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Investigating the Effectiveness of Energy Saving Devices Onboard Ro-Ro Vessel

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ABSTRACT

This study aimed at investigating the effectiveness of energy saving devices onboard Ro-Ro vessels on the Gulf of Guinea. The energy saving devices available onboard ships were understudied, and the effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of fuel consumption and cargo volume (dead weights) was investigated. The effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of ship speed and voyage distance — as well as in terms of cost of ship operation — was analyzed. Energy Efficiency Operational Index (EEOI) methods were employed to assess the effectiveness of energy saving devices onboard Ro-Ro vessels as regards fuel consumption, speed, voyage distance and cost of ship operation. Results showed that energy efficiency operation index depends significantly on speed, voyage distance travelled and fuel consumption, except dead weight which showed no direct relationship. High energy efficiency operation index is the consequence of high speed, voyage distance travelled and fuel consumption. It was discovered that the energy efficiency operation index for MV Mary, which used MDO and HFO as fuels, is 1.80336×10^{-5} g CO_2/ton mile — which is more than that of MV Indigo, which used MDO and LPG and whose EEOI is 1.79×10^{-5} g CO_2/ton mile. Also, the amount of money spent on fuel by MV Mary in 2018 is ₦612,500.00, which is less than the amount of money spent on fuel by MV Indigo in the same year, which is ₦927,500.00. This is similar for the voyages of the two vessels for subsequent years in the study period. Conclusion and recommendations were made that further research should be carried out on investigating the effectiveness of energy saving devices onboard other types of ships other than Ro-Ro vessels.

Keywords: Energy Saving Devices, Ro-Ro Vessel, Gulf of Guinea, Energy Efficiency Operational Index (EEOI), Energy Efficiency Design Index (EEDI), Low Carbon Fuels, Ship Emissions.

1. INTRODUCTION

1.1 Background of the Study

Maritime transport is responsible for over 90% of all international freight movements in terms of volume in Nigeria and Africa, and is thus the most important facilitator of the region's participation in the global market (Wilmsmeier and Hesse, 2011). Shipping, despite being the most efficient mode of commercial transport in terms of CO_2 emitted per tonne-km of cargo carried, currently accounts for about 3% of global anthropogenic CO_2 emissions, but its share is expected to grow as a result of increased transportation combined with difficulties in implementing energy saving and emission reducing measures. As fuel efficiency is inextricably linked to air emissions, measures and policies that successfully improve energy efficiency will have positive implications for the region's emission levels. The maritime transport sector is under considerable pressure to enhance the effectiveness of energy saving measures in ships, especially cargo ships, operating on international waters.

Energy saving devices onboard ships encompass the measures and methods for saving energy in ship operation compared to conventional ships. They include, among other things, the asymmetric after-body (stern-bulb form), propeller, nozzles, guide fins and the rudder, alone and in combination. Energy saving devices onboard ships effectively satisfy the EEDI, EEOI and EEXI requirements as they can be easily applied to existing ships. The International Maritime Organization (IMO), considering its responsibility to reduce the impact of shipping on climate change, adopted mandatory measures in July 2011, making the Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Index (EEOI) and Energy Efficiency Existing Index (EEXI) mandatory for new ships and all existing ships above 400 GRT respectively (IMO, 2011). The Energy Efficiency Design Index (EEDI) is the measure of total CO_2 emission per tonne mile. The amount of CO_2 emitted depends upon fuel consumption, and fuel consumption depends upon the total power requirement, which means the EEDI formulation eventually has certain impacts on ship design parameters that are closely related to the economic performance of the ship. The EEDI requires a minimum energy efficiency level in terms of CO_2 emissions per capacity mile for different ship types and size segments (IMO, 2009).

Due to these regulations, ship design is required to be adapted, and any changes to basic design features such as speed and deadweight have an impact on shipping economics. There are various measures which can be used to meet EEDI requirements. It is very important to study the financial and economic impacts of EEDI regulations on ship owners and charterers, because ship owners and charterers operate in the industry to maximize their profits from the shipping business, and any negative impact of these regulations on a ship's earnings potential may put them out of business.

The EEDI requires a specified energy efficiency, primarily expressed by fuel consumption per capacity mile (e.g. tonne mile) for different ship types and sizes (Hon & Wang, 2019). With the level being tightened over time, the EEDI will stimulate continued technical development of all the components influencing the energy efficiency of a ship. In order to meet the energy efficiency index regulations, the main aim of a ship builder is to reduce the EEDI value. This can be done in different ways, which include: firstly, the reduction of individual emissions of main engine, auxiliary engine and shaft generator/motor; secondly, by using efficient technologies as it reduces CO_2 emissions from the overall emissions; and finally, by increasing the transport work. Considering the first option — reducing the individual emissions of main engine, auxiliary engine and shaft generator/motor — means instalment of highly efficient engines, i.e. engines with lesser specific fuel consumption or engines that use low carbon fuel such as LNG (Hon & Wang, 2019).

Furthermore, another option to meet the energy efficiency design and operational index regulations is to reduce the designed power of the main engine, because at less power, fuel consumption is less and thus

CO_2 emissions are reduced. However, as per IMO guidelines, a ship owner cannot reduce the power of the ship to such an extent that would limit its manoeuvrability under adverse conditions. Considering the second option — making use of efficient technologies — means use of energy saving technologies such as waste heat recovery systems and solar power. Design measures that can be used to improve a ship's EEDI include optimized hull design, hydrodynamic modification to hull, advanced hull coatings, lightweight construction, and improved propeller design such as contra-rotating propellers (Hughes, 2011). Considering the third option — increasing transport work — a ship owner who wants to improve EEDI of his vessel has two main options: first, to increase the deadweight (capacity) of the ship; and second, to reduce the design speed of the ship, because at a reduced speed, power required by the main engine will be reduced considerably, as power is the cubic function of the speed. In short, a ship owner has a number of options available that can be used to improve EEDI of the ship. But the question is which of these options is cost effective, because from a ship owner's point of view, cost effectiveness of implementing such measures is of paramount importance.

This research work analysed the concept of energy efficiency design and operational index by studying all the components of energy efficiency index formula separately in order to quantify the impact of the changes adapted to Ro-Ro ship design and operation to meet the energy efficiency design and operational index requirements. This work also highlighted the feasible options available to ship owners to meet the energy efficiency design and operational index requirements and assessed different approaches available to find out how a ship owner can decide which measure is cost effective. This work, in general, investigated the cost benefit of the energy efficiency design and operational index to ship owners and operators commercially, or whether it is a regulation developed by IMO to reduce CO_2 emissions which would burden ship owners with extra costs. This dissertation is based on the critical review of energy efficiency design and operation index formula on the basis of available literature, and it focused on statistical analysis of calculating the energy efficiency index of different ship voyages.

1.2 Statement of the Problem

Maritime transport is still the backbone of global transport over the entire world due to its large trade volume and low unit transportation cost. Around 80% of global trade by volume and over 70% of global trade by value are carried by sea and handled by ports worldwide (UNCTAD, 2018). Over the last decade, there has been an overall increase in the number of vessels of the world commercial fleet, with more emissions laying the burden on the environment notably. For example, the global warming caused by greenhouse gas (GHG) emissions such as carbon dioxide (CO_2) brings negative impact on global agriculture and trade (MAN Diesel & Turbo, 2007). To limit the GHG emission of marine vessels, the International Maritime Organization (IMO) has put forward energy efficiency index regulations. Energy efficiency design and operational index is an indicator of the ship energy efficiency, which is calculated — based on a complex formula — as the ratio of the ship's potential CO_2 emission to its available capacity for transporting useful weight. As a result, higher requirements are placed on the propulsion design of ships, especially conventional ones, in order to meet the energy efficiency index regulations (Hon & Wang, 2019). The consequences of these higher requirements — such as increasing the deadweight (capacity) of the ship while reducing the individual emissions of main engine, auxiliary engine and shaft generator/motor, as well as reducing the designed power of the main engine — affect the ship engine power output, thrust and specific fuel consumption. This is the major concern of this study, as it impacts on the ship design and operation in terms of efficiency, cost and time. Therefore, investigating the effectiveness of energy saving devices onboard Ro-Ro vessels on the Gulf of Guinea is the motivation of this research work.

1.3 Aim and Objectives of Study

The aim of this research is to investigate the effectiveness of energy saving devices onboard Ro-Ro vessels on the Gulf of Guinea. The objectives of this research include:

i. To understudy the energy saving devices available onboard ships.

ii. To investigate the effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of fuel consumption and cargo volume (dead weights).

iii. To assess the effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of ship speed and voyage distance.

iv. To analyze ships energy efficiency data to determine the effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of cost of ship operation.

