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LIQUEFIED NATURAL GAS AS AN ALTERNATIVE FUEL: A VOYAGE-BASED MODEL

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Abstract:

The impact from shipping pollutants has the potential of human health damage and contributes for climate change. CO_2 is a greenhouse gas that contributes for climate change and wherever it emissions take place, its impacts are global. Ozone formed through the reaction of nitrogen oxide reduce life expectancy and yield loss for crops. Sulphur dioxide is a PM precursor and contributes to acid deposition leading to potential changes in soil and water quality, also damaging infrastructures, buildings and cultural monuments also increasing human morbidity and mortality. Fuel switch by means of lesser noxious fuels like marine gas oil (MGO) is dependent of refinery capacity for distillates and promotes business-as-usual practices and oil dependency. By the other hand, the adoption of onboard cleaning technologies requires additional energy consumption on board to operate further increasing carbon dioxide life-cycle emissions due to the extra energy required for the refining process. Thus, this is not a sufficient condition for a step-change towards long-term low-carbon perspective for shipping, rather should be seen as mitigation strategies instead. This article assesses to which extend Liquefied Natural Gas (LNG) as an energy end-use fuel for marine purposes produces less externalities compared with traditional fuels, from the viewpoint of the society as a whole. The outcome indicates that benefits are largely superior compared to other oil-based fuels. Although estimating Portuguese particularities, the findings are aimed to be reproduced and applied elsewhere.

Key words:
Shipping; Environmental sustainability; Liquefied Natural Gas; Voyage-based model.

INTRODUCTION

International shipping is a vital link for global trade and a key element for world's economy. However, this argument underestimates the real costs: shipping has direct health and environmental harmful impacts. According to the IMO (International Maritime Organization), international shipping emitted in 2012 approximately 796 million tonnes (Mt) CO_2 and 816 Mt carbon dioxide equivalent (CO_2e) for greenhouse gases (GHGs) combining CO_2, methane (CH_4) and nitrous oxide (N_2O). The traditional hard fuels burnt in vessels' engines accounts for approximately 3.1% on average for global GHGs worldwide [1]. The impact from primary and secondary pollutants resulting from the combustion of hard fuel oils (HFOs) has the potential of acidification, eutrophication, human health damage and photochemical ozone formation [2]. Health costs caused by PM emissions are by far the most important cost category. Acute and chronic PM exposure can induce to, respectively, short-term (e.g. cardiovascular diseases or asthma) and long-term health effects (e.g. lung cancer). Premature mortality is related to a specific PM with aerodynamic diameters of 2.5 micrometers (µm) or less ($PM_{2.5}$); exposure to $PM_{2.5}$ have been closely associated with increases in cardiopulmonary and lung cancer mortalities in exposed populations [3]. As for SO_2 this acid causes physical structure degradation due to corrosive processes and contributes for the acidification and eutrophication of ecosystems, health costs, building/material damages, crop losses and costs for further damages for the biosphere, soil and water [4]. Ozone (O_3) formed through the reaction of precursor species; NO_x and volatile organic compounds (VOCs) reduce life expectancy due to acute effects and yield loss for crops. Albeit a considerable part of emissions occur far from shore they also reach inland due to prevailing wind conditions. Even though diesel-based fuels correspond to present and future Tier III Regulation issued by the IMO for maximum sulphur and strictest NO_x limits, air emissions from diesel fuels were recently classified as human carcinogens by the International Agency for Research on Cancer [5]. Scrubber and selective catalytic reduction devices require additional energy consumption on-board to operate further increasing CO_2 consumption, and cannot be considered as a step-change for long-term low-carbon perspective, rather they should be seen as operational mitigation measures instead of drivers of change. LNG as end-use fuel capable to reduce noxious emissions has also lower acidification and eutrophication potential and less human health impact than diesel fuels, a low life-cycle CO_2 emissions and higher hydrogen-to-carbon ratio which results in lower specific CO_2 emissions (kg of CO_2/kg of fuel). According to several authors [1]; [6] LNG offers end-of-pipe environmental benefits such as: practically 100% elimination of SO_x emissions and PM, between 85-90% reductions of NO_x due to lower peak temperatures in the combustion process, nearly 100% of VOCs and a reduction of 20-25% in CO_2 emissions [7]; [8]; [9]; [10]; [11]. Human health and environmental damages reduction are thus the concern behind the evaluation of LNG as an alternative fuel to ships' engines. The ultimate objective is to verify to what extent the substitution of oil-based fuels by natural gas can reduce pollutant emissions while contributing to the phasing out of oil dependency. In this sense, a voyage-base model for estimating societal costs from energy use and emissions was performed. From this analysis LNG emerges as the best cost-effective solution in terms of emissions mitigation translated into societal benefits.

