8], [9]. Given the very high implementation costs, a measurable assessment of the relationship between the technical condition of a ship and the quantity of emissions in operation is required. For the reasons set out above, estimating the impact of maritime transport on the environment is an objective for the attention not only of scientists but also of shipping companies, governments, or international organizations.

Subsequently, emissions from ships are an important issue for the medium and long-term sustainability of maritime transportation. Numerous studies and research highlight both the quantities of pollutants and the contribution of each type of emission to the deterioration of air quality [10], [11], [12], [13]. The maritime industry has recognized the necessity to reduce shipping air pollution by the fact that maritime transportation is becoming one of the most important sectors in terms of transferring cargo with the constantly increasing number of ships [14].

Scientists have constantly emphasized the negative impact that human activity has on the environment. Based on the results obtained, in existing studies and research in the field of marine protection, international organizations have adapted and developed the regulatory conditions in support of the protection of the marine environment [15], [16], [17], [6].

Emissions from ships are mainly represented by: carbon oxides (CO and CO_2), particulate matter (PM), volatile organic compounds (VOCs), nitrogen and sulphur oxides (NO_x and SO_x), etc. Numerous papers propose algorithms that can calculate these emissions, and the data can be used to determine the effect that each ship has on the marine environment [18], [19], [20], [21].

Estimating emissions from ships based on data provided by the automatic identification system (AIS) is a step forward in determining the footprint associated with a ship's activity [22]. The proposed methods for estimating Energy Efficiency Operational Indicator (EEOI) are based on available data (ship details, environmental data), independent of the actual fuel oil consumption (FOC) [23], [24].

Scientists say that emissions from shipping contribute to both the deterioration of human health and climate change, by changing the structure of the atmosphere in large areas, especially in coastal areas [25], [26], [27]. From the same perception, studies and analyses of the activity of maritime transportation and port operation show that between 65-75% of emissions from ships occur in coastal areas and in ports with heavy traffic [10], [28], [29]. Measurements show that the affected areas can extend up to 350-450 km from the coastline to inland territory. Consequently, emissions from ships create air quality issues through the formation of ground-level ozone, emissions of sulphur and aerosol precursors, etc. Even if emissions from ships are produced in the marine environment, they can be transported into the atmosphere hundreds of kilometres away, contributing to continental air quality issues [30], [31], [32].

Current technical and operational solutions such as weather routing software, propeller polishing, hull cleaning, air lubrication system, high-performance coating, ballast management, voyage planning, alternative propulsion, solar power, or speed optimization could be measures for emissions reductions [8]. Advanced software solutions have made it possible to optimize the voyage of ships by thoroughly analyzing all factors affecting fuel consumption and cargo operation, with the possibility of monitoring emissions from merchant ships. Proper use of a voyage monitoring system can reduce pollution of the marine environment, and in addition to the economical benefits, can make shipping more sustainable [33], [34], [35]. The voyage planning/optimization software assists the vessel's crew in finding the optimal routes in the given hydro-meteorological conditions [33], [36]. [36] is proposing algorithms with potential fuel oil savings of 7.6%, as well as a reduction in voyage times by 8.4%. The optimal solution involves meeting the optimal conditions from the following perspective: the performance of the voyage from an economical and safety point of view and the reduction of pollution of the marine environment [37], [38]. The experience has shown that within the same shipping company an efficient voyage planning system contributes to increasing the competitiveness and sustainability of shipping. Solutions based on dynamic 3D programming, the isochrone method, different algorithms, dynamic programming, or artificial intelligence, find the optimal route and speed, based on the hydro-meteorological conditions [39], [40], [41].

All the above show that the matter associated with the impact of maritime transportation activities on the environment and especially air pollution, is diverse and complex, and some of the identified technical and operational issues are being investigated and rectified.

Therefore, the decarbonization of maritime transportation has become a viable solution, which will definitely contribute in the future to the sustainability of maritime transport [42]. Consequently, the current literature allows the identification of measures to reduce and control greenhouse gas emissions from ships [6], [43], [44], [45].

To reduce the level of greenhouse gases by ships, many studies suggest the use of alternative marine fuels having low carbon content [46]. However, this solution will also require substantial technological changes to the architecture of the propulsion system [47], [48].

The sulphur content of the fuel used in maritime transport is another problem of air pollution, which cannot be neglected [49], [50]. The research identified a number of technical solutions that could be implemented in the near future [51], [52], [53].

The topics highlighted above show that the issue of the impact of maritime transportation on air pollution is extremely important and is analyzed in numerous publications. An important direction of research is the development of models for the determination of emissions from ships. The second direction of research is the development of technical solutions to reduce the impact.

In addition to the two directions of research, the experience of international shipping shows that the reduction of emissions from ships can be achieved through proper voyage management, such as reducing the ship's speed or route optimization [54], [55], [56], [57].

The practicality of such research is obvious, the results obtained can be adapted to the hydro-meteorological conditions in which the voyage takes place, to the design characteristics of the ship (including those of the propulsion system), to the type of fuel used.

