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Research Article

Autoregressive Distributed Lag model study of an alternative fuel, Liquefied Natural Gas, used on ships and its effect on the environment

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Abstract

The increase in global trade and manufacturing has caused an increase in ship transportation, from 16 % to about 90 %, of the number of goods transported internationally, and this has caused an increase in the consumption of Heavy Fuel Oil (HFO), which is the predominant fuel used in the maritime industry. The use of HFO not only affects the environment, but also affects the maintenance of a ship's machinery. This work investigates the effect of an alternative fuel, Liquefied Natural Gas, on the environment and the maintenance of ship machinery. It employs an Autoregressive Distributed Lag (ARDL) model to ascertain the impact of HFO consumption and natural gas consumption on the CO_2 emission rate. It also reviews the works that have been done on the impact of alternative fuels on ship maintenance, the effect of HFO on the environment, and the maintenance cost periodicity of vessels. The result of the model shows that an increase in the consumption of HFO increases the emission of CO_2 and other greenhouse gases more than when natural gas is used. Also, an increased HFO consumption increases the CO_2 emission of both the current year and the next year as per the lags, whereas an increased LNG consumption reduces the CO_2 emission of the current year and decreases the CO_2 emission of the preceding year. The reviewed works indicate that the use of alternative fuels reduce the maintenance cost and the maintenance periodicity of a vessel. It also shows that the use of HFO affects the environment negatively.

1. Introduction

Marine transportation, which includes cargo-carrying commercial shipping and non-cargo commercial shipping (e.g., ferries, cruise ships) is gaining ground in our contemporary times. About 90 % of the world's international trade is affected by ships (IMO, 2017a; Walker, 2016). In 2015, the estimated world sea transportation surpassed 10 billion tons. This has made marine transportation grow, and it will also increase in the nearest future, as long as manufacturing is increasing globally (Corbett & Fishbeck, 2000; Marmer et al., 2009; US-EPA, 2009).

The majority of these ships use Heavy Fuel Oil (HFO) to power their main engines and perform their daily operations. Ship managers, in the bid to reduce the cost of operation, buy some fuels which are of substandard quality, or the suppliers, in the bid to make profit, supply bunker fuels which are not healthy for ship machinery or the environment.

HFO is a mixture of hydrocarbons, composed of residual fractions from crude oil distillation and processing. It has the following characteristics: black color, high specific gravity (0.92 to 0.98), and high viscosity. HFO is composed mostly of carbon (86 % wt.), hydrogen (11 % wt.), and sulfur (currently averaging around 3 % wt.). HFO also contains impurities such as ash, metals, and water. Other impurities include vanadium, asphalts, nitrogen, nickel, and so on. It is essentially an industrial fuel that is suitable for use in power plants, big ships, and industrial operations whereby pre-heat facilities are required to lower its viscosity. HFO is preferred because of the calorific value it generates when it is being used.

HFO has a high number of impurities that are generated after combustion, which affects the machines or generators in ships, and also affects the environment. Some of these emissions, in the long run, cause wear and breakdown of ships, which increases the cost of maintenance for ship operators/owners. Most times, these fuels undergo incomplete combustion, which backfires and destroys the engines in ships, thereby increasing the cost of maintenance.

HFO, being the most prevalent fuel used in the maritime industry, has been proved to cause damages on ships when used over long periods. This is because of the impurities and the sulfur content of HFO. The sulfur reacts with oxygen and water vapor to form tertraoxosulphate (VI) acid (H_2SO_4), which is a strong acid and exercises its properties as an acid when it comes in contact with any material. When HFO is used to run an engine for a long time, studies have shown that it causes a breakdown of the engine (Alkaff et al., 2005). Breakdowns, such as blockage/wear of fuel nozzles, wear and corrosion of pistons, piston rings, and liner, and high and low-temperature corrosion, are due to high vanadium and sulfur content in the fuel. Another effect of HFO on a ship include corrosion of the exhaust vents. Less air in the combustion chambers does not just decrease engine power, but also increases exhaust temperature, turbine contamination, and surging, contaminates lubricant oil, etc. Alkaff et al. (2005) conducted a study on a diesel engine that ran on HFO; the research showed that, after 17,000 h of use, the engine had a serious leakage on the cylinder heads and corrosion of the exhaust valves. This breakdown was attributed to the sulfur and water vapor content in the HFO, which reacted after combustion to form sulfuric acid, which is a strong acid.

For a ship to be effective, maintenance has to be carried out regularly on these parts to ensure they are up and running, in other not to allow the effect of HFO on the engine to reduce efficiency. Therefore, this will increase the cost of maintenance and the maintenance time interval of a ship.

1.1 Statement of problem

There has been an alarming geometric increase in the emissions of greenhouse gas (GHG) into the climate/environment. Shipping activities contribute about 3.3 % to this change due to the combustion of HFO and MGO, and ship maintenance cost is also on the increase due to the effect of the impurities in the current fuel type used for the engines of ships.

The emissions from the combustion of these heavy oil fuels by these ships have been a major concern because of the effect they are having on the climate/environment. Emissions depend on the type of fuel, engine, and engine efficiency (Pham and Nguyen, 2015). Ship transportation is responsible for about 33 % of the CO_2 that is released into the atmosphere (Crist, 2009; Cristea et al., 2013). Other gas emissions released during HFO combustion include sulfur oxides ($SO_{x)}$, nitrogen oxides ($NO_{x)}$, carbon (II) oxide (CO), and other volatile gases.