1 CASE-STUDY

A voyage-base model to test real-world effects from the adoption of LNG as a marine fuel opposed to other two oil-based fuel ships will be performed. This practical case-study transmits the results of such an adoption in the context of a society's "value for money". This case-study uses a bottom-up approach in which total external costs are derived from ship engines emissions multiplied by marginal external costs, performed by means of a statistical spreadsheet to calculate ships' fuel gas emissions and energy efficiency herein adapted to a particular case: three feeder vessels in a round trip comparison between one 3.5% sulphur content heavy fuel oil (HFO) fuelled vessel engine equipped with scrubber, to reduce emissions from exhaust stream, and selective catalytic reduction (SCR) devices (Scenario 1), one marine gas oil (MGO) fuelled vessel with 0.1% sulphur content together with SCR (Scenario 2) and another LNG fuelled vessel (Scenario 3) between two main continental Portuguese ports taking into account pollution rural values for Portugal from ships close to shore as calculated elsewhere [12] updated to Consumers Price Index (CPI) 2016.

From specific engine fuel consumption, onboard technologies and sulphur content in the fuel, the emissions factor for each scenario is calculated. Final results gives the amount of CO_2, NO_x, SO_x and PM emitted from ships as the product of fuel consumption resulting from the engine load, including auxiliary engines at harbour, multiplied by correspondent emission factors.

***Tab 1** Engine type and technologies.*

Engine type & Technology	un.	Scenario 1 HFO	Scenario 2 MGO	Scenario 3 LNG
Main engine type (slow speed = 1; medium speed = 2)	(-)	2	2	2
Main engine service rate	pct. MCR	90	90	90
Fuel type (HFO = 1; MGO = 2; LNG = 3	-	1	2	3
SFOC at 75% MCR in normal ME mode (default = 1)	g/kW/hour	1	1	1
Normal tunning = 1; low load = 2	-	1	1	1
Sulphur content in HFO	pct	3.5	0	0
Sulphur content in MGO	pct	0	0.1	0
Derated 2 stroke main engine? (NO = 0; YES = 1)	-	0	0	0
Fuel optimised main engine? (NO = 0; YES = 1)	-	0	0	0
Tier 1, 2 or 3 engine? (1 - 3)	-	3	3	3
NOx reduction technology: EGR = 1; SCR = 2	-	2	2	-
Scrubbers (NO = 0; YES = 1)	-	1	0	0

Moreover for Scenario 1 and 2 the following assumptions were taken as depicted in Table 1 above: HFO fuelled vessel equipped with both cleaning technologies – scrubber and SCR - and an MGO vessel equipped with SCR to reduce NO_x emissions, in an anticipated scenario for a Emission Control Area (ECA) for NO_x (NECA) and SO_x (SECA) in the North-East Atlantic (comprising the Bay of Biscay and the Iberian Coast). In order to find which scenario is the best alternative, what is the final external cost of pollutants, there will be no need for a base case since final performance is just what we want to compare. Indeed, Scenarios 1 or 2 are not "business-as-usual" scenarios due to the fact that abatement measures are already in place and an alternative less pollutant fuel is in use, for the HFO fuelled vessel and MGO, respectively. In fact, HFO engines equipped with scrubbers and SCR devices are able to comply with the IMO's Tier III low sulphur requirements and further NO_x limits. The "end of pipe" emissions, i.e., the engines exhaust gases have the advantage of being cheaper solutions.