From this perspective, the paper proposes the combination of the specialized software solution proposed by the University of Denmark (DTU) and the University of Southern Denmark with an algorithm developed by the authors in order to assess the environmental impact associated with merchant ships.

The paper proposes a method of monitoring the voyage of seagoing ships to determine the impact of their activity on the environment. The authors present in an organized way the results obtained according to the variants of operation corresponding to the conditions in which the voyage takes place, the characteristics of the ship (including those of the propulsion system), the type of fuel used. For each case, the fuel consumption, the gas emissions from the ships (with an emphasis on greenhouse gases) were determined. The research was carried out within the project POC / 163/1/3 SMIS / 2014 + / 120201-2022-2024. An innovative integrated maritime platform for real-time intervention through simulated disaster risk management assistance in coastal and port areas (PLATMARISC). The authors believe that the results of the research can be used by company management in both decision-making and crew training through modelling and simulation in order to promote the concept of environmentally friendly shipping and the sustainable development of maritime transportation.

2. Research Methodology

The Technological University of Denmark (DTU) and the University of Southern Denmark developed a tool that can calculate ships' gas emissions, fuel consumption, and energy efficiency. The calculation method can be used for the analysis of CO_2 and other emissions from ships, in order to comply with the IMO Energy Efficiency Limits (EEDI). By entering a ship's size, service speed, engine type, and technology, the calculation model will return the approximate figures for CO_2 emissions, fuel consumption, NO_x (nitrogen oxides) and SO_x (sulphur oxides), CO, hydrocarbons, particulate matter emissions [58].

2.1. Calculation methodology

2.1.1. Emission calculation. The simplified general formula for calculating emissions is [59], [60]:

$$Emission = Fuel\ consumption \times Control\ factor \times Emission\ factor$$

Where:
Control factor is referring to technologies that permit reduction of emissions

2.1.2. EEXI calculation. The simplified formula for EEXI is [61], [57], [62]:

$$EEXI = \frac{(P_{ME} \times ME\ SFOC \times C_F) + (P_{AE}\ \times AE\ SFOC \times C_F)}{DWT \times V_{ref}}\ (\frac{gCO_2}{ton\ mile})$$

Where:
EEXI – Energy Efficiency for Existing Ships Index
P_{ME} – Main engine power;
ME SFOC – Main engine specific oil consumption;
C_F - the conversion factor between fuel consumption and CO_2 emissions;
P_{AE} – Auxiliary engine power;
AE SFOC - Auxiliary engine specific oil consumption;
V_{ref} – Reference speed at 75% or 87% MCR_{lim}
MCR_{lim} – Limited Maximum Continous Rating

2.1.3. CII calculation. CII formula is presented below [63], [64]:

$$CII = \frac{Annual\ fuel\ consumption \times CO_2\ _{factor}}{Annual\ distance\ travelled \times Capacity} \times Correction\ factors\ (to\ be\ developed)$$

Where:
CII – Carbon Intensity Indicator

2.2. Emission types

Most of the emissions from marine engines consist of nitrogen, oxygen, carbon dioxide and small quantities of carbon monoxide, sulphur oxides, nitrogen oxides. There are as well non-combusted hydrocarbons and particulate matter. The main characteristics and adverse effects of main pollutants are mentioned in [59], [65].

2.3. Case study

The case study is focused on the calculation of different types of emissions, EEXI and CII for a container vessel, using different technologies. The ship's main characteristics are indicated in Table 1:

Table 1. Ship's specifications

Ship data	Value
Capacity (TEU)	13 000
Length overall (m)	381.1
Length between pp (m)	363.71
Breadth mld. (m)	49.41
Depth (m)	30.20
Draught design (m)	13.69
Draught maximum (m)	15.33
Deadweight (t)	145 600
Displacement at design draught (t)	168508
Displacement at maximum draught (t)	194 446
Speed Maximum (knots)	25.7
Coefficient block at design draught	0.668
Coefficient block at maximum draught	0.689
Main engine type	Slow speed
Main engine power (MCR) (kW)	84 814
Auxiliary power at sea at designed draught (kW)	2370
Propeller type	Conventional

There will be considered the following cases:

Table 2. Case studies

Conditions	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Hydro-meteo conditions	3 Bf/ 6 m/s	3 Bf/6 m/s	3 Bf/6 m/s	3 Bf/6 m/s	3 Bf/6 m/s	3 Bf/6 m/s
Vessel's speed	24 knots	18 knots	20 knots	20 knots	20 knots	20 knots
Fuel type	HFO	HFO	HFO	HFO	LSFO	LNG
Sulphur content	1.5	1.5	1.5	1.5	0.5	0
SO_x reduction technology	-	-	-	EGCS	-	-

Cases 1 and 2 will be studied together, vessel is navigating in good weather, she is using the same type of fuel (HFO), with a sulphur content of 1.5%. The difference between the cases is only the speed, 24 knots in the first case and 18 knots in the second case.