All these gases are greenhouse gases that have an enormous effect on the climate/environment. Data from the maritime industry, based on engine size and the quality of fuel typically used by ships and cars, shows that just 15 of the world's biggest ships may now emit as much pollution as the entire world’s 760 million cars. Low-grade ship bunker fuel (or fuel oil) has up to 2,000 times the sulfuric content of diesel fuel used in US and European automobiles. The International Maritime Organization (IMO) has found that international maritime activities accounted for 843 Mt of CO_2 in 2007, or 45 % more than previous emission estimates from marine bunkers. This shows that, if these fuels are used in the next few years, the environment will be so damaged that it will be difficult to survive in it. Other shipping activities, such as ballasting water, oil spillage, vessel dredging, dumping at sea, and the use of pesticides to control marine growth, have also added to this effect. Currently, the amount of sulfur in fuels is about 3.5 %, which is on the high side, considering the effect it is having on the environment. Even so, technological advancement has introduced techniques, such as the use of scrubbers, to be used to reduce these emissions from ships and discharge them to the sea. This technique may reduce the emission of these greenhouse gases into the atmosphere but, at the same time, it increases the pollution of the marine environment, which may affect some sensitive organisms. The use of scrubber technology negates Sustainable Development Goals 6 and 13, which mention clean water sanitation and life below water, respectively.

In line with Sustainable Development Goals 7, which is "affordable and clean energy", and 13 and 14, which are about climate action and life below water, respectively, technologists, scientists, heads of shipping industries, and research organizations are on the lookout for other forms of energy that will be used as marine fuels effectively and efficiently and which reduce maintenance cost, environmental effect, and maintenance time intervals. This has led to the development of alternative fuels, which are now being used as marine fuels to reduce the use of HFO. Currently, solar energy, wind energy (Flettner rotor), cold ironing (mostly used in ports), and Liquefied Natural Gas (LNG) turbines are now incorporated in ships to reduce the use of HFO.

While looking for alternative marine fuels that can conquer these difficulties, it has been found that LNG could offer significant advantages over the current marine fuel, HFO. There are around 143 vessels recorded that are currently powered by LNG. This has made LNG be a major alternative fuel that will be used to replace HFO as a marine fuel. This is because other forms of energy, such as wind and solar energy, presently cannot produce enough power to carry the capacity of most ocean-going vessels.

The bone of contention now is: will the use of alternative fuels reduce greenhouse gas emissions (GHG) on the climate and ocean acidification and improve local air quality in the environment, and will it reduce the maintenance cost, as well as the maintenance time interval, of ship machinery?

1.2 Research objectives

The objective of this work is twofold. Firstly, to determine the effect of alternative fuels (LNG) on the environment. Secondly, to determine the effect of alternative fuels (LNG) on maintenance cost and maintenance time interval.

1.3 Research aim

This research aims to determine the effect of HFO and alternative fuels (LNG) used by ships on the climate, the environment, and ship maintenance costs.

1.4 Research questions

The questions which the work seeks to answer are also twofold. What is the effect of alternative fuels on the environment? How do alternative fuels affect maintenance cost and maintenance time interval?

1.5 Hypothesis

H_0: Alternative fuels have no effect on the environment.
H_1: Alternative fuels do not affect maintenance cost or maintenance time interval.

2. Literature review

Alternative fuels in the maritime industry will reduce global carbon emissions. (DNV GL, 2018) claims that marine fuel currently contributes approximately 3 % to global man-made CO2 emissions, and most seagoing ships are still using heavy fuel oil (HFO) or marine gas oil (MGO). From **Figure 1** below, the emissions of alternative fuels like hydrogen, Liquefied Petroleum Gas (LPG), methanol, and LNG are lower than those of HFO and MGO.

Figure 1 below shows the CO_2 emission rates of the various alternative fuels in consideration as a replacement for the carbon-based fuels currently in use. The term Well-To-Tank (WTT) represents emissions for all processes in the life cycle chains of the fuels, including extraction and pre-treatment of the raw materials, fuel production, storage and transport, and distribution. The term Tank-to-Propeller (TTP) represents emission data due to combustion in a dual-fuel marine engine. As we can see, apart from methanol and hydrogen (obtained from CH_4), LNG still represents the most viable alternative, especially due to its availability and price. The common factor for this comparison is the CO_2 emission of the fuels, as measured in g/MJ (Note: 3.6 MJ = mega joule(s) == 1 kW·h = kilowatt-hour(s); thus, 1 g/MJ = 3.6 g/kW·h). Moirangthem (2016), in his independent work, also presented evidence to support the results in **Figure 1**.