Hence, the 3.5% sulphur content of the HFO makes the fuel costs smaller than MGO and LNG although there are costs that are not negligible from the installation of such abatement technologies among others (e.g. educational costs for crews to operate with). In the case of the MGO fuelled feeder ship the 0.1% diesel fuel sulphur content complies with IMO's Tier III; plus, the use of a SCR for NO_x reduction is considered. The distinction of LNG technology is usually made between dual fuel engines and single fuel engines. The single fuel engines have slightly higher efficiency and lower emissions than comparable dual fuel engines [13]. Therefore, Scenario 3 only addresses a single fuel engine. The model for the case-study is presented as below:

$$C_{ij} = E_{ij} \bullet MC_i \quad (1)$$

Where:

i represents four types of substances; NO_x, SO_x, PM and CO_2;

C_{ij} represents the external costs of substance i from ship j (in Euro);

E_{ij} represents the total amount (g/kWh) of substance i from ship j;

MC_i is the marginal external costs (Euro per nautical mile) of substance i.

Ships characteristics

The vessels chosen for this study have all the same main particulars and characteristics and are considered as new builds; exception is made to fuels. Therefore we analyse a 10,569 deadweight (dwt), 7.82 meters maximum draught, 2-stroke engine type feeder vessel with a load capacity up to 800 TEU. The following route is established: Sines - Leixões – Sines. The distance per leg is found to be 209 nautical miles (nm) resulting in a roundtrip of 418 nm (c. 774 km) with a constant speed of 16.7 knots while at sea. The operational profile has two modes; "in harbour" including time spent hotelling, loading, unloading and manoeuvring, and "at sea". The sea mode is responsible for around 80% of total emissions. Manoeuvring is responsible for around 5% of emissions and operations for the remaining 15% [13]. Each ship spends 25 hours in transit per roundtrip, 24 hours loading/unloading and 4 hours manoeuvring. It is estimated that the vessel has 56 roundtrips every year, one per week which gives a total of 2,968 duty hours/year. In order to calculate the fuel consumption and emissions, assumptions regarding the engine load are necessary for the different ship operational modes. While at sea, the specific fuel oil consumption (SFOC) for the main engine is calculated as a function of the main engine loading in % of the maximum engine power, also known as maximum continuous rating (MCR). In this case it refers to a 75% of engine tuning at which rate the lowest fuel consumption occurs. Main engine power (MCR) for the HFO fuelled ship is assumed to be 8,086 kW engine and 8,015 for both the MGO and LNG fuelled ships. Thus, since this value is below 10,000 MCR the auxiliary power is set in 5% of the MCR in accordance with the IMO guidelines on Energy Efficiency and Design Index for new ships (EEDI) for operational mode while at harbour. Assumptions are presented in Table 2.

***Tab. 2** Pollutant emissions from different ship fuels.*

Emissions (at sea and at harbour)		HFO	MGO	LNG
CO2	g/kWh	3,400,000	3,200,000	2,300,000
NOx	g/kWh	13,000	13,000	7,000
SOx	g/kWh	1,000	2,000	0
Particulate matter (PM)	g/kWh	4,000	1,400	200

For the "at sea" operational mode the total emissions *i* from ship *j* is:

$$E_{ij} = EF_{ij} \bullet D_j \quad (2)$$

Where:

EF_{ij} is the emission factor (g/kWh);

D_j is the sailing distance in hours between origin and destination of ship *j*.

Calculating fuel oil consumption

The energy consumption is found by multiplying the installed power and the engine load according to the following equation:

$$EC_j\,[\text{kWh}] = \sum_{j=1}^{n} P_j\,[\text{kW}] \bullet MCR_j\,[\%] \quad (3)$$

Where:

j is the index referring to the engine (ME, AE);

Pj is the power of engine *j* (kW); and

MCRj is the engine load for engine *j* (%).