The following 4 cases will be analyzed in favourable weather conditions, 3Bf, constant ship speed of 20 knots, using different technologies, as follows:

Case 3 - the case when HFO type fuel will be used, 1.5% sulphur content

Case 4 - the case when HFO type fuel will be used, 1.5% sulphur content. An EGCS (Exhaust Gas Cleaning System) is fitted onboard the ship.

Case 5 - the vessel will use LSFO (Low Sulphur Fuel Oil), having a sulphur content of 0.5%.

Case 6 - LNG (Liquefied Natural Gas) fuel with a sulphur concentration of 0% will be used.

The results will then be compared, and conclusions will be drawn on the results obtained.

3. Results

For each case the following pollutants (per hour and per mile) will be calculated:

- CO_2 (carbon dioxide) emissions
- NO_x emissions (nitrogen oxides)
- SO_x (sulphur oxide) emissions
- CO (carbon monoxide) emissions
- HC (hydrocarbon) emissions
- PM emissions (particulate matter)

In addition, there will be calculated: fuel consumption (per hour and per mile), EEXI, and CII indicators.

3.1. Results and interpretation

3.1.1. Fuel consumption and emission calculation

Table 3. The fuel consumption per case

Fuel consumption	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Per hour (t/hr)	9.94	4.61	6	6.18	5.72	5.17
Per mile (kg/NM)	414	256	300	309	286	258

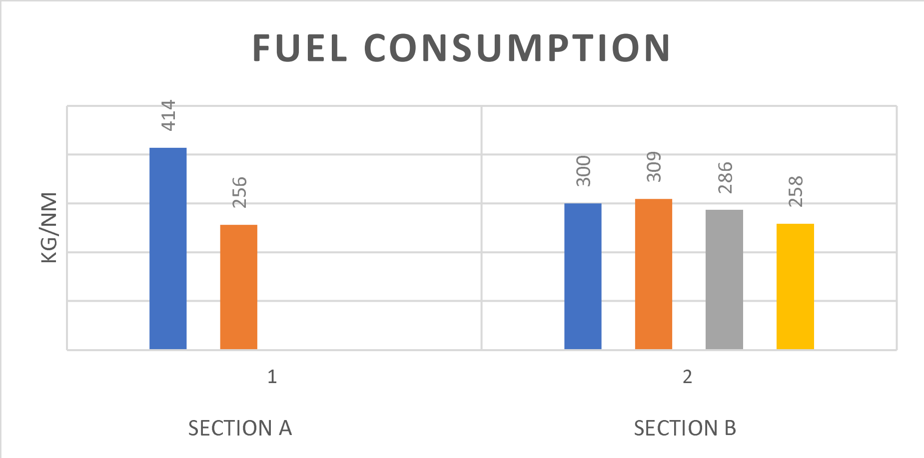

Figure 1. Graphical representation of fuel consumption

It is observed in Section A that the fuel consumption decreases by about 40% per mile, at a speed reduction of 6 knots.

In Section B, the fuel consumption is comparable, irrespective of the technology used. There is a slight decrease in Case 6, when the vessel is using LNG fuel.

Table 4. CO_2 emissions per case

CO_2 Emissions	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Per hour (t/hr)	31	14.4	18.7	19.3	18.3	1.1
Per mile (kg/NM)	1291	800	937	965	916	54

Table 5. NO_x emissions per case

NO_x emissions	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Per hour (kg/hr)	742	338	443	443	443	3
Per mile (kg/NM)	30.9	18.8	22.2	22.2	22.2	0.2