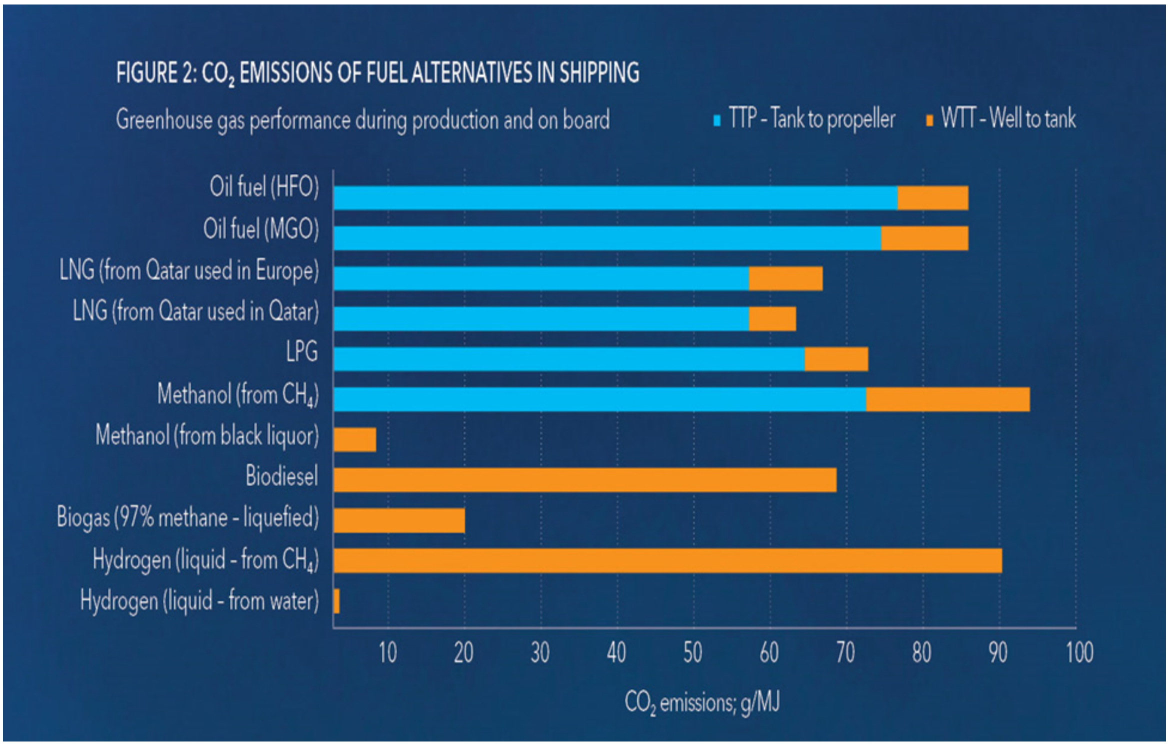

Figure 1 CO_2 Emissions of fuel alternatives in shipping.
Source: Alternative Fuels: The Options - GNV GL.

In DNV GL's (Det Norske Veritas (Norway) and Germanische Lloyd (Germany)), an international accredited registrar and classification society headquartered in Norway, report on alternative fuels, they contended that:

"When it comes to CO_2 emissions, LNG is the fossil fuel producing the lowest amounts. However, the release of unburned methane (so-called methane slip) could reduce the benefit over HFO and MGO in certain engine types. Methane (CH_4) has 25 to 30 times the greenhouse gas effect of CO_2. Nevertheless, engine manufacturers claim that the tank-to-

propeller (TTP) CO_2-equivalent emissions of Otto-cycle dual-fuel (DF) and pure gas engines are lower than those of oil-fueled engines.
If produced from renewable energy or biomass the carbon footprints of methanol and hydrogen can be significantly lower than those of HFO and MGO."

The most important factor in the reduction of emissions by ships using alternative fuels is the engine type. We now introduce maintenance as an activity for ship owners.

"Maintenance is defined as the combination of all the technical and administrative actions, including supervision, intended to retain an item or restore it to a state in which it can perform a required function" (IEC, 2006) "The combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function" (BS 3811).

Intricate mechanical systems, such as offshore structures, bridges, ship hulls, pipelines, wind turbines, and process systems, are designed to ensure economical, consistent, and effective operation throughout the projected life span of the said equipment. However, deterioration and depreciation processes come into play once these systems are put to use, and their inherent strengths will progressively reduce, thus limiting the performance abilities of the systems beyond what is acceptable. Hence, to ensure that acceptance criteria are fulfilled throughout the service life of mechanical systems, it is necessary to control for deterioration and install proper maintenance measures.

2.1 Alternative fuels in the maritime industry

The shipping industry moves about 80 % of world trade by volume, making it an integral part of the global economy. With the world fleet expected to expand to keep pace with global economic development, the shipping industry will be under increasing pressure to improve its safety and environmental performance (DNV GL, 2014).

DNV GL (2015), in their publication LNG as Ship Fuel, said that the main drivers leading to the advent of alternative fuels in the future of shipping can be classified into 2 broad categories:

- Regulatory requirements and environmental concerns, and
- Availability of fossil fuels, cost, and energy security.

This correlates with our work in that we are looking at alternative fuel as a means to reducing maintenance costs and environmental emissions from the maritime industry.

The introduction of any alternative energy source will take place at a very slow pace initially as technologies mature and the necessary infrastructure becomes available. In addition, the introduction of any new fuel will most likely take place first in regions where the fuel supply will be secured in the long term. Due to the uncertainty related to the development of appropriate infrastructure, new energy carriers will first be utilized in smaller short sea vessels, and small ferries are expected to be some of the first movers. As technologies mature and the infrastructure starts to develop, each new fuel can be used in larger vessels.
At present, LNG represents the first, and most likely, alternative fuel to be seen as a genuine replacement for HFO for ships. The adoption of LNG will be driven by fuel price developments, technology, regulation, the increased availability of gas, and the development of the appropriate infrastructure.

Over the next 4 decades, the energy mix in the maritime industry will likely feature, to a very large extent, a lot of diversification. LNG has the potential to become the fuel of choice for all shipping segments, an assertion that has been acknowledged by different authors and bodies. Liquid biofuels could gradually also replace oil-based fuels. Electricity from the grid will most likely be used more and more to charge batteries for ship operations in ports, but also for the propulsion of relatively small vessels. Renewable electricity could also be used to produce hydrogen, which in turn can be used to power fuel cells, providing auxiliary or propulsion power. If a drastic reduction of GHG emissions is required, and appropriate alternative fuels are not readily available, carbon capture systems such as scrubbers could provide a radical solution for substantial reduction of CO_2 and sulfur emissions from vessels.