1.4 Scope of Work

In order to achieve the set objectives of the research work, the scope of this research shall be limited to:

i. The study of energy saving devices in ships.

ii. The focus on investigating the effectiveness of energy saving devices onboard Ro-Ro vessels on the Gulf of Guinea.

iii. The effectiveness of energy saving devices on energy efficiency design and operational index of Ro-Ro vessels in the Gulf of Guinea.

1.5 Research Approach

In this study, in order to investigate the effectiveness of energy saving devices onboard Ro-Ro vessels on the Gulf of Guinea, MATLAB and SPSS computer software were employed to investigate the effectiveness of energy saving devices on the energy efficiency design and operation index of Ro-Ro vessels operating in the Gulf of Guinea — in terms of the specific fuel consumption of ship, the ship speed, the voyage distance and the ship dead weight (cargo volume). Using this tool, it is possible to make parametric analyses for all types of ships that cover the current energy efficiency design and operation index formulations and requirements by IMO.

1.6 Significance of Study

This study is significant as it provides evidence of investigating the effectiveness of energy saving devices on the energy efficiency design and operation index of Ro-Ro vessels operating in the Gulf of Guinea in terms of the specific fuel consumption of ship, the ship speed, the voyage distance sailed and the ship dead weight (cargo volume). This study is also significant as it may serve as an impetus to other academics for curriculum development and research work. Finally, this work will be of immense benefit as it may serve as an aid and guide to future research on investigating the effectiveness of energy saving devices onboard Ro-Ro vessels on the Gulf of Guinea.

1.7 Limitation of the Study

In the process of carrying out this research study, diverse constraints were encountered, as follows:

i. There was difficulty in gathering the necessary information or materials required for the successful completion of this research study.

ii. Time also posed as a constraint to the successful completion of this research study. The researcher had to combine the time for work, lectures, and family when carrying out this research. Though it was not easy, the researcher was still able to carry out the research work.

iii. There was not enough finance on the part of the researcher to complete this research study.

Irrespective of these constraints, the researcher was still able to successfully carry out this research study.

2. MATERIALS AND METHODS

2.1 Material

In this study, the materials used to investigate the effectiveness of energy saving devices on the energy efficiency design and operation index of Ro-Ro vessels operating in the Gulf of Guinea are extractions from data of ship voyages from Clarkson's World Fleet database. MATLAB and SPSS computer software also constituted part of the materials employed to analyze the effectiveness of energy saving devices on the energy efficiency design and operation index of Ro-Ro vessels operating in the Gulf of Guinea in terms of the specific fuel consumption of ship, the ship speed, the voyage distance and the ship dead weight (cargo volume). Using this tool, it is possible to make parametric analyses for all types of ships that cover the current energy efficiency index formulations and requirements by IMO.

2.2 Method for Energy Efficiency Design Index for Ship Design and Operation

Technical measures, operational measures and economic instruments are being studied as methods for reducing CO_2 emissions according to recent discussions at the IMO. The technical and operational measures are direct measures for improving the ship's hardware (equipment), while the latter are implemented by improvements or innovations in the operation of the ship. In contrast, economic instruments are not meant to reduce CO_2 emissions directly; they may be considered as instruments that offer economic incentives to promote implementation of technical or operational measures. Therefore, for the purpose of this research work, the methods used in marine emission control are the technical and operational measures.

2.2.1 Technical Design Measures of Controlling Marine Emissions

Technical measures aim to enhance the energy efficiency by hardware (equipment) improvements of the ship, as mentioned earlier. Some specific examples of the technical measures are given below:

- Modified hull form (reduction in propulsion resistance)
- Modified propeller (enhanced propulsion efficiency)
- Energy saving appendages on hull
- Increase in dead weight capacity by increasing the hull size
- Use of energy from exhaust heat recovery
- Use of low conversion factor fuels and renewable energy (wind power or solar power)

IMO has proposed the Energy Efficiency Design Index (EEDI) as the index for evaluating the technical measures. EEDI is an index expressing the energy efficiency of new ships and is estimated by the following equation (IMO, 2012):

$$\text{EEDI (g/ton mile)} = \frac{CO_2 conversion\ factor \left(\frac{g}{kWh}\right) \times engine\ output(kW)}{capacity(ton) \times speed(mile/h)} \tag{3.1}$$

In the equation above, the EEDI is a value calculated taking design values as parameters, and it expresses the CO_2 emission reduction potential. EEDI is required to satisfy the IMO standard value (set according to Deadweight (DWT) of each type of ship) for new ships to be built henceforth.

2.2.2 Operational Measures of Controlling Marine Emissions

Operational measures aim to enhance the energy efficiency through improvements or innovation in the operation of the ship. The operational measures are applicable to individual ships. Specific examples of the operational measures are:

- Optimization of operational plan of individual ships and fleets
- Operation at reduced speed
- Weather routing
- Just-in-time entry into port
- Hull maintenance (for instance, reduction in propulsion resistance by cleaning the hull)
- Machinery maintenance

IMO has proposed the Energy Efficiency Operational Indicator (EEOI) and the Ship Energy Efficiency Management Plan (SEEMP) as tools for promoting the implementation of operational measures. The

EEOI is an indicator expressing the energy efficiency of the ship in operation and is estimated by the following equation (Bazari & Longva, 2011):

$$\text{EEOI (g/ton mile)} = \frac{CO_2 conversion\ factor\left(\frac{g}{kWh}\right)\times fuel\ consumption(g)}{Actual\ cargo\ weight(ton)\times actual\ voyage\ distance(mile)} \quad (3.2)$$

The EEOI also expresses the CO_2 emission rate of the ship, similar to the EEDI. However, it differs from the EEDI in that it is calculated from values measured during an actual voyage. As seen from the equation, the EEOI readily varies according to the difference in operation (route, load) and thus it is not appropriate to use the obtained value for comparison with the EEOI values of other ships. It should be used as an indicator to evaluate energy efficiency improvement in the same ship.

The SEEMP is a management plan that should be used for implementing improvements in energy efficiency by operational measures. The EEOI and SEEMP are both effective tools that ship operators can use to improve the energy efficiency of their ships. The impact of energy efficiency is finally computed by subtracting the average for energy efficiency for the less efficient half of the sample from the average obtained for the remaining ships.

Due to different carrying capacity of different segments, the cargo factor R is defined as:

$$R = \frac{M_{cargo}}{DW} \quad (3.3)$$

M_{cargo} = actual mass of the cargo (tonnes)

DW = Design load of the ship (tonnes)

Substituting equation (3.3) into (3.2):

$$EEOI = \frac{\sum_i \sum_i FC_{ji}\times C_f}{DW_i \sum_i (R\times D)} \quad (3.4)$$

FC = Fuel consumption of the ship

R = Cargo factor of segment

Cf = Conversion factor

D = Voyage distance

The fuel consumption of the ship during navigation is mainly concentrated on the main engines, auxiliary engines and boiler, with proportions of the total fuel consumption of 86%, 10% and 3% respectively. Equation (3.4) can then be written as:

$$EEOI = \frac{\sum_i \sum_i FC_{Mji}\times C_{FM} + FC_A\times C_{FA} + FC_B\times C_{FB}}{DW_i \sum_i (R\times D_i)} \quad (3.5)$$

FC_M = Fuel consumption of the ship main engines

FC_A = Fuel consumption of the ship auxiliary engines

FC_B = Fuel consumption of the ship boiler

C_{FM}, C_{FA}, C_{FB} = Conversion factors for main engines, auxiliary engines and boiler respectively

The fuel consumption of the main engines can be expressed as:

$$FC_M = P_M \times SFC_M \times T_M \tag{3.6}$$

P_M = main engine power (kW)
SFC_M = specific fuel consumption rate of the main engines
T_M = working (running) time of the main engines

Substituting equation (3.6) into (3.4):

$$EEOI = \frac{\sum_i \sum_i (P_M \times SFC_M T_M C_{FM}) + (FC_A \times C_{FA}) + (FC_B \times C_{FB})}{1000 DW_i \sum_i (R \times D_i)} \tag{3.7}$$

During the period of time when the vessel is in port, the ship auxiliary engines and boiler are also running. Equation (3.7) can be further simplified as:

$$EEOI = \frac{\sum_i \sum_i (P_M \times SFC_M T_M C_{FM}) + (P_A \times SFC_A T_A C_{FA}) + (P_B \times SFC_B T_B C_{FB}) \times T_p \times V_s}{1000 DW_i \sum_i (R \times D_i)} \tag{3.8}$$

P_A = ship auxiliary engine power (kW)
SFC_A = specific fuel consumption rate of the auxiliary engines
T_A = working (running) time of the auxiliary engines
P_B = boiler power (kW)
SFC_B = specific fuel consumption rate of the ship boiler
T_B = working (running) time of the ship boiler
T_p = time of arrival of the ship
V_s = ship speed

CF is a non-dimensional conversion factor between fuel consumption measured in grams and CO_2 emission also measured in grams, based on carbon content. The values of CF for different fuel types are given in Table 3.1 below.