The fuel oil consumption, FOC_j, is then calculated by multiplying the specific fuel oil (or gas) consumption, $sfoc_j$, with the energy consumption. The total fuel oil and gas consumption for each ship class is then found by summing the fuel oil consumption for all the engines in both operational modes:

$$FOC_j\,[\text{g}] = \sum_{j=1}^{n} EC_j\,[\text{kWh}] \bullet sfoc_j \left[\frac{g}{\text{kWh}}\right] \quad (4)$$

The specific fuel oil consumption for the Scenario 1 (HFO) is assumed to be 203.2 g/kWh, 187.1 g/kWh for Scenario 2 (MGO) and 152.6 g/kWh for Scenario 3 (LNG).

Calculating emissions

The amount of fuel used is based on a "bottom-up" approach, using vessel and engine characteristics to generate an estimate of the NO_x, SO_x, PM and CO_2 emissions based on the emission factor for each pollutant. The amount of emissions of a certain pollutant, m_i, from a certain ship is found by summing the product of the engine load, MCR_j , the engine size, P_j , the ships estimated time at sea and the emission factor, EF_{ij} . This can be calculated by the equation below:

$$m_i\,[\mathrm{g}] = \sum_{j=1}^{n} EF_{i,j}\left[\frac{g}{\mathrm{kWh}}\right] \bullet P_j\,[\mathrm{kW}] \bullet MCR_j\,[\%] \bullet t_j\,[h] \quad (5)$$

Where:

i refers to the selected pollutant;

j is the index referring to main and auxiliary engines (ME, AE);

m_i is the amount of pollutant emission i (g); and

EF_{ij} is the emission factor for pollutant i for engine j (g/kWh).

Calculating SO_x emissions

The SO_x Emission Factor

Since the molar mass of SO_2 (64 g/mol) is two times the molar mass for sulphur (32 g/mol), the theoretical amount of sulphur dioxide formed is two times the amount of sulphur in the fuel [13]. Based on the specific fuel consumption for the engine and the sulphur content in the fuel, the sulphur emission factor for each scenario is calculated:

$$EFSO_2\left[\frac{g}{\mathrm{kWh}}\right] = \frac{2 \bullet S\% \bullet sfc_j\left[\frac{g}{\mathrm{kWh}}\right]}{100} \quad (6)$$

Where:

$S\%$ is the sulphur content in the fuel; and

sfc_j is the specific fuel (or gas) consumption for engine j (g/kWh).

For Scenario 1 we have 0.27 g/kWh emissions of SO_x from AE and 0.01 from AE and 0.36 g/kWh ME + 0.40 for AE in the MGO case for Scenario 2. Since LNG produces almost zero amounts of SO_x no emissions were considered.

SO_x emissions are derived assuming that all the sulphur present in the fuel is burnt to SO_2.

Calculating NO_x emissions

NO_x Emission Factor

The emission factor is assumed to be at 3.40 g/kWh and 2.40 g/kWh for ME and AE, respectively, for both the HFO and MGO fuelled ships. For the LNG fuelled ship this value is

1.30 g/kWh for both engines. The NO_x emission is calculated according to the following formula (Scenarios 1 and 2):

$$m\,NO_x\,[g] = 2.4\left[\frac{gNOx}{Kg\ fuel}\right] \cdot \frac{FCj\ [g]}{1{,}000\ [g/kg]} \qquad (7)$$

PM emission factor

The emission factor for PM is assumed to be 0.81 for the ME and 0.12 g/kWh for the AE, in the case of the HFO fuelled ship. For the MGO and LNG ships, emission factors are equal for both main and auxiliary engines: 0.27 and 0.03 g/kWh respectively.

Calculating CO_2 emissions

CO_2 Emission Factor

The emission factor for CO_2 is assumed to be 575 for the ME and 627 for the AE, for the HFO fuelled ship. For the MGO ship, emission factors are 545 for the main and 609 for the auxiliary engine. The LNG fuelled ship presents the values of 426 for both engines.