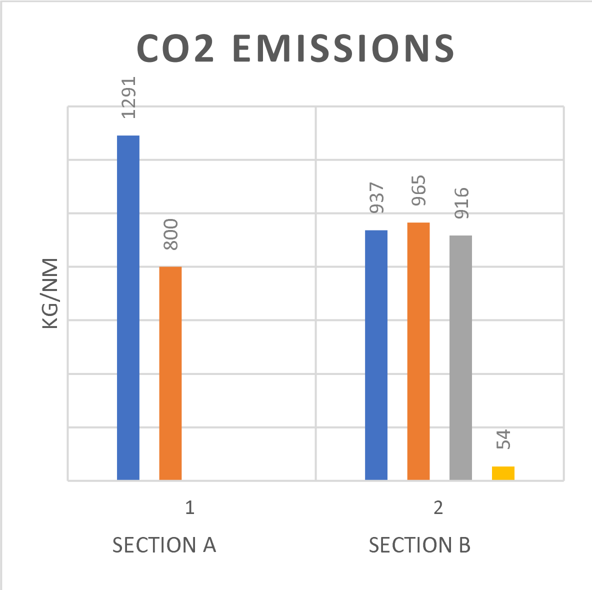

Figure 2. Graphical representation of CO_2 emissions

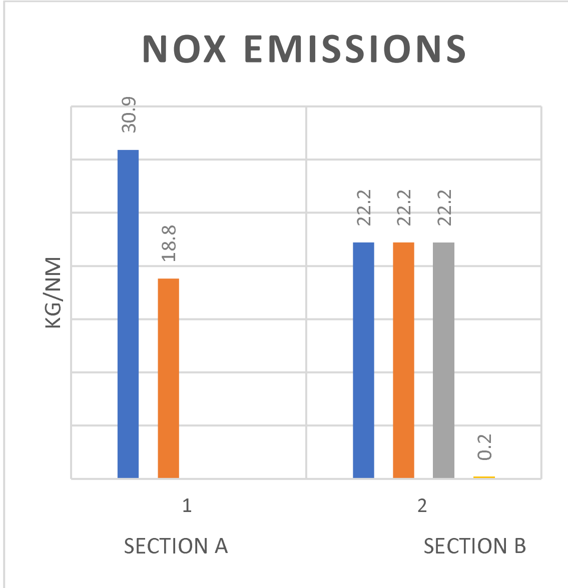

Figure 3. Graphical representation of NO_x emissions

It is observed in Section A that both CO_2 and Nox emissions decrease with speed and fuel consumption.

In Section B, CO_2 and NO_x emissions are reduced only by the use of LNG-type fuel, while the use of fuel with a sulphur content of more than 0.5% increases significantly the amount of CO_2 (NO_x) emissions.

Tabel 6. SO_x emissions per case

SOx emissions	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Per hour (kg/hr)	308	140	184	4	60	0
Per mile (kg/NM)	12.8	7.8	9.2	0.2	3	0

Tabel 7. PM emissions per case

PM emissions	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Per hour (kg/hr)	33.5	5.3	20	9	10.9	1
Per mile (kg/NM)	1.39	0.85	1	0.45	0.54	0.05

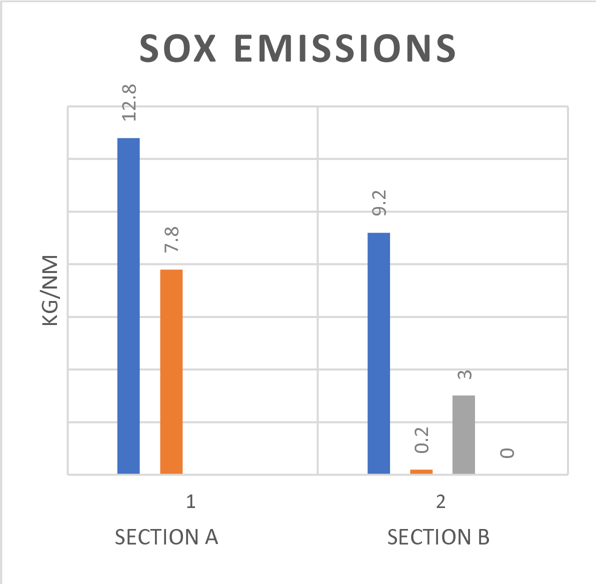

Figure 4. Graphical representation of SO_x emissions

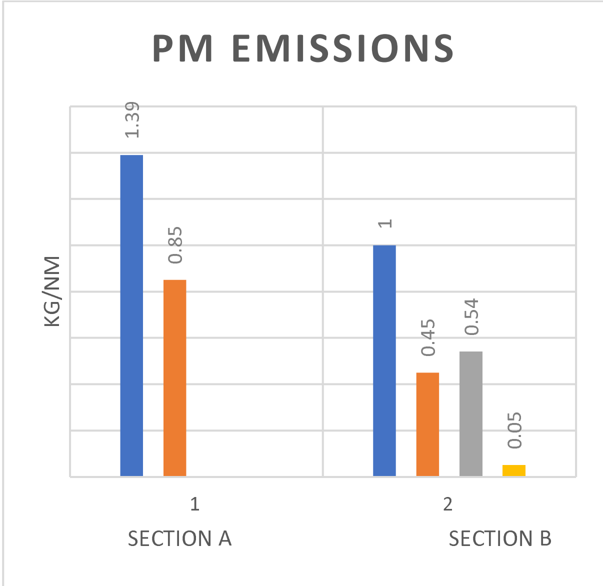

Figure 5. Graphical representation of PM emissions

It can be observed that SOx emissions decrease with speed reduction and with low sulphur fuel type, as well as installation of Scrubber (EGCS) technology.

PM emissions decrease with the sulphur concentration in fuel and decrease with the ship's speed and fuel oil consumption.