Table 3.1: Reference Values of CF for Different Fuel Types

Type of Fuel	**Reference**	**Carbon Content**	**CF (t-CO_2/t-Fuel)**
1. Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400

Type of Fuel	Reference	Carbon Content	CF (t-CO_2/t-Fuel)
4. Liquefied Petroleum Gas (LPG) — Propane		0.819	3.000000
4. Liquefied Petroleum Gas (LPG) — Butane		0.827	3.030000
5. Liquefied Natural Gas (LNG)		0.75	2.750000

(Source: Bazari & Longva, 2011)

Rolling Average

Rolling average, when used, can be calculated in a suitable time period — for example, one year closest to the end of a voyage for that period, or a number of voyages (e.g. six or ten voyages) that are agreed as statistically relevant to the initial averaging period. The Rolling Average EEOI is then calculated for this period or number of voyages by Equation 3.9.

Where the average of the indicator for a period or for a number of voyages is obtained, the Indicator is calculated as:

$$Average\ EEOI = \frac{\Sigma_i \Sigma_j FC_{ij} \times CF_j}{\Sigma_i (m_{cargo,i} \times D_i)} \tag{3.9}$$

j = the fuel type

i = the voyage number

FC_{ij} = the mass of consumed fuel j at voyage i

CF_j = the fuel mass to CO_2 mass conversion factor for fuel j

m_{cargo} = cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships

D = the distance in nautical miles corresponding to the cargo carried or work done

The unit of EEOI depends on the measurement of cargo carried or work done, e.g., tonnes CO_2/(tonnes·nautical miles), tonnes CO_2/(TEU·nautical miles), tonnes CO_2/(person·nautical miles), etc.

2.3 Data Collection

Data characterizing ships' technical specifications were obtained from Clarksons World Fleet Register. The dataset includes all ships active in 2020 (including ships built in previous years). Data characterizing ships' operational characteristics (speed, loading condition and voyage characteristics) are obtained from individual ship logs. The ship log dataset is for the period 1st January 2018 to 31st December 2021 only. Where necessary (e.g. missing data), the technical and operational data is supplemented or compared with data and assumptions from the IMO 2nd GHG Study, or in some instances other third-party sources. Market data describing prices in different shipping markets are obtained from Clarksons Shipping Intelligence Network (2018–2021).

2.4 Data Analysis

In this study, MATLAB and SPSS computer software were employed to analyze the effectiveness of energy saving devices on the energy efficiency design and operation index of Ro-Ro vessels operating in the Gulf of Guinea, in terms of the specific fuel consumption of ship, the ship speed, the voyage distance and the ship dead weight (cargo volume). Using this tool, it is possible to make parametric analyses for all types of ships that cover the current energy efficiency design and operation index formulations and requirements by IMO.

3. RESULTS AND DISCUSSIONS

3.1 Results

3.1.1 Understudying the Energy Saving Devices Available Onboard Ships

The first objective of this study is to understudy the energy saving devices available onboard ships. Using the empirical review and assessment of extant studies, the energy saving devices available onboard ships are technical measures aimed to enhance the energy efficiency by hardware (equipment) improvements of the ship, as enumerated in Table 4.1.

Table 4.1: Energy Saving Devices Available Onboard Ships

S/N	Energy Saving Devices Available Onboard Ships
1	Modified hull form (reduction in propulsion resistance)
2	Modified propeller (enhanced propulsion efficiency)
3	Energy saving appendages on hull
4	Increase in dead weight capacity by increasing the hull size
5	Use of energy from exhaust heat recovery
6	Use of low conversion factor fuels and renewable energy (wind power or solar power)

This study analyses the effectiveness of energy saving devices using low conversion factor fuels on the energy efficiency design and operation index of Ro-Ro vessels operating in the Gulf of Guinea. EEOI is a comprehensive data indicator which is influenced by many factors — these include the ship's main engine, auxiliary engine, boiler fuel consumption and all kinds of fuel CO_2 emission factor (Cf) — as well as ship operating data, ship design load, ship cargo load and voyage.

This study focuses on two Ro-Ro ships (MV Mary and MV Indigo) operating with two different fuel types, and their data are presented in Table 4.2. In order to compute EEOI using the standard method specified in equation (3.9), 8 voyages of the two ships' trips between 2018 and 2021 were selected. The voyage defined as a ship trip in a period of time, including stops at anchorages, ports, road-steads, etc.

Table 4.2: Main Particulars of Case Study Ro-Ro Vessels (MV Mary and MV Indigo)

Ship Parameter	MV Mary	MV Indigo
Length (m)	275.2	289
Beam (m)	39.4	32.2
Moulded depth (m)	23.6	21.5
Draft (m)	12.5	11.7
Dead weight — DWT (tonnes)	54,665	58,900
Gross Tonnage (tonnes)	60,000	60,000
Speed (knots)	24.2	18
Power (kW)	42,720	42,970
Capacity (TEUs)	4,340	4,354
Main Engine	MAN B&W 6S60MC	MAN B&W 6S60MC / LM9000 Aeroderivative Gas Turbine (42.9 MW, 50/60 Hz)
Main engine speed	90	90
Auxiliary engines	WÄRTSILÄ VASA 4RCC/26	WÄRTSILÄ VASA 4RCC/26
Boiler model	AQ12/AQ-2	AQ12/AQ-2

Source: Clarkson, 2022

From the results obtained for the amount of emission from the different marine fuel types using the Energy Efficiency Operational Indicator method, based on data from the operation of the ship, it is shown that more emission of CO_2 was produced in the voyage per tonne-mile for MV Mary, which used MDO and HFO Marine fuel, compared to the voyage for MV Indigo, which used Marine Diesel Oil (MDO) and LPG fuels. This demonstrates the effectiveness of energy saving using devices with low conversion factor fuels such as LPG.

3.1.2 Effectiveness of Energy Saving Technologies on EEOI in Terms of Fuel Consumption and Cargo Volume (Dead Weights)

i. Impact of EEOI on Ship MV Mary — Fuel Consumption

The result of the impact of energy efficiency operational index (EEOI) on fuel consumption of the MV Mary ship is presented in Figure 4.1. The figure shows that the energy efficiency operational index (EEOI) increases with increase in fuel consumption, as indicated by the fourth voyage (Voyage 4). The seventh voyage (Voyage 7), with the least fuel consumption (50 tonnes), had the least energy efficiency operational index (EEOI). This conforms to results obtained by previous authors (Devanney, 2011; Hon & Wang, 2019).