2.2 Alternative fuels and the environment: A maritime industry outlook

Sea transportation has high importance and constitutes a large percentage of the total worldwide trade (Deniz & Zincir, 2016). Stricter international maritime regulations about emissions affect the majority of merchant ships. These regulations are MARPOL Annex VI Regulation 13 for NOx emission limitation, Regulation 14 for SOx and PM emission limitation, and Regulations on Energy Efficiency for Ships for CO_2 emission, which were entered into force by the International Maritime Organization (IMO). In addition to IMO regulations, there is a new European Monitoring, Reporting, and Verification (EU MRV) regulation, which aims to annually monitor, report on, and verify CO_2 emissions of ships that are larger than 5,000 GT and are working at EU ports. To comply with these regulations, shipbuilders, engine manufacturers, and ship owners use different methods. These methods can be pre-treatment applications, after-treatment applications, and the usage of low-sulfur marine diesel oil. In addition to these methods, alternative fuel usage is another method for emission abatement.

Due to the incompliance of traditional marine fuels with the latest emission regulations and the continuous increase in fuel prices, the search for alternative marine fuels is deemed of paramount importance, despite the challenges that it will face. Many researchers in this area, notably provided by Levender (2011) and Stuer-Lauridsen (2010), have realized the fact that the selection of alternative marine fuel is facing the following problems: fuel availability, bunkering operation in ports, storage onboard, ship sailing time, and engine room design.

2.3 LNG as the most promising alternative fuel for the maritime industry

The major characteristics of LNG are highlighted below:

"...the energy density per mass (Low Heating Value-LHV in MJ/kg) is about 18 % higher than that of HFO, but the volumetric density is only 43 % of HFO (kg/m³). This results in roughly twice the volume compared to the same energy stored in the form of HFO. Factoring in the shape-related space requirements, cylindrical LNG tanks typically occupy 3 times the volume of an equivalent amount of energy stored in the form of fuel oil." (DNV GL, 2018)

Evidence supports that there is a movement towards LNG as the solution for the emission and cost challenges faced by the maritime industry. For example, Asian governments are endorsing LNG as a marine fuel. South Korea's government announced plans worth 2.8 trillion Won (2.48 billion dollars) in December 2018 to develop LNG bunkering facilities in the country. Recently, Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) announced its support of the country's first LNG bunker vessels to supply Ise Bay and Mikawa Bay near Nagoya port, close to Japan's key manufacturing center, and Tokyo Bay, Japan's center for cruise passenger ships and container traffic, near Yokohama port. Singapore, the world's largest bunkering port, granted subsidies to build LNG bunkering vessels for its 2 licensed LNG bunker suppliers.

IMO imposed a 0.5 % global cap on HFO sulfur content by 2020. This has been put into effect, and there is a growing consensus among authors that LNG is the best solution for today and into the future towards 2050, as there are no alternative solutions that can match LNG's emission profile, scalability, and cost savings. Given the growth of LNG infrastructure (bunkering and supply locations) worldwide, the concerns about the supply of LNG to the maritime community are being effectively addressed. Peter (2019) adds that:

"The economic case for LNG as the marine fuel of choice for new builds is growing stronger each month. An independent study commissioned by SEA\LNG and was released in 2019 shows that Asia-US west coast liner service involving less than 10 % of sailing time spent in ECAs, the greatest investment returns come from choosing LNG as the ship marine fuel. Historically, high capital expenditure (CAPEX) hurdles for LNG engines - when compared with traditional alternatives - have reduced dramatically due to additional significant CAPEX now being required for conventional HFO engines to meet IMO rules, and the shipyard prices for new build LNG engines being discounted to encourage orders".

This means that, relative to the new technologies needed to meet the IMO specifications, LNG-fueled ships have become a competitive option. This is in terms of retrofitting ships with scrubber systems or new engines to meet this specification. The impracticalities and economics of retrofitting existing vessels with LNG tanks, and the lack of ready access to LNG bunkers in some parts of the globe, necessitate a portfolio approach to marine fueling solutions for ship-owners and managers, with different fuels best suited to different vessels and trading routes. However, in the coming years, we expect to see an increasing percentage of new builds within the global fleet moving over to LNG for economic reasons to gain commercial trading advantages. A perfect example of this is the news that Qatar's Petroleum entered into 3 agreements for the construction of LNG-powered ships. This agreement will result in the construction of 100 LNG carriers, valued at nearly $20 billion. We can wholeheartedly assert that LNG is the future fuel for the maritime industry across the world.

In terms of pricing, the price of LNG has remained competitively low when compared to other oil fuels. DNV GL: Assessment of Selected Alternative Fuels and Technologies shows that LNG has had the minimum price, when compared to Brent Crude, lower than all other alternative fuels investigated. Brent Crude was used as a benchmark for this comparison because HFO and MGO are by-products.

2.4 LNG emissions

For us to check the benefits of LNG as an alternative fuel with regards to its environmental factors, we will have to compare its emissions with the currently-used industrial standard fuel. By substituting the average emission factors of SOx, NOx, CO2, and PM for both HFO and LNG for 2-stroke diesel engines, Elgohary et al. (2015) were able to use data from Banawan et al. (2010); California Air Resources Board (2005); and Gerilla et al. (2005), at the same power and running hours, discovering that it was possible to estimate the environmental benefits due to shifting from HFO to LNG (in the case of dual-fuel engines).