Tabel 8. CO emissions per case

CO emissions	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Per hour (kg/hr)	19.7	9.3	12	12	12	12.5
Per mile (kg/NM)	0.82	0.52	0.6	0.6	0.6	0.63

Tabel 9. HC emissions per case

HC emissions	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Per hour (kg/hr)	27.6	12.8	16.7	16.7	16.7	16.7
Per mile (kg/NM)	1.15	0.71	0.83	0.83	0.83	0.83

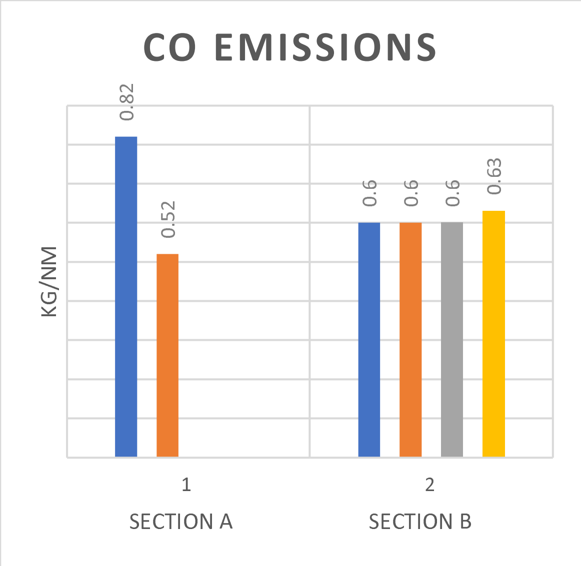

Figure 6. Graphical representation of CO emissions

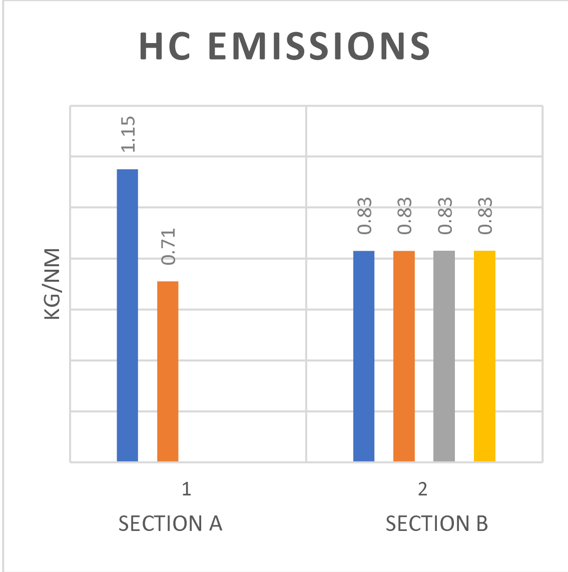

Figure 7. Graphical representation of HC emissions

Emissions of CO and HC are not influenced by the technology used and they are decreasing only with speed reduction and fuel oil consumption.

3.1.2. EEXI calculation

EEXI regulates CO_2 emissions relative to engine power, the transport capacity of the vessel, and speed.

EEXI attained for the specified ship is calculated as below [66]:

$$EEXI\ attained = \left(1 - \frac{Y}{100}\right) \times EEDI\ reference$$

Where:

Y - reduction factor specific for the vessel's type. For a 13 000 TEU container vessel, Y = 12% [57]

EEDI reference = 15.97 g/DWT/NM

EEXI attained = 0.88 x 15.97 = 14.05 g/DWT/NM

For Case 3-6, EEXI is indicated in Table 10.

Table 10. EEXI by case, by different technologies

	Case 3	**Case 4**	**Case 5**	**Case 6**
EEXI (g/DWT/NM)	14.59	15.07	14.05	11.13

It can be observed, from 1 January 2023, the vessel will have an EEXI compliant only if it changes HFO fuel to either LSFO or LNG fuel.

The vessel may take the following measures:
- Limiting engine power
- Improvements in vessel's performance
- Fuel type change

3.1.3. CII calculation

CII is the operational factor that measures how efficient the ship is and it is expressed in g CO_2 emitted on transport capacity and nautical miles. CII is an operational indicator, whereas EEXI, is a technical indicator. The CII will be calculated annually, and its value will indicate how efficient the ship is in relation to a reference value. The vessels will receive an efficiency indicator, from 'A' to 'E', an indicator that will become stricter by 2030. A vessel ranked 'A' will be the most efficient, while 'E' will be the least efficient vessel.

$$CII\ reference = a \times DWT^{-c}$$

Where:
a and c values are based on vessel type and capacity [67]

CII reference = $1984 \times 101920^{-0,489} = 1984 \times 0,0035 = 7,05$

CII required is calculated in Table 11.

Tabel 11. CII required

	2023	2024	2025	2026
CII required	6.69	6.55	6.41	6.27

Assuming the distance travelled in one year is 89000 NM, CII for Case 3 and Case 6 is:

$CII_3 = \frac{83393\ t}{89000\ NM * 101920\ t} = 9.19$

$CII_6 = \frac{4806\ t}{89000\ NM * 101920\ t} = 3.85$

With the current technology and HFO used, the vessel cannot comply with IMO regulations from 1st January 2023.

4. Conclusions

In the decarbonization process, there can be short-term, medium-term, and long-term possible measures and actions to be implemented.

The short-term measures are mainly based on operational measures, reducing the speed which leads to decreasing the fuel oil consumption or using fuel with low sulphur content.

At the operational/logistical level, a possible outcome of the measures could be an increase in travel time.