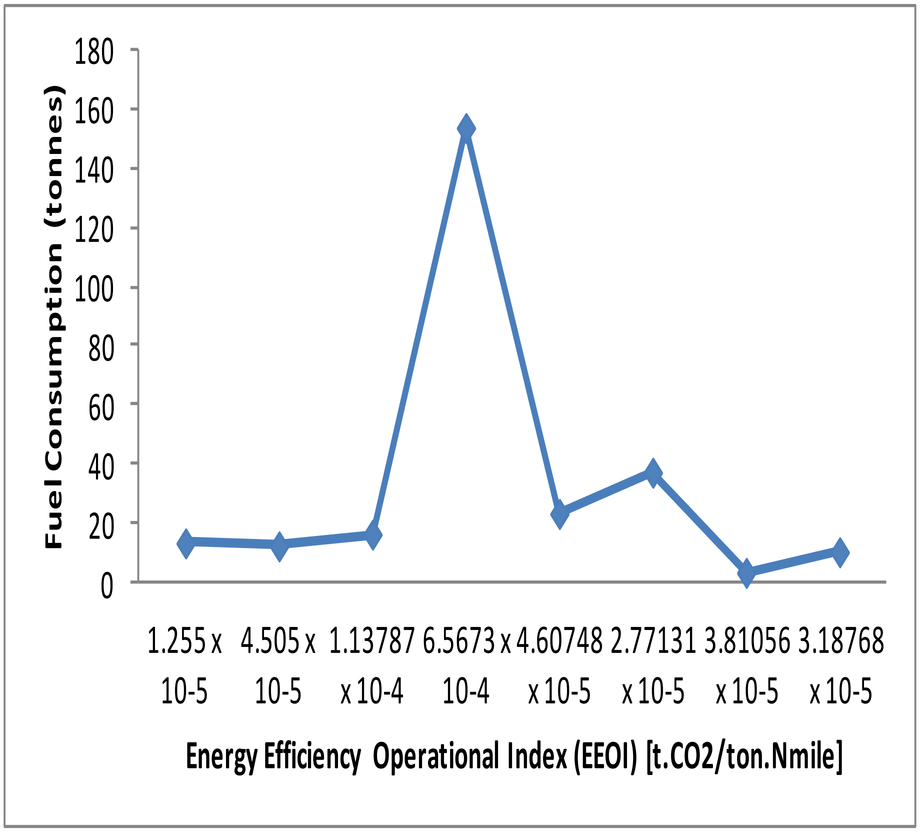

Figure 4.1: Impact of EEOI on Ship MV Mary — Fuel Consumption

ii. Impact of EEOI on Ship MV Indigo — Fuel Consumption

The result of the impact of energy efficiency operational index (EEOI) on fuel consumption of the MV Indigo ship is presented in Figure 4.2. The figure shows that the energy efficiency operational index (EEOI) increases with increase in fuel consumption, as indicated by the fourth voyage (Voyage 4). The seventh voyage (Voyage 7), with the least fuel consumption, had the least energy efficiency operational index (EEOI). This conforms to results obtained by previous authors (Devanney, 2011; Hon & Wang, 2019).

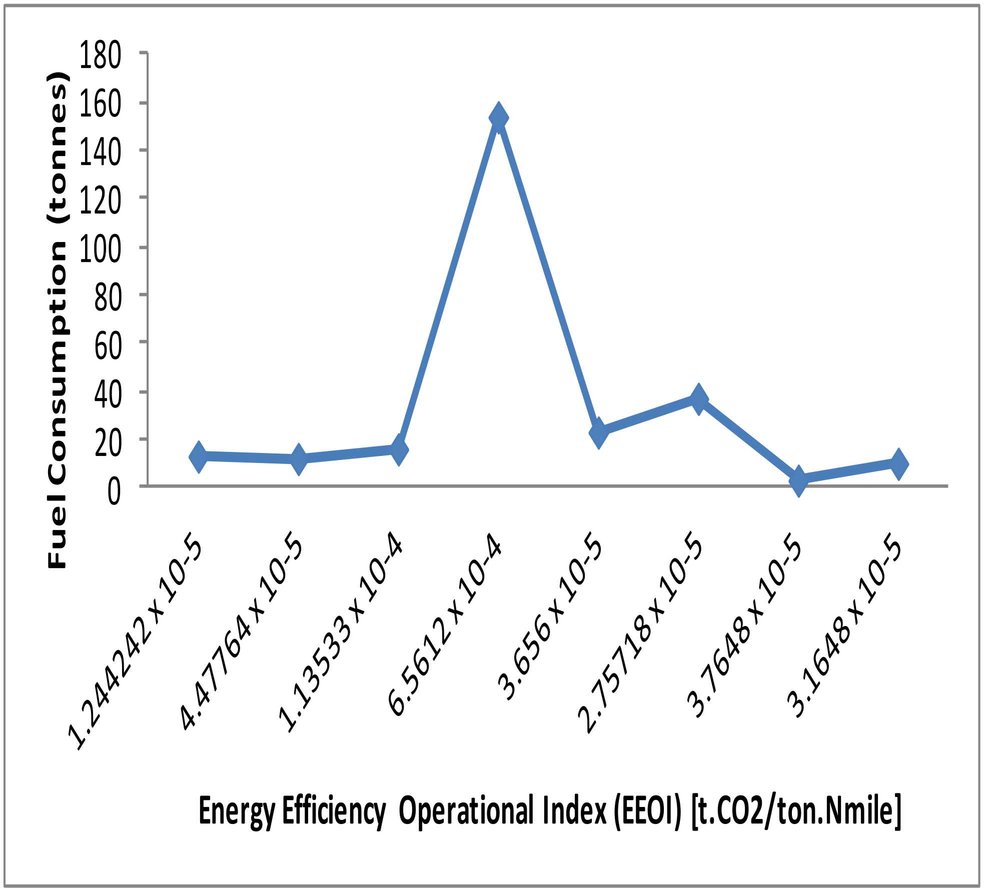

Figure 4.2: Impact of EEOI on Ship MV Indigo — Fuel Consumption

iii. Impact of EEOI on Ship MV Mary — Dead Weight (Cargo Volume)

The result of the impact of energy efficiency operational index (EEOI) on dead weight (cargo volume) of the MV Mary ship is presented in Figure 4.3. The figure shows that there was no direct relationship between energy efficiency operational index (EEOI) and dead weight, which is proven from the analysis that the results for the indicator values pulsate with different dead weights throughout the entire voyages. This conforms to results obtained by previous authors (Devanney, 2011; Hon & Wang, 2019).

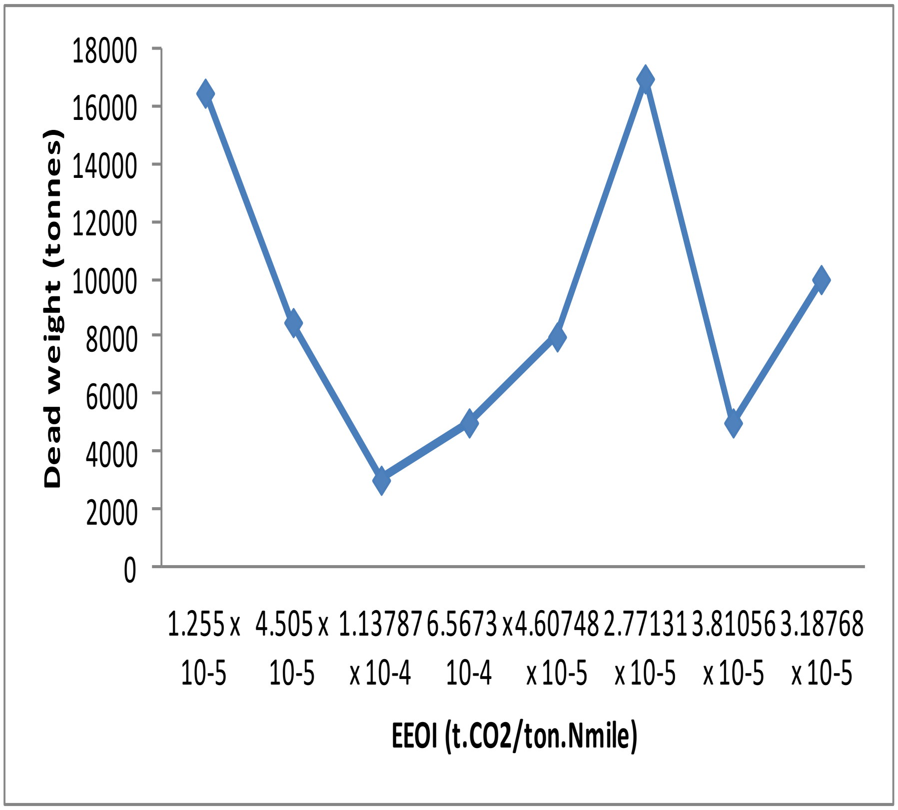

Figure 4.3: Impact of EEOI on Ship MV Mary — Dead Weight (Cargo Volume)

iv. Impact of EEOI on Ship MV Indigo — Dead Weight (Cargo Volume)

The result of the impact of energy efficiency operational index (EEOI) on dead weight (cargo volume) of MV Indigo is presented in Figure 4.4. The figure shows that there was no direct relationship between energy efficiency operational index (EEOI) and dead weight, which is proven from the analysis that the results for the indicator values pulsate with different dead weights throughout the entire voyages. This conforms to results obtained by previous authors (Devanney, 2011; Hon & Wang, 2019).