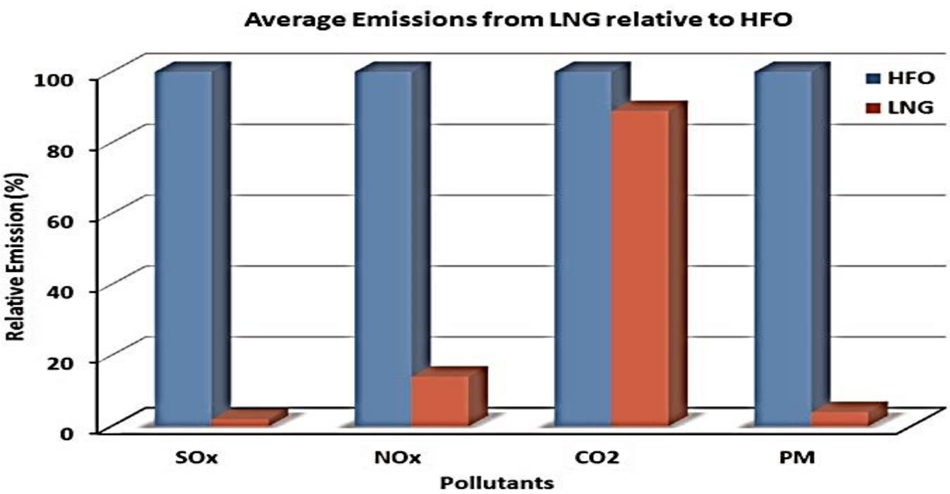

Figure 2 Emissions of LNG relative to HFO.

Figure 2 shows the results of this estimation. It is apparent from these results that the shift from HFO to LNG has resulted in a reduction in SOx, NOx, CO_2, and Particulate Matter (PM) emissions by approximately 98, 86, 11, and 96 %, respectively.

We have reviewed the literature as it relates to the use of LNG, an alternative fuel, in the maritime industry and its impact on maintenance cost/expenditure by ship owners/operators. We will try to understand whether there is a significant reduction in costs of running the engines on ships utilizing these 2 fuel types, HFO and LNG.

Banawan et al. (2010) and Radwan et al. (2007) performed a comparative comparison amongst the different alternative fuels which can be used in the maritime industry. **Table 1** shows the result of their comparisons. They agreed that LNG remains the best alternative fuel, lending credence to our assertion in this work.

Table 1 Comparison between alternative fuels for maritime use.

	Coal	**Biodiesel**	**F-T diesel**	**Alcohol**	**H_2**	**LNG**
Availability	Good	Very good	Good	Very good	Excellent	Very good
Renewability	Fairly good	Good	Good	Very good	Excellent	Fairly good
Safety	Excellent	Excellent	Excellent	Very good	Fairly good	Excellent
Cost	Excellent	Good	Good	Good	Fairly good	Excellent
Adaptability	Good	Excellent	Excellent	Good	Good	Excellent
Performance	Good	Very good	Very good	Good	Good	Excellent
Environmental impact	Bad	Good	Very good	Good	Excellent	Excellent

The comparisons were based on availability, renewability, safety, cost, adaptability, performance, and environmental impact. LNG scored high in all categories because we have the technology now to harness the full potentials of this fuel source. Our focus here, however, will be on the cost potentials.

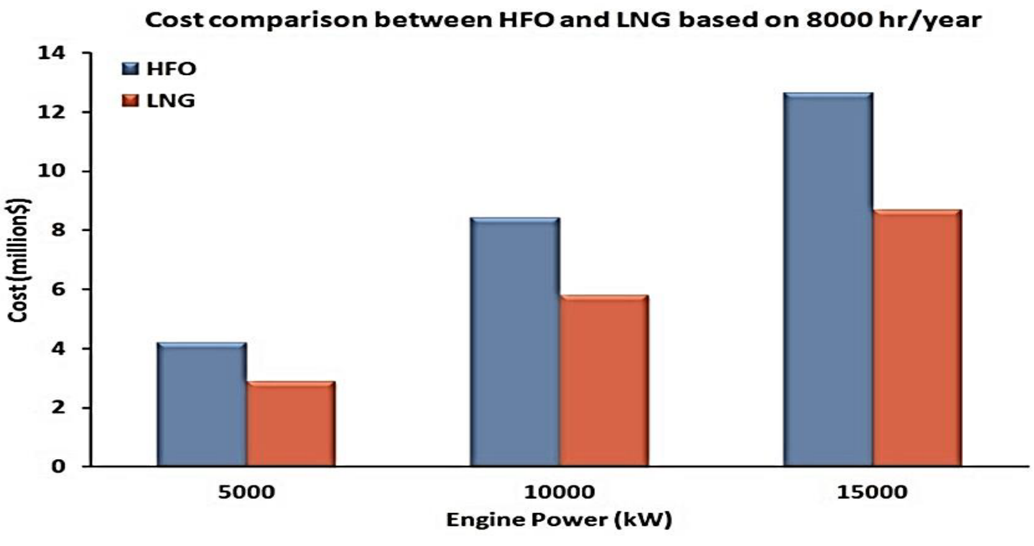

Figure 3 Cost comparison between HFO and LNG based on 8,000 hr/year.
Source: (Elgohary et al., 2015)

Referring to **Figure 3**, we can see that LNG is a cheaper fuel alternative and can reduce running costs for a fleet. Elgohary et al. (2015) went further to provide an in-depth analysis of the costs of using HFO and LNG. They asserted that, taking into account the lower heating value (LHV) of fuels, the price of LNG is lower than that of HFO. They explained that:

"Based on typical load for all diesel engines at 85 % maximum continuous rating (MCR) and 8,000 working hours per year, the fuel-saving cost is estimated for 3 different engine ratings, namely, 5,000, 10,000 and 15,000 kW, and the estimations revealed average fuel saving costs of 1.32, 2.63 and 3.95 million USD/year, respectively. This is equivalent to an annual cost reduction of about 31 % at each engine rating".