The following potentially negative impacts can be identified:

• The increase in travel time can have a negative impact on the quality of the goods transported

• Higher shipping rates. Any change in the supply-demand chain has the consequence of increasing transport fees

• Higher greenhouse gas emissions. In the long run, more ships (or modes of transport) will be needed for the rapid transport of goods between the world's ports.

In the medium term, the measures will focus on the implementation/introduction of low carbon fuels as well as zero-carbon fuels. This will increase the efficiency of new and existing ships. But the potential adverse effects include huge costs for modernizing old ships or investing in new ships and new technologies.

In the long term, after 2030, the strategies will focus on the development, supply, and improvement of new technologies and fuels. This will also include changes to vessels' design. In addition, there is already the issue of the availability of these fuels, the price, storage, supply, and all that logistics means.

Hydrogen and ammonia are currently considered the most efficient in the decarbonization process, with high energy density and low emissions. However, the most important obstacles are the high investment costs and the uncertainty in the supply of these types of fuels. Electric ships, which can be powered by land and have both economic and environmental benefits, also have great potential.

This case study was presented to determine the values of the main pollutants in different navigation situations and different fuel types used, having HFO as a reference. It is noticed that the use of low carbon fuels is the first step towards decarbonizing the maritime industry and achieving the increasingly strict IMO targets for the coming years in an attempt to halt global warming.

EEXI and CII are indicators that clearly show that existing ships that use high sulphur fuel, are extremely polluters and can no longer meet the regulations that will come into force in the coming years.

Switching to alternative fuels is a challenge now and, as mentioned above, involves huge costs in research, implementation, change in the supply chain, and finally the design of new ships, shipyards modifications, training of specialists, etc.

Acknowledgements
The research was carried out within the project POC / 163/1/3 SMIS / 2014 + / 120201-2022-2024. An innovative integrated maritime platform for real-time intervention through simulated disaster risk management assistance in coastal and port areas (PLATMARISC). The authors believe that the results of the research can be used by company management in both decision-making and crew training through modeling and simulation in order to promote the concept of environmentally friendly shipping and the sustainable development of maritime transport.

References:

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[1] Review of Maritime Transport 2021. United Nations Conference on Trade and Development. ISBN: 9789210000970. DOI: https://doi.org/10.18356/9789210000970

[2] Simpson Spence Young Outlook 2022. Published January 2022. https://www.ssyonline.com/media/2016/ssy-2022-outlook-final.pdf

[3] IMO, 2021. Energy Efficiency Of Ships. Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2020). International Maritime Organization. MEPC 77/6/1 20 August 2021. Marine Environment Protection Committee 77th session Agenda item 6.

[4] Bullock, S., Mason, J., Broderick, J., & Larkin, A. (2020). Shipping and the Paris climate agreement: a focus on committed emissions. *BMC Energy*, *2*(1), 1-16.

[5] International Maritime Organisation. Greenhouse Gas Emissions. Available online: https://www.imo.org/en/OurWork/Environment/Pages/GHG-Emissions.aspx (accessed on 06.03.2022)

[6] Joung, T. H., Kang, S. G., Lee, J. K., & Ahn, J. (2020). The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *4*(1), 1-7.

[7] Sharafian, A., Blomerus, P., & Mérida, W. (2019). Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential. *Energy Policy*, *131*, 332-346.

[8] Kachi, A., Mooldijk, S., Warnecke, C., & BMU, N. S. (2019). Carbon pricing options for international maritime emissions. *New Climate-Institute for Climate Policy and Global Sustainability gGmbH: Berlin, Germany.*

[9] Fang, S., Xu, Y., Li, Z., Ding, Z., Liu, L., & Wang, H. (2019). Optimal sizing of shipboard carbon capture system for maritime greenhouse emission control. *IEEE Transactions on Industry Applications, 55*(6), 5543-5553.

[10] Corbett, J. J., & Fischbeck, P. (1997). Emissions from ships. *Science*, *278*(5339), 823-824.

[11] Skjølsvik, K. O., Andersen, A. B., Corbett, J. J., & Skjelvik, J. M. (2000). Study on greenhouse gas emissions from ships. *MT Rep. Mtoo A23-038. Trondheim, Norway: MARINTEK.*

[12] Michaelowa, A., & Krause, K. (2000). International maritime transport and climate policy. *Intereconomics*, 35(3), 127-136.

[13] Olmer, N., Comer, B., Roy, B., Mao, X., & Rutherford, D. (2017). Greenhouse Gas Emissions from Global Shipping, 2013–2015 Detailed Methodology. *International Council on Clean Transportation: Washington, DC, USA*, 1-38.