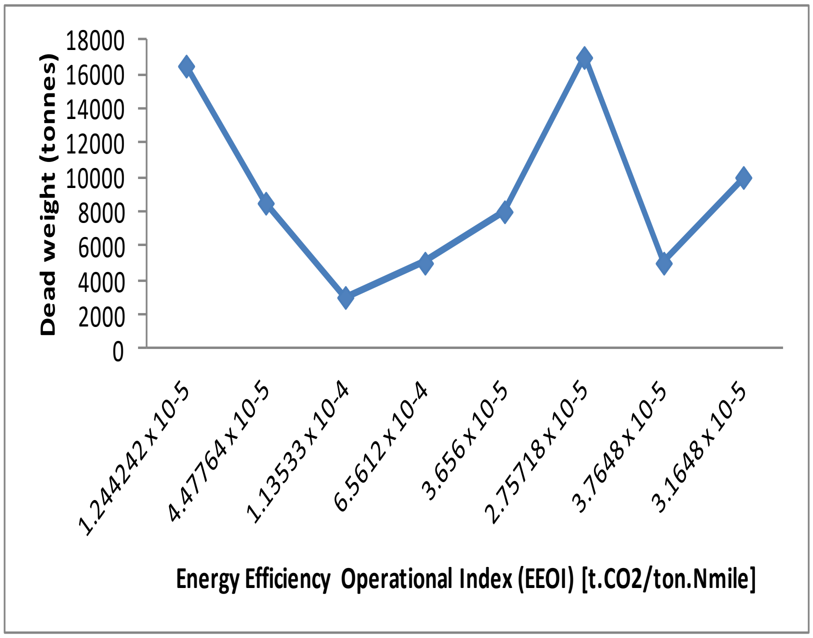

Figure 4.4: Impact of EEOI on Ship MV Indigo — Dead Weight (Cargo Volume)

3.1.3 Assessing the Effectiveness of Low Carbon Fuels on EEOI in Terms of Ship Speed and Voyage Distance

i. Impact of EEOI on Ship MV Mary — Voyage Distance

The result of the impact of energy efficiency operational index (EEOI) on the distance covered by MV Mary is presented in Figure 4.5. The figure shows that the energy efficiency operational index (EEOI) increases with increase in voyage distance travelled, as indicated by the sixth voyage (Voyage 6). The seventh voyage (Voyage 7), with the least distance covered, had the least energy efficiency operational index (EEOI).

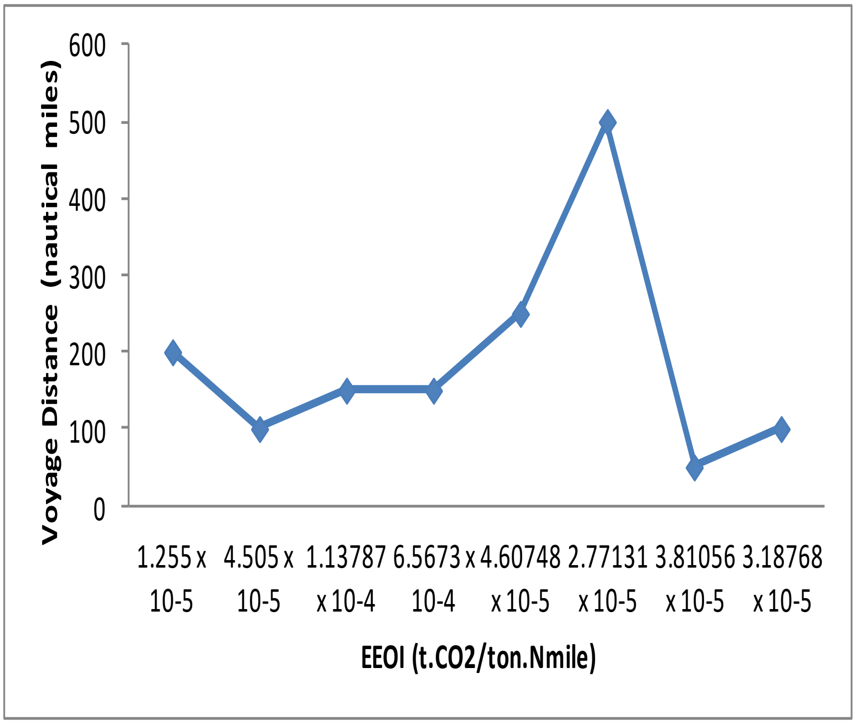

Figure 4.5: Impact of EEOI on Ship MV Mary — Voyage Distance

ii. Impact of EEOI on Ship MV Indigo — Voyage Distance

The result of the impact of energy efficiency operational index (EEOI) on the distance covered by MV Indigo is presented in Figure 4.6. The figure shows that the energy efficiency operational index (EEOI) increases with increase in voyage distance travelled, as indicated by the sixth voyage (Voyage 6). The seventh voyage (Voyage 7), with the least distance covered, had the least energy efficiency operational index (EEOI). This conforms to results from previous research (Devanney, 2011; Hon & Wang, 2019).

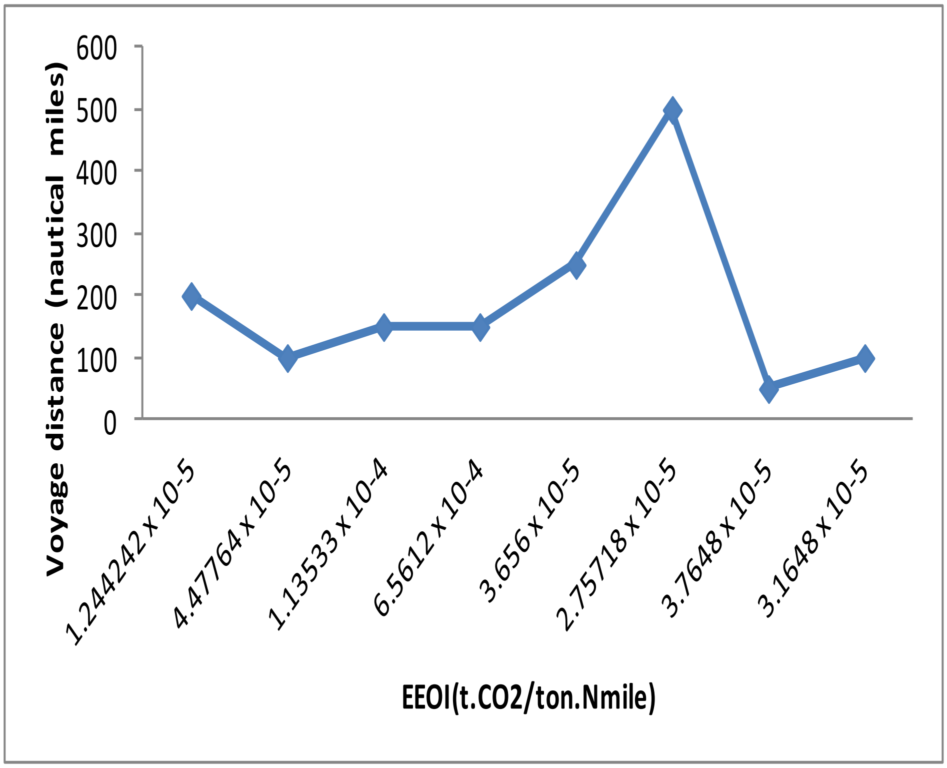

Figure 4.6: Impact of EEOI on Ship MV Indigo — Voyage Distance

iii. Impact of EEOI on Ship MV Mary — Speed

In the transport operations of the ships, the average fuel consumption for each voyage is 99%, and light oil consumption accounts for 1%. From the voyage data in Table 4.2, ship MV Mary uses MDO and HFO fuel for the entire voyages; the emissions of CO_2 are therefore all based on MDO and HFO calculations. The CO_2 emission factors for MDO and HFO are 3.2060 and 3.1144 respectively. With voyage distance D = 250 nautical miles, assuming that the vessel is docked at the departure port and the terminal port, and both MDO and HFO were consumed for the entire voyages, and the environmental impact loading factors take values of 0.8, 0.6 and 0.4 respectively. When the main engine changes load from 100% to 50%, the ship's speed is reduced from 24.199 knots to 17.5 knots, and the EEOI is calculated using equation (3.9) to determine the relationship between the ship EEOI and the ship speed.