This means that LNG has been proven to be a cheaper fuel alternative given the different possible engine types. Coming to the cost aspect of switching the operating engines in ships to reap the benefits of reduced fueling cost, other costs are related to:

- Investment
- Installation and
- Maintenance costs

Levander in his work for the Wartsila Company, investigated such costs and found that, in changing from an HFO-fueled engine (fitted with scrubbers) to an LNG-fueled engine, the costs can be summarized as follows:

- Machinery Investment cost was estimated to be about 14 $/kW for both HFO-fueled engines and LNG-fueled engines.
- The annual machinery costs (including annual capital, lubricating oil, maintenance, scrubber, and SCR operating costs) were 2,600 and 2,100 $/kW for HFO- and LNG-fueled engines, respectively.

This means that changing to an LNG-fueled engine will result in annual machinery maintenance cost savings of 500 $/kW used on the vessel. This is in addition to the reduced fuel costs. Benefits can also be derived from the ability of these ships to ply their trade in the Emission Control Areas (ECA); they can do business in these areas, given the strict carbon control guidelines there. This opens up market potentials for shipping companies.

The conversion of engines to LNG specifications is a very large financial undertaking and, given that the payback occurs over a very long time, investors are discouraged to convert their ships. Balaon et al. (2012) and Deal (2013) contend that, with payback on the conversion typically occurring over 10 years, not all operators will be willing or able to take on such a long-term investment.

"LNG conversion can cost up to $7 million for a medium-sized tug, almost $11 million to convert a large ro-ro/passenger ferry, and up to $24 million to convert a Great Lake bulk carrier." (Elgohary et al., 2015). These high costs are because such conversions need major changes to be made to intricate systems on ships. Banawan et al. (2010), however, explained a possible offset for this high cost in the long run. They said that the mean time between maintenance (MTBM) for natural gas-fueled (LNG) engines can be increased by 3 to 4 times over diesel-fueled engines. This means that the total running hours of natural gas-fueled engines will be at least 3 times those of engines working on diesel oil, for example. These gas-fueled engines require less attention, and fail less often, than their diesel-powered counterparts. For other maintenance activities, which include routine maintenance, lubricating oil consumption, and spare parts consumption, the cost is expected to be reduced in the case of using natural gas, by about 50 % of the original cost.

3. Materials and methods

3.1 Research instrument

The data used in this analysis was obtained from different sources. The data is secondary data sourced from:

- Energy Data (Intelligence and Consulting), Global Statistics Yearbook 2018.
- Our World in Data: CO2 and other Green House Gases Emission.

The variables run from the years 1990 to 2017. The data for CO_2 emission from our source ended in 2017; we deemed it wise not to use data extrapolation to complete the data set, as this is not a widely accepted econometric practice. Data extrapolation was used in the few cases where some annual variables were missing.

3.2 Method of data analysis

This research work employs an Autoregressive Distributed Lag model. The choice of this model was influenced by the need to explain and satisfy objective one of the study, to determine the effect of alternative fuels (LNG) on the Environment. ARDL is abbreviated from the term Autoregressive Distributed Lag model. It is a common model used when working with time-series data. It deals with single co-integration and was introduced originally by Pesaran and Shin (1999), and further extended by Pesaran et al. (2001). The ARDL approach has the advantage that it does not require all variables to be I (1), as per the Johansen framework, and it is still applicable if we have I (0) and I (1) variables in our set. The bounds test method co-integration has certain econometric advantages in comparison to other methods of co-integration, which are the following:

- All variables of the model are assumed to be endogenous.
- The bounds test method for co-integration is being applied irrespective of the order of integration of the variable. There may be either integrated first-order I (1) or I (0).
- The short-run and long-run coefficients of the model are estimated simultaneously.

The ARDL technique still follows the Ordinary Least Squares Method of Estimation, attributed to a German philosopher, Carl Friedrich Gauss. This method is adopted because of the BLUE (Best Linear Unbiased Estimators) properties of the estimators, i.e., the estimators are linear, unbiased, and efficient (possess the minimum variance in the group of linear and unbiased estimators).

We will be using the ARDL model because it can tell us how Liquefied Natural Gas and Heavy Fuel Oil consumption impact global CO_2 emission. This model is very significant because it can tell us how much the consumption of these fuels in the previous years can impact the current year's CO2 level. We will run an ARDL model with no intercept because the intercept in this model involving CO2 emissions cannot aptly be explained as a meaningful statistical variable.

For the second objective, to determine the effect of alternative fuels (LNG) on maintenance cost and maintenance time intervals, we shall use the conclusions of other authors who have carried out more in-depth research into the question posed. This is as a result of the high amount of time and resources needed to source up-to-date and meaningful data. We shall use a literature review approach to answer the question posed by the second objective and, from this, we can reject or not reject our null hypothesis.

Model

- **Functional form of the model**

LCO2EM = f (LNG and LHFO) (1)

- **Deterministic/ Mathematical form of the model**

$$LCO2EM_t = \beta_1 LNG_t + \beta_2 LHFO_t + \lambda_i LNG_{t-k} + \phi_i LHFO_{t-k} + \delta LCO2EMt_{-k} \quad (2)$$

- **Econometric form of the model**

$$LCO2EM_t = \beta_1 LNG_t + \beta_2 LHFO_t + \lambda_i LNG_{t-k} + \phi_i LHFO_{t-k} + \delta_i LCO2EM_{t-k} + \mu_t \quad (3)$$

where;

$LCO2EM_t$ = Log of CO_2 emission in tons at time t
LNG_t = Log of Natural Gas consumption in billion cubic meters (bcm) at time t
$LHFO_t$ = Log of Heavy Fuel Oil consumption in tons at time t
LNG_{t-k} = Lags of the variable LNG_t
$LHFO_{t-k}$ = Lags of the variable $LHFO_t$
$LCO2EM_{t-k}$ = Lags of the variable $LCO2EM_{t.}$
β_1 = Coefficient of LNG_t
β_2 = Coefficient of $LHFO_t$
λ_i = Coefficients of the lag variable(s) of LNG_{t-k}
ϕ_i = Coefficients of the lag variable(s) of $LHFO_{t-k}$
δ_i = Coefficients of the lag variable(s) of $LCO2EM_{t-k}$
k = 1, 2, 3, … (successive lags)
i = 1, 2, 3,... (successive lag parameters)
μ_t = Stochastic error term

4. Results and discussion

4.1 Results

We ran model (3) and obtained the following results. Due to the length of the results, we have attached only the variables specifically of interest to us; these are the coefficients of the variables and their one-year lags (**Table 2**). Please see appendices for the full results.