[14] Styhre, L., Winnes, H., Black, J., Lee, J., & Le-Griffin, H. (2017). Greenhouse gas emissions from ships in ports–Case studies in four continents. *Transportation Research Part D: Transport and Environment, 54*, 212-224.
[15] Psaraftis, H. N. (2012). Market-based measures for greenhouse gas emissions from ships: a review. *WMU Journal of Maritime Affairs*, *11*(2), 211-232.
[16] IMO, M. (2000). Study of Greenhouse Gas Emissions from Ships. Issue no.
[17] Bodansky, D. (2018). Regulating greenhouse gas emissions from ships: The role of the International Maritime Organization. *In Ocean Law Debates* (pp. 478-501).
[18] Ekmekçioğlu, A., Kuzu, S. L., Ünlügençoğlu, K., & Çelebi, U. B. (2020). Assessment of shipping emission factors through monitoring and modelling studies. *Science of the Total Environment*, *743*, 140742.
[19] Nunes, R. A. O., Alvim-Ferraz, M. C. M., Martins, F. G., & Sousa, S. I. V. (2017). The activity-based methodology to assess ship emissions-A review. *Environmental Pollution*, *231*, 87-103.
[20] Matsukura, H., Udommahuntisuk, M., Yamato, H., & Dinariyana, A. A. B. (2010). Estimation of CO2 reduction for Japanese domestic container transportation based on mathematical models. *Journal of marine science and technology, 15*(1), 34-43.
[21] Trozzi, C. (2010). Emission estimate methodology for maritime navigation. *Techne Consulting, Rome.*
[22] Yang, D., Wu, L., Wang, S., Jia, H., & Li, K. X. (2019). How big data enriches maritime research–a critical review of automatic identification system (AIS) data applications. *Transport Reviews, 39*(6), 755-773.
[23] Kim, S. H., Roh, M. I., Oh, M. J., Park, S. W., & Kim, I. I. (2020). Estimation of ship operational efficiency from AIS data using big data technology. *International Journal of Naval Architecture and Ocean Engineering, 12*, 440-454.
[24] Peng, X., Wen, Y., Wu, L., Xiao, C., Zhou, C., & Han, D. (2020). A sampling method for calculating regional ship emission inventories. *Transportation Research Part D: Transport and Environment*, 89, 102617.
[25] Eyring, V., Isaksen, I. S., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., ... & Stevenson, D. S. (2010). Transport impacts on atmosphere and climate: Shipping. *Atmospheric Environment, 44*(37), 4735-4771.
[26] Johansson, L., Jalkanen, J. P., & Kukkonen, J. (2017). Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. *Atmospheric Environment, 167*, 403-415.
[27] Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–A review. *Transportation Research Part D: Transport and Environment, 52*, 408-421.
[28] Lindstad, H., Eskeland, G. S., Psaraftis, H., Sandaas, I., & Strømman, A. H. (2015). Maritime shipping and emissions: A three-layered, damage-based approach. *Ocean Engineering, 110*, 94-101.
[29] Sorte, S., Rodrigues, V., Borrego, C., & Monteiro, A. (2020). Impact of harbour activities on local air quality: A review. *Environmental Pollution, 257*, 113542.
[30] Poulsen, R. T., Ponte, S., & Sornn-Friese, H. (2018). Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport. *Geoforum, 89*, 83-95.
[31] Murena, F., Mocerino, L., Quaranta, F., & Toscano, D. (2018). Impact on air quality of cruise ship emissions in Naples, Italy. *Atmospheric Environment, 187*, 70-83.
[32] Zhang, Y., Yang, X., Brown, R., Yang, L., Morawska, L., Ristovski, Z., ... & Huang, C. (2017). Shipping emissions and their impacts on air quality in China. *Science of the Total Environment, 581*, 186-198.
[33] Yu, H., Fang, Z., Fu, X., Liu, J., & Chen, J. (2021). Literature review on emission control-based ship voyage optimization. *Transportation Research Part D: Transport and Environment, 93*, 102768.
[34] Kjetil 2015. Maritime routing and speed optimization with emission control areas. *Transportation Research Part C: Emerging Technologies Volume 52, March 2015*, Pages 57-73
[35] Li, L., Gao, S., Yang, W., & Xiong, X. (2020). Ship's response strategy to emission control areas: From the perspective of sailing pattern optimization and evasion strategy selection. *Transportation Research Part E: Logistics and Transportation Review, 133*, 101835.
[36] Khan, S., Grudniewski, P., Muhammad, Y. S., & Sobey, A. J. (2022). The benefits of co-evolutionary Genetic Algorithms in voyage optimisation. *Ocean Engineering, 245*, 110261.
[37] Perera, L. P., & Mo, B. (2016). Emission control based energy efficiency measures in ship operations. *Applied Ocean Research, 60*, 29-46.