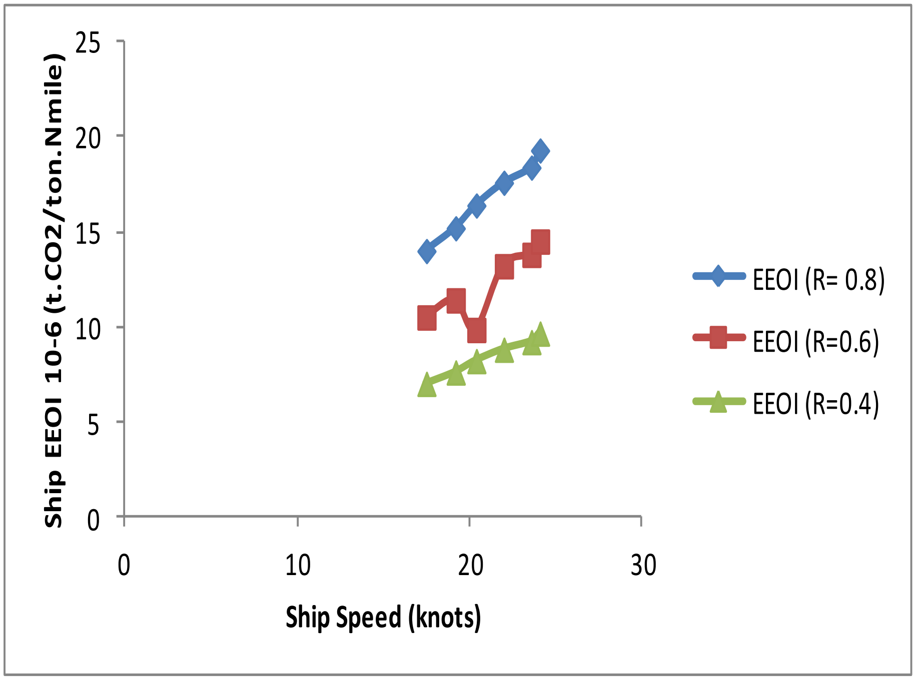

Figure 4.7: Impact of EEOI on MV Mary — Ship Speed

The result of the impact of energy efficiency operational index (EEOI) on speed of the MV Mary ship is presented in Figure 4.7. The figure shows that the energy efficiency operational index (EEOI) increases with increase in speed. When the ship gradually decreases speed from 24.1999 knots to 17.55 knots, the EEOI reduces from 19.3×10^{-6} t.CO_2/ton.Nmile to 14.0×10^{-6} t.CO_2/ton.Nmile. The figure shows that the EEOI of the MV Mary ship is positively correlated to the ship speed. This conforms to results from previous research (Devanney, 2011; Hon & Wang, 2019).

iv. Impact of EEOI on Ship MV Indigo — Speed

From the voyage data in Table 4.2, ship MV Indigo uses MDO and LPG fuel for the entire voyages; the emissions of CO_2 are therefore all based on MDO and LPG calculations. The CO_2 emission factors for MDO and LPG are 3.2060 and 3.000 respectively. With voyage distance D = 250 nautical miles, assuming that the vessel is docked at the departure port and the terminal port, and loading factors take values of 0.8, 0.6 and 0.4 respectively. When the main engine changes load from 100% to 50%, the ship's speed is reduced from 17.99 knots to 11.4 knots, and the EEOI is calculated using equation (3.9) to determine the relationship between the ship EEOI and the ship speed.

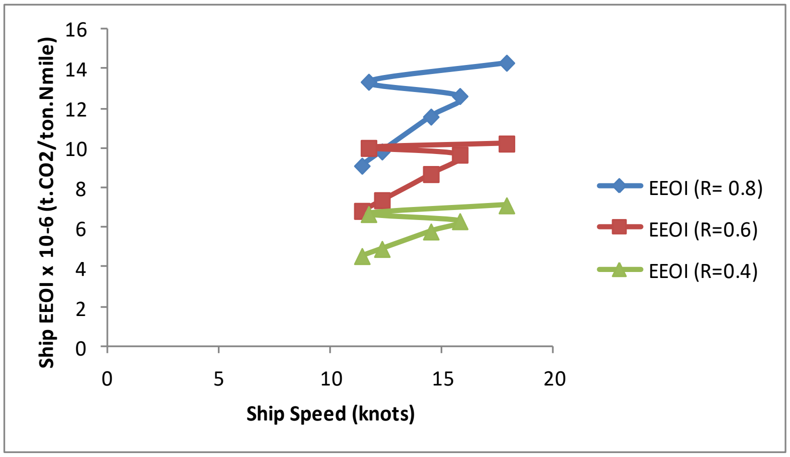

Figure 4.8: Impact of EEOI on MV Indigo — Ship Speed

The result of the impact of energy efficiency operational index (EEOI) on speed of the MV Indigo ship is presented in Figure 4.8. The figure shows that the energy efficiency operational index (EEOI) increases with increase in speed. When the ship gradually decreases speed from 17.999 knots to 11.4 knots, the EEOI reduces from 14.32×10^{-6} t.CO_2/ton.Nmile to 9.12×10^{-6} t.CO_2/ton.Nmile. The figure shows that the EEOI of MV Indigo is positively correlated to the ship speed. This conforms to results from previous research (Devanney, 2011; Hon & Wang, 2019).

3.1.4 Analyzing Ships Energy Efficiency Data to Determine the Effectiveness of Low Carbon Fuels on EEOI in Terms of Cost of Ship Operation

To analyze the energy efficiency data for the tanker vessels and determine the extent to which the fuel-saving benefits of energy efficiency are reflected in market prices, the cost of the fuel consumed during different voyages is determined. The fuel prices used by Eide and others (2019) were US\$350/tonne for heavy fuel oil and US\$530/tonne for LPG. With higher prices (the price today for LPG is over US\$600/tonne), it is obviously possible to reduce CO_2 emissions even further while simultaneously reducing costs. Marginal Abatement Cost Curves are very sensitive to assumptions such as discount rates, investment costs, vessel service life and annual transport work (Kesicki & Ekins, 2012).

The fuel cost analysis for MV Mary is presented in Table 4.7 for the four years from 2018 to 2021. It showed the cost implication of the quantity of fuel consumed by MV Mary. From the result, the highest amount of money spent on fuel to run the vessel was in 2021. The fuel cost analysis for MV Indigo is presented in Table 4.9 for the four years from 2018 to 2021. From the result, the highest amount of money spent on fuel to run MV Indigo was in 2018. The cost benefit analysis for the two ships showing the amount of money spent on fuel is presented in Figure 4.9. From the graphical illustration, a greater amount of money was spent by MV Indigo during the study period compared to MV Mary during the same period. This inferred that MV Mary is more cost-efficient than MV Indigo.

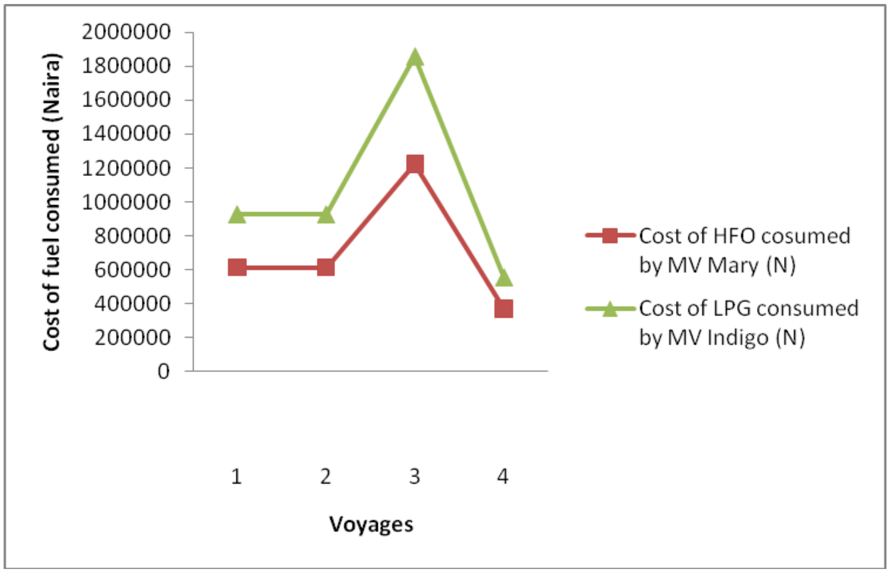

Figure 4.9: Cost Benefit Analysis for MV Mary and MV Indigo

From Figure 4.9, it is clear that if a ship owner abides by the EEDI regulations by using various measures defined in this dissertation, they are likely to have reduced fuel consumption on ships — which would have a huge impact on voyage costs — but this advantage comes at an initial capital investment in better ship design and efficient machinery.

3.2 Discussion

From the EEOI analysis, the results showed that the EEOI of the two case study vessels (MV Mary and MV Indigo ships) is positively correlated to their speed, voyage distance travelled and fuel consumption, except the dead weight which showed no direct relationship. From the cost benefit analysis of the voyages between the ships MV Mary and MV Indigo, it is discovered that the energy efficiency operation index for MV Mary, which used MDO and HFO as fuels, is at 1.80336×10^{-5} g CO_2/ton mile — which is more than that of MV Indigo, which used MDO and LPG and whose EEOI is 1.79×10^{-5} g CO_2/ton mile. Also, the amount of money spent on fuel by MV Mary in 2018 is ₦612,500.00, which is less than the amount of money spent on fuel by MV Indigo in the same year, which is at ₦927,500.00. This is similar for the voyages of the two vessels for subsequent years in the study period.