Table 2 Model results.

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LCO2EM(-1)	0.501815	0.155069	3.236084	0.0119
LCO2EM(-2)	-0.879013	0.169234	-5.194053	0.0008
LHFO	0.811118	0.074780	10.84671	0.0000
LHFO(-1)	-0.128503	0.150725	-0.852567	0.4187
LNG	-0.089205	0.113616	-0.785142	0.4550
LNG(-1)	-0.543758	0.113789	-4.778661	0.0014
C	11.069770	1.797981	6.156778	0.0003
@TREND	0.032407	0.004750	6.822564	0.0001

Source: Authors' calculations
R-sq: 0.999649

4.2 Explanation

R-Squared

R-squared shows the percentage of the variance in the dependent variable explained by the change in the independent variable. It is a test of goodness of fit. From our results, we have an overall r-squared of 0.999. This high R-squared shows that our model is a good fit.

4.3 Coefficients

- **LNG:** The relationship between LNG and CO2 emission is negative. From our results, we can see that a percentage increase in the consumption of natural gas will decrease the CO2 emission by about 0.08 %. This variable is insignificant at the 5 % testing interval.
- **LNG(-1):** From our results, the relationship between natural gas consumption lagged for one year and CO2 emission was negative. This means that a percentage increase in the consumption of natural gas in the previous year decreases CO_2 emission in the current year. This means that the use of natural gas as an energy source in the present year, for instance, will reduce the CO2 emission levels of the next year by about 0.54 %. This variable is significant at the 5 % testing interval.
- **LHFO:** From our results, the consumption of Heavy Fuel Oil or Residual Fuel Oil has a positive relationship with CO2 emission. This means that, on average, a percentage increase in HFO consumption will lead to a 0.84 % increase in the CO2 emission rate. This variable is significant at the 5 % testing interval.
- **LHFO (-1):** This is the first lag variable of LHFO. From our results, we can see that, on average, a percentage increase in the consumption of HFO in the previous year will lead to about a 0.128 % decline in the CO2 emission rate. This variable is insignificant at the 0.05 level of significance.
- **LCO2EM (-1) and LCO2EM (-2):** We will explain these 2 lag variables together. This variable represents an estimation of the impact of the previous year's CO2 emission on the current year. We can see from our result that a percentage increase in last year's CO2 emission levels will increase the current year's CO2 emission level by about 0.5 %, lending credence to the runaway greenhouse effect argument. We look at the impact of the last 2 years' emission rates on the current year. From our results, we can see that a percentage increase in the CO2 emission rate 2 years ago will lead to about a 0.87 % decline in the CO2 levels for this year. This means that CO2 levels of the current year will impact that of the next 2 years.

4.4 Z-Statistics

This is a test of statistics to check whether the coefficients estimated are statistically significant, i.e., if they are statistically different from zero (0). From our model, we have that all the variables, except LHFO(-1) and LNG, are significant, at the level of significance of $\alpha = 0.05$.

4.5 Discussion of findings

Our hypothesis was to check to see if alternative fuels, particularly Liquefied Natural Gas, have an impact on the environment relative to the current used fuel type, HFO. We can see from our model that HFO contributes more to environmental degradation by CO_2 emissions than LNG. This is because the impact from our model is higher, 0.81 % for HFO and −0.54 % for LNG (one-year lag). Additionally, from the lags, we can see that increased consumption of HFO increases CO2 emission even in the next 2 years by about 0.73 %, whereas increased consumption of natural gas reduces CO2 emission levels in the next year by about 0.54 %. This model has helped us elucidate the gainful impact with which alternative fuels can and do have on the environment in the area of carbon emission. Thus, we will reject the first null hypothesis, and conclude that alternative fuels have an impact on the environment, a positive impact.

We went ahead to conduct an ARDL bounds test to check whether there exists a long-run relationship amongst the variables used. The results of this test are in our appendices. We can see that our F-statistics in the results are greater than our I0 and I1 bounds at the 5 % confidence interval. We can, thus, reject our null hypothesis, and conclude that there exists a long-run relationship between these variables and that, over time, an equilibrium state will be attained.

For our second hypothesis, we will reject the null hypothesis based on our reviewed literature. We will conclude that alternative fuels, LNG in particular, have a positive impact on ship maintenance costs and maintenance intervals. The works of Elgohary et al. (2015), Levander (2011), Banawan et al. (2010), and Radwan et al. (2011) lend credence to our conclusions.

5. Conclusions

HFO, being the predominantly used source of fuel in the maritime industry, has been causing a detrimental effect to the environment and ship machinery when used over time. The sulfur content of HFO, and other impurities, have led to the breakdown of ship machinery. This has caused an increase in the cost of maintenance of ship machinery, which negates the actual objective of any business. Every manager wants a reduced cost. The call by the IMO to reduce the sulfur content of HFO to 0.5 % by 2020 has prompted the need to look for alternative fuels.