[38] Yan, R., Wang, S., & Du, Y. (2020). Development of a two-stage ship fuel consumption prediction and reduction model for a dry bulk ship. *Transportation Research Part E: Logistics and Transportation Review, 138*, 101930.
[39] Zaccone, R., Ottaviani, E., Figari, M., & Altosole, M. (2018). Ship voyage optimization for safe and energy-efficient navigation: A dynamic programming approach. *Ocean engineering, 153*, 215-224.
[40] Wang, H., Lang, X., & Mao, W. (2021). Voyage optimization combining genetic algorithm and dynamic programming for fuel/emissions reduction. *Transportation Research Part D: Transport and Environment, 90*, 102670.
[41] Zis, T. P., Psaraftis, H. N., & Ding, L. (2020). Ship weather routing: A taxonomy and survey. *Ocean Engineering, 213*, 107697.
[42] Serra, P., & Fancello, G. (2020). Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping. *Sustainability*, *12*(8), 3220.
[43] Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy conversion and management*, *182*, 72-88.
[44] Traut, M., Larkin, A., Anderson, K., McGlade, C., Sharmina, M., & Smith, T. (2018). CO2 abatement goals for international shipping. *Climate Policy*, *18*(8), 1066-1075.
[45] Christodoulou, A., Dalaklis, D., Ölcer, A., & Ballini, F. (2021). Can Market-Based Measures Stimulate Investments in Green Technologies for the Abatement of GHG Emissions from Shipping? A Review of Proposed Market-Based Measures. *Transactions on Maritime Science*, *10*(01), 208-215.
[46] Ash, N., & Scarbrough, T. (2019). Sailing on solar: Could green ammonia decarbonise international shipping. *Environmental Defense Fund: London, UK.*
[47] Salmon, N., & Bañares-Alcántara, R. (2021). Green ammonia as a spatial energy vector: a review. *Sustainable Energy & Fuels, 5*(11), 2814-2839.
[48] Fasihi, M., Weiss, R., Savolainen, J., & Breyer, C. (2021). Global potential of green ammonia based on hybrid PV-wind power plants. *Applied Energy, 294*, 116170.
[49] Moshiul, A. M., Zaki, N. M., & Husain, M. A. (2019). Review of Sulphur Emission from International Shipping-Effects and Regulatory Global Abatement Steps. *International Journal of Mechanical Engineering and Technology, 10*(2), 924-933.
[50] Lindstad, H. E., Rehn, C. F., & Eskeland, G. S. (2017). Sulphur abatement globally in maritime shipping. *Transportation Research Part D: Transport and Environment, 57*, 303-313.
[51] Wang, Z., Zhang, H., & Gan, X. (2019, November). Research on solution of ship low sulphur fuel based on IMO sulphur limitation regulation. *In IOP Conference Series: Earth and Environmental Science* (Vol. 401, No. 1, p. 012012). IOP Publishing.
[52] Kim, A. R., & Seo, Y. J. (2019). The reduction of SOx emissions in the shipping industry: The case of Korean companies. *Marine Policy, 100*, 98-106.
[53] Psaraftis, H. N., Amboy, P., & Psaraftis. (2019). Sustainable shipping. *Berlin: Springer International Publishing.*
[54] Ma, W., Lu, T., Ma, D., Wang, D., & Qu, F. (2021). Ship route and speed multi-objective optimization considering weather conditions and emission control area regulations. *Maritime Policy & Management, 48*(8), 1053-1068.
[55] Zhen, L., Hu, Z., Yan, R., Zhuge, D., & Wang, S. (2020). Route and speed optimization for liner ships under emission control policies. *Transportation Research Part C: Emerging Technologies, 110*, 330-345.
[56] DNV. (2021). MARITIME FORECAST TO 2050—Energy Transition Outlook 2021. DNV, Oslo.
[57] Rutherford, D., Mao, X., & Comer, B. (2020). Potential CO2 Reductions under the Energy Efficiency Existing Ship Index. *International Council on Clean Transportation Working Paper, 27.*
[58] Danish Shipping (2016). Calculation tool for assessment of ships' energy consumption and fuel gas emissions, including CO_2_ (EEDI), https://www.danishshipping.dk/en/policy/klimapolitik/beregningsvaerktoejer/ (accessed on 07.03.2022)
[59] Kristensen, H. O. (2012). Energy demand and exhaust gas emissions of marine engines. *Clean Shipping Currents, 1*(6), 18-26

[60] Lee, H., Park, D., Choo, S., & Pham, H. T. (2020). Estimation of the non-greenhouse gas emissions inventory from ships in the port of Incheon. *Sustainability*, *12*(19), 8231.

[61] Resolution MEPC.333(76) (2021). *2021 Guidelines on the method of calculation of the attained energy efficiency existing ship index (EEXI).*

[62] Li, F. (2021, March). Energy Efficiency Measurement Method of Operating Ship Based on Data Mining. In *Journal of Physics: Conference Series* (Vol. 1802, No. 3, p. 032144). IOP Publishing.

[63] Der Norkse Veritas (2021). CII – Carbon Intensity Indicator. Available online: https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/implementation.html (accessed 07.03.2022).

[64] Resolution MEPC.336(76) (2021). *2021 Guidelines on operational carbon intensity indicators and the calculation methods (CII Guidelines, G1).*

[65] Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: a review. Frontiers in public health, 14.

[66] Resolution MEPC.328(76) (2021). *2021 Revised MARPOL Annex V.*

[67] Resolution MEPC.337(76) (2021). *2021 Guidelines on the reference lines for use with operational carbon intensity indicators (CII reference lines guidelines, G2), Annex 11.*