From the results, it is clear that if a ship owner abides by the EEDI regulations by using various measures defined in this dissertation, they are likely to have reduced fuel consumption on ships — which would have a huge impact on voyage costs — but this advantage comes at an initial capital investment in better ship design and efficient machinery.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

From the results and outcome of this study, the following conclusions were made:

i. The energy saving devices available onboard ships were evaluated. Using the empirical review and assessment of extant studies, the energy saving devices available onboard ships are technical measures aimed to enhance the energy efficiency by hardware (equipment) improvements of the ship. These technical measures include: modified hull form (reduction in propulsion resistance), modified propeller (enhanced propulsion efficiency), energy saving appendages on hull, increase in dead weight capacity by increasing the hull size, use of energy from exhaust heat recovery, and use of low conversion factor fuels and renewable energy (wind power or solar power).

ii. The effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of fuel consumption and cargo volume (dead weights) was investigated. The result showed that the energy efficiency operational index (EEOI) increases with increase in fuel consumption, and that there was no direct relationship between energy efficiency operational index (EEOI) and dead weight — which is proven from the analysis that the results for the indicator values pulsate with different dead weights throughout the entire voyages.

iii. The effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of ship speed and voyage distance were determined. The result showed that the energy efficiency operational index (EEOI) increases with increase in speed: when the ship gradually decreases speed from 24.1999 knots to 17.55 knots, the EEOI reduces from 19.3×10^{-6} t.CO_2/ton.Nmile to 14.0×10^{-6} t.CO_2/ton.Nmile. The results showed that the EEOI of the ship is positively correlated to the ship speed. Also, the result showed that ship energy efficiency operational index (EEOI) increases with increase in voyage distance travelled.

iv. The ships energy efficiency data to determine the effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of cost of ship operation was assessed. It was discovered that the energy efficiency operation index for MV Mary, which used MDO and HFO as fuels, is at 1.80336×10^{-5} g CO_2/ton mile — which is more than that of MV Indigo, which used MDO and LPG and whose EEOI is 1.79×10^{-5} g CO_2/ton mile. Also, the amount of money spent on fuel by MV Mary in 2018 is ₦612,500.00, which is less than the amount of money spent on fuel by MV Indigo in the same year, which is at ₦927,500.00. This is similar for the voyages of the two vessels for subsequent years in the study period.

4.2 Recommendations

Based on the results and findings of this research, the following recommendations are proffered:

i. The Government of the Federal Republic of Nigeria should assist in making provision for grants and funds for Universities and scholars to facilitate more research of this peculiarity, as finance was a major limitation of this study.

ii. The energy efficiency operation index depends significantly on speed, voyage distance travelled and fuel consumption, except the dead weight which showed no direct relationship. High energy efficiency operation index is the consequence of high speed, voyage distance travelled and fuel consumption.

iii. Further research bordering on investigating the effectiveness of energy saving devices onboard other types of ships other than Ro-Ro vessels should be embarked on.

4.3 Contribution to Knowledge

This research adds to the pool of existing knowledge as:

i. The energy saving devices available onboard ships have been understudied.

ii. The effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of fuel consumption and cargo volume (dead weights) has been analyzed.

iii. The effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of ship speed and voyage distance has been assessed.

iv. The ships energy efficiency data to determine the effectiveness of use of energy saving technologies such as low carbon fuels on energy efficiency design and operational index of ship in terms of cost of ship operation has been analyzed.

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APPENDICES

Appendix A — MATLAB Program: EEOI Calculation for MV Mary

MATLAB Computer Programme Algorithm — A Programme to Calculate the Energy Efficiency Operational Index (EEOI) in tonnes CO_2/tonnes·nautical miles.

```
%% A Programme to calculate the energy efficiency operational index (EEOI)
% in tonnes CO2/tonnes.nautical miles
% using:
% EEOI = (Sum of mass of consumed fuel x CO2 conversion factor)
%        / (Sum of mass of cargo carried x distance in nautical miles)

%% Parameters:
% FC  = mass of consumed fuel
```

```
% Cf  = fuel mass to CO2 mass conversion factor for fuel
% mc  = mass of cargo carried
% d   = distance in nautical miles corresponding to the cargo carried
% EEOI = energy efficiency operational index (tonnes CO2/tonnes.nautical miles)

disp('================================================================')
disp(' ')
disp(' The input parameters are:')

FC = [100; 23]
Cf = [3.206; 3.114]
mc = [25000; 0; 25000; 15000]
d  = [300; 300; 750; 150]

% At the end of four years
EEOI     = sum(FC .* Cf) ./ sum(mc .* d);
EEOI_AVG = mean(EEOI)

% Results of the energy efficiency operational index for MV Mary voyages:
% _______________________________________________________________
% EEOI_AVG =
% 1.80336e-05
% >>
```

Appendix B — MATLAB Program: EEOI Calculation for MV Indigo

MATLAB Computer Programme Algorithm — A Programme to Calculate the Energy Efficiency Operational Index (EEOI) in tonnes CO_2/tonnes·nautical miles for MV Indigo.

```
%% A Programme to calculate the energy efficiency operational index (EEOI)
% in tonnes CO2/tonnes.nautical miles

FC = [100; 23]
Cf = [3.206; 3.000]     % MDO and LPG
mc = [25000; 0; 25000; 15000]
d  = [300; 300; 750; 150]

% At the end of four years
EEOI     = sum(FC .* Cf) ./ sum(mc .* d);
EEOI_AVG = mean(EEOI)

% Results of the energy efficiency operational index for MV Indigo voyages:
```

```
% ____________________________________________________________
% EEOI_AVG =
% 1.79124e-05
% >>
```

Appendix C — Ship Voyage Report Sheets and EEOI Calculations

C-i: MV Mary — Ship Voyage Report Sheet

Table C-1: Ship Voyage Report Sheet — MV Mary (Ro-Ro Ship)

Voyage Year	Voyage S/N	Period	Distance (nm)	Mass of Cargo (tonnes)	FC MDO (tonnes)	FC HFO (tonnes)	CF MDO	CF HFO
2018	1	16/02/18 – 27/02/18	200	16,500	10	3	3.2060	3.1144
2018	2	02/03/18 – 13/03/18	100	8,500	10	2	3.2060	3.1144
2019	3	21/06/19 – 30/06/19	150	3,000	15	1	3.2060	3.1144
2019	4	14/08/19 – 19/08/19	150	5,000	150	4	3.2060	3.1144
2020	5	26/05/20 – 29/05/20	250	8,000	20	3	3.2060	3.1144
2020	6	07/07/20 – 11/07/20	500	17,000	30	7	3.2060	3.1144
2021	7	05/01/21 – 09/01/21	50	5,000	2	1	3.2060	3.1144
2021	8	12/06/21 – 15/06/21	100	10,000	8	2	3.2060	3.1144

Source: Clarkson, 2020

The energy efficiency operational indicator (EEOI) based on data from the ship voyage operations sheet of the bulk carrier ship MV Mary, in tonnes CO_2/(tonnes·nautical miles), is calculated from Equation (3.9):

<u>For Voyage 1:</u>

EEOI = [(10 × 3.2060) + (3 × 3.1144)] / [16,500 × 200] = [32.060 + 9.343] / [3,300,000]

EEOI = 1.2546×10^{-5} t.CO_2/ton.Nmile

For Voyage 2:

$EEOI = [(10 \times 3.2060) + (2 \times 3.1144)] / [8{,}500 \times 100] = [32.060 + 6.229] / [850{,}000]$

$EEOI = 4.505 \times 10^{-5}$ $t.CO_2/ton.Nmile$

For Voyage 3:

$EEOI = [(15 \times 3.2060) + (1 \times 3.1144)] / [3{,}000 \times 150] = [48.090 + 3.114] / [450{,}000]$

$EEOI = 1.13787 \times 10^{-4}$ $t.CO_2/ton.Nmile$

For Voyage 4:

$EEOI = [(150 \times 3.2060) + (4 \times 3.1144)] / [5{,}000 \times 150] = [480.90 + 12.458] / [750{,}000]$

$EEOI = 6.5673 \times 10^{-4}$ $t.CO_2/ton.Nmile$

For Voyage 5:

$EEOI = [(20 \times 3.2060) + (3 \times 3.1144)] / [8{,}000 \times 250] = [64.120 + 9.343] / [2{,}000{,}000]$

$EEOI = 4.60748 \times 10^{-5}$ $t.CO_2/ton.Nmile$

For Voyage 6:

$EEOI = [(30 \times 3.2060) + (7 \times 3.1144)] / [17{,}000 \times 500] = [96.180 + 21.801] / [8{,}500{,}000]$

$EEOI = 2.77131 \times 10^{-5}$ $t.CO_2/ton.Nmile$

For Voyage 7:

$EEOI = [(2 \times 3.2060) + (1 \times 3.1144)] / [5{,}000 \times 50] = [6.412 + 3.114] / [250{,}000]$

$EEOI = 3.81056 \times 10^{-5}$ $t.CO_2/ton.Nmile$

For Voyage 8:

$EEOI = [(8 \times 3.2060) + (2 \times 3.1144)] / [10{,}000 \times 100] = [25.648 + 6.229] / [1{,}000{,}000]$

$EEOI = 3.18768 \times 10^{-5}$ $t.CO_2/ton.Nmile$

The total EEOI for the 8 voyages for MV Mary is: $EEOI\_AVG = 1.80336 \times 10^{-5}$ $t.CO_2/ton.Nmile$.