While looking for alternative marine fuels that can conquer these difficulties, it has been found that LNG could offer significant advantages over the current marine fuel (HFO). The results of an analysis conducted using the ARDL model shows that the emission of CO_2 was reduced by 0.11, which is about a 40 % reduction in the emission of CO_2, when natural gas was used. The use of alternative fuels is gradually gaining ground in the marine industry, with LNG taking the lead; a report has it that, as of 2020, the total number of LNG-powered ships was about 143.

Mohamed et al. (2014) stated that LNG has environmental benefits through an average reduction of SOx, NOx, CO_2, and PM pollutants by an amount of about 98, 86, 11, and 96 %, respectively. This indicates that powering ship machinery with alternative fuels (LNG) will reduce the amount of environmental depletion caused by shipping activities.

Integrating LNG-powered vessels will reduce the cost of operation by 60 %, which will also reduce maintenance cost and maintenance time interval. The amount of soot produced by LNG-powered vessels is of a minimum value, which also indicates a reduction in environmental degradation. On the issue of the safety of LNG-powered vessels, the IMO has liaised with other standardization societies, such as the International Standard Organization (ISO), the National Fire Protection Association (NFPA), the American Petroleum Institute (API), and several classification societies which are members of the International Association of Classification Societies (IACS), in other to ensure the safety of vessels that are powered by LNG.

6. Recommendations

Nigeria, being a major producer and exporter of LNG, has the advantage to attract ships that use alternative fuel (LNG) to African waters. The advantages of Liquefied Natural Gas have been exhaustively treated in this work. From our results, the opinions of previous authors on the subject matter, and the glaring changes in the energy sector with regards to increased emphasis on cleaner energy supply sources, environmental impacts, and excess capacity utilization, we will make the following recommendations. We advise the Nigerian Government and the Nigerian National Petroleum Co-operation (NNPC) on the far-reaching benefits of utilizing LNG, which was still recently being flared in the upstream sector. Our ability to develop relevant LNG bunkering facilities will not only translate to an increased revenue generation stream, increased employment, and reduced environmental degradation as a result of gas flaring, but we will also be looking at the possibility of transforming Nigeria into the first port of call for these new LNG-powered ships plying their trade in the great oceans of the world. We will be able to provide LNG bunkering ships for the high sea refueling of crude oil tankers, cargo ships, and offshore supply vessels, as well as to develop the domestic market, which is hereto non-existent.

We have established in this paper that LNG as an energy source is cheaper and very environmentally-friendly; thus, the gains will, in the long run, outweigh the heavy investments needed to match these ambitions. Developing our LNG infrastructure will even add to our power generating capacity; this is because we will be able to use gas-fired turbines to add megawatts to our national grid. This will provide cheap electricity, because we will be using an extract from our oil mining industry to generate power and to power our ever-expanding economy.

This will also entirely stop the gas flaring in the upstream sector of oil exploration, thereby reducing the environmental impacts on our climate.

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Appendices

Appendix I

Result from Autoregressive Distributed Lag model

Dependent variable: LCO2EM
Method: ARDL
Date: 06/06/21 Time: 17:26
Sample (adjusted): 1994 2017
Included observations: 24 after adjustments
Maximum dependent lags: 4 (automatic selection)
Model selection method: Akaike info criterion (AIC)
Dynamic regressors (4 lags, automatic): LHFO LNG
Fixed regressors: C @TREND
Number of models evaluated: 100
Selected model: ARDL(4, 4, 4)

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LCO2EM(-1)	0.501815	0.155069	3.236084	0.0119
LCO2EM(-2)	-0.879013	0.169234	-5.194053	0.0008
LCO2EM(-3)	0.230662	0.163218	1.413214	0.1953
LCO2EM(-4)	-0.485172	0.146208	-3.318381	0.0106
LHFO	0.811118	0.074780	10.84671	0.0000
LHFO(-1)	-0.128503	0.150725	-0.852567	0.4187
LHFO(-2)	0.730752	0.139149	5.251580	0.0008
LHFO(-3)	-0.296382	0.124279	-2.384817	0.0442
LHFO(-4)	0.699426	0.132342	5.284977	0.0007
LNG	-0.089205	0.113616	-0.785142	0.4550
LNG(-1)	-0.543758	0.113789	-4.778661	0.0014
LNG(-2)	-0.198034	0.088490	-2.237922	0.0556
LNG(-3)	-0.191740	0.100116	-1.915183	0.0918
LNG(-4)	0.118412	0.080641	1.468383	0.1802
C	11.06977	1.797981	6.156778	0.0003
@TREND	0.032407	0.004750	6.822564	0.0001

R-squared	0.999649	Mean dependent variable	9.728323
Adjusted R-squared	0.998989	S.D. dependent variable	0.054735
S.E. of regression	0.001740	Akaike info criterion	-9.635204
Sum squared residuals	2.42E-05	Schwarz criterion	-8.849835
Log likelihood	131.6224	Hannan-Quinn criterion	-9.426845
F-statistic	1516.854	Durbin-Watson statistic	2.108346
Prob(F-statistic)	0.000000		

*Note: p-values and any subsequent tests do not account for model selection.

Appendix II

Autoregressive Distributed Lag model bounds test

ARDL Bounds Test
Date: 06/06/21 Time: 17:27
Sample: 1994 2017
Included observations: 24
Null Hypothesis: No long-run relationships exist

Test Statistic	Value	k
F-statistic	15.56347	2

Critical Value Bounds

Significance	I0 Bound	I1 Bound
10 %	4.19	5.06
5 %	4.87	5.85
2.5 %	5.79	6.59
1 %	6.34	7.52