Table C-2: EEOI Results for MV Mary

Voyage Year	Voyage S/N	Period	D (nm)	Mcargo (tonnes)	FC MDO (t)	FC HFO (t)	CF MDO	CF HFO	EEOI ($t.CO_2/ton.Nmile$)
2018	1	16/02/18 – 27/02/18	200	16,500	10	3	3.2060	3.1144	1.255×10^{-5}
2018	2	02/03/18 – 13/03/18	100	8,500	10	2	3.2060	3.1144	4.505×10^{-5}
2019	3	21/06/19 – 30/06/19	150	3,000	15	1	3.2060	3.1144	1.13787×10^{-4}
2019	4	14/08/19 – 19/08/19	150	5,000	150	4	3.2060	3.1144	6.5673×10^{-4}
2020	5	26/05/20 – 29/05/20	250	8,000	20	3	3.2060	3.1144	4.60748×10^{-5}
2020	6	07/07/20 – 11/07/20	500	17,000	30	7	3.2060	3.1144	2.77131×10^{-5}
2021	7	05/01/21 – 09/01/21	50	5,000	2	1	3.2060	3.1144	3.81056×10^{-5}
2021	8	12/06/21 – 15/06/21	100	10,000	8	2	3.2060	3.1144	3.18768×10^{-5}

C-ii: MV Indigo — Ship Voyage Report Sheet

Table C-3: Ship Voyage Report Sheet — MV Indigo (Ro-Ro Ship)

Voyage Year	Voyage S/N	Period	Distance (nm)	Mass of Cargo (tonnes)	FC MDO (tonnes)	FC LPG (tonnes)	CF MDO	CF LPG
2018	1	16/02/18 – 27/02/18	200	16,500	10	3	3.2060	3.000
2018	2	02/03/18 – 13/03/18	100	8,500	10	2	3.2060	3.000
2019	3	21/06/19 – 30/06/19	150	3,000	15	1	3.2060	3.000
2019	4	14/08/19 – 19/08/19	150	5,000	150	4	3.2060	3.000
2020	5	26/05/20 – 29/05/20	250	8,000	20	3	3.2060	3.000
2020	6	07/07/20 – 11/07/20	500	17,000	30	7	3.2060	3.000
2021	7	05/01/21 – 09/01/21	50	5,000	2	1	3.2060	3.000

Voyage Year	Voyage S/N	Period	Distance (nm)	Mass of Cargo (tonnes)	FC MDO (tonnes)	FC LPG (tonnes)	CF MDO	CF LPG
2021	8	12/06/21 – 15/06/21	100	10,000	8	2	3.2060	3.000

Source: Clarkson, 2020

EEOI calculations for MV Indigo voyages (using MDO CF = 3.2060 and LPG CF = 3.000):

For Voyage 1:

EEOI = [(10 × 3.2060) + (3 × 3.000)] / [16,500 × 200] = [32.060 + 9.000] / [3,300,000]

EEOI = 1.244242×10^{-5} $t.CO_2/ton.Nmile$

For Voyage 2:

EEOI = [(10 × 3.2060) + (2 × 3.000)] / [8,500 × 100] = [32.060 + 6.000] / [850,000]

EEOI = 4.47764×10^{-5} $t.CO_2/ton.Nmile$

For Voyage 3:

EEOI = [(15 × 3.2060) + (1 × 3.000)] / [3,000 × 150] = [48.090 + 3.000] / [450,000]

EEOI = 1.13533×10^{-4} $t.CO_2/ton.Nmile$

For Voyage 4:

EEOI = [(150 × 3.2060) + (4 × 3.000)] / [5,000 × 150] = [480.90 + 12.000] / [750,000]

EEOI = 6.5612×10^{-4} $t.CO_2/ton.Nmile$

For Voyage 5:

EEOI = [(20 × 3.2060) + (3 × 3.000)] / [8,000 × 250] = [64.120 + 9.000] / [2,000,000]

EEOI = 3.656×10^{-5} $t.CO_2/ton.Nmile$

For Voyage 6:

EEOI = [(30 × 3.2060) + (7 × 3.000)] / [17,000 × 500] = [96.180 + 21.000] / [8,500,000]

EEOI = 2.75718×10^{-5} $t.CO_2/ton.Nmile$

<u>For Voyage 7:</u>

EEOI = [(2 × 3.2060) + (1 × 3.000)] / [5,000 × 50] = [6.412 + 3.000] / [250,000]

EEOI = 3.7648×10^{-5} $t.CO_2$/ton.Nmile

<u>For Voyage 8:</u>

EEOI = [(8 × 3.2060) + (2 × 3.000)] / [10,000 × 100] = [25.648 + 6.000] / [1,000,000]

EEOI = 3.1648×10^{-5} $t.CO_2$/ton.Nmile

The total EEOI for the 8 voyages for MV Indigo: EEOI_AVG = 1.79124×10^{-5} g CO_2/ton.Nmile.

Table C-4: EEOI Results for MV Indigo

Voyage Year	Voyage S/N	Period	D (nm)	Mcargo (tonnes)	FC MDO (t)	FC LPG (t)	CF MDO	CF LPG	EEOI ($t.CO_2$/ton.Nmile)
2018	1	16/02/18 – 27/02/18	200	16,500	10	3	3.2060	3.000	1.244242×10^{-5}
2018	2	02/03/18 – 13/03/18	100	8,500	10	2	3.2060	3.000	4.47764×10^{-5}
2019	3	21/06/19 – 30/06/19	150	3,000	15	1	3.2060	3.000	1.13533×10^{-4}
2019	4	14/08/19 – 19/08/19	150	5,000	150	4	3.2060	3.000	6.5612×10^{-4}
2020	5	26/05/20 – 29/05/20	250	8,000	20	3	3.2060	3.000	3.656×10^{-5}
2020	6	07/07/20 – 11/07/20	500	17,000	30	7	3.2060	3.000	2.75718×10^{-5}
2021	7	05/01/21 – 09/01/21	50	5,000	2	1	3.2060	3.000	3.7648×10^{-5}
2021	8	12/06/21 – 15/06/21	100	10,000	8	2	3.2060	3.000	3.1648×10^{-5}

Appendix D — Cost Benefit Analysis Tables

D-i: MV Mary — Fuel Cost Analysis

Table D-1: Cost Benefit Analysis for MV Mary

Voyage Year	Fuel Type (MDO) tonnes	Fuel Type (HFO) tonnes	Cost of HFO (US$/tonne @ US$350)	Cost of HFO in Naira @ ₦350/$ (₦)	Cargo (tonnes)	Distance (nm)
2018	20	5	1,750.00	612,500.00	25,000	300
2019	20	5	1,750.00	612,500.00	0	300
2020	50	10	3,500.00	1,225,000.00	25,000	750
2021	10	3	1,050.00	367,500.00	15,000	150

Table D-2: MV Mary — HFO Fuel Cost Analysis by Year

S/N	Voyages at Year	Cost of HFO in Market Price @ ₦350/$ (₦)
1	2018	612,500.00
2	2019	612,500.00
3	2020	1,225,000.00
4	2021	367,500.00

D-ii: MV Indigo — Fuel Cost Analysis

Table D-3: Fuel Cost Analysis for MV Indigo

Voyage Year	Fuel Type (MDO) tonnes	Fuel Type (LPG) tonnes	Cost of LPG (US$/tonne @ US$530)	Cost of LPG in Naira @ ₦350/$ (₦)	Cargo (tonnes)	Distance (nm)
2018	20	5	2,650.00	927,500.00	25,000	300
2019	20	5	2,650.00	927,500.00	0	300
2020	50	10	5,300.00	1,855,000.00	25,000	750
2021	10	3	1,590.00	556,500.00	15,000	150

Source: Clarkson, 2022

Table D-4: MV Indigo — LPG Fuel Cost Analysis by Year

S/N	Voyages at Year	Cost of LPG in Market Price @ ₦350/$ (₦)
1	2018	927,500.00
2	2019	927,500.00
3	2020	1,855,000.00
4	2021	556,500.00