Based on the operational profile, the engine specifications and the calculated emission factors, the amounts of NO_x, SO_2, PM and CO_2 per roundtrip are found. In the possession of all data we multiply correspondent emissions emitted during the 56 weeks and then by pollutant marginal external costs in rural areas for Portugal as provided by Table 3. The external costs from those substances were calculated after adjusted to Consumer price Index 2016 (June 30, 2000 - June 30, 2016).

Tab. 3 *Marginal external costs in rural areas for Portugal, 2016.*

Pollutant	NOx	SO_2	PM
Portugal (€/tonne 2016)	5,400	3,960	7,700

We have considered feeder vessels due to its trade nature to navigate close to shore. Therefore, as suggested, applicable emission values are those from national rural areas for Portugal [12]. With respect to CO_2, the mean value of 49€ tonne is based on Korzhenevych et al estimates from 232 different studies without any CPI adjustment [14]. Given the inputs (fuel consumption, speed, distance, etc) and the outputs (emissions per pollutant per roundtrip) generated by the spreadsheet multiplied by external damage costs per pollutant in rural areas, it is now possible to calculate the final results in the context of a "value for society" instead of "value for money" (Table 4).

CO_2 emissions are overwhelming and accounts for more than 60% of total emissions, for both HFO and MGO ships and for more than 70% in the case of the LNG fuelled ship, followed by NO_x, PM and SO_x in decreasing order of importance.

Tab. 4 *Marginal external costs of emissions from case-study.*

		Scenario 1 HFO	Scenario 2 MGO	Scenario 3 LNG
Fuel consumption per hour	kg/kWh	570	530	430
Total yearly consumption	kg/kWh	31,920	29,680	24,080
NOx emissions per year	g/kWh	38,584,000	38,584,000	20,776,000
Total damage costs per year	€	208,354	208,354	112,190
SOx emissions per year	g/kWh	2,968,000	5,936,000	0
Total damage costs per year	€	11,753	23,507	0
Particulate emissions per year	g/kWh	11,872,000	4,155,200	593,600
Total damage costs per year	€	91,414	31,995	4,571
CO_2 emissions per year	kg/kWh	10,091,200	9,497,600	6,826,400
Total damage costs per year	€	494,469	465,382	334,494
Totals	€	**805,990**	**729,238**	**451,255**

2 CONCLUSIONS DRAWN FROM VOYAGE-BASED MODEL

The main goal of this case-study was to quantify and give a monetary value to pollutant emissions from a voyage-based model. After impacts to society have been evaluated, in order to achieve better air quality, to improve human health and promote sustainable use of ecosystem goods and services, the best available technique and best environmental practice should be elected. This view is in accordance with the ecosystem approach - a comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics - as recognised by the Convention for the Protection of the Marine Environment of the North-East Atlantic ("OSPAR Convention"). The results from this case-study show that both HFO fuelled ship equipped with scrubber in combination with SCR and an MGO fuelled SCR equipped ship are not cost-effective solutions. Marginal external costs from an LNG fuelled ship are lower by large if we compare with the other two alternatives. Regardless of which compliance strategy a ship-owner chooses this study do not address operational and investment costs neither this was meant to be done. What matters the most is that from the viewpoint of the society as a whole LNG is the most environmentally friendly alternative and cost-effective solution. This case-study addresses climate change impacts from CO_2 only. Together with the high level of uncertainty surrounding downstream effects from methane slip, marginal carbon dioxide equivalent emissions (CO_2e) from the LNG fuelled ship might have to be considered. However, modern 2-stroke LNG engines produce almost no methane emissions and if so, the amount of CH_4 released into the atmosphere can be reduced from tank-to-propeller perspective to almost zero. The LNG vessel Scenario shows that environmental benefits range between 1.8 and 1.6 times compared with the HFO and MGO vessels, respectively. Assuming Portuguese waters as included in a future ECA region and evaluating the impacts for the society as a whole, this paper contributes for a deeper understanding within the wider scope of environmental sustainability perspective for the feasibility of LNG as an alternative fuel for marine purposes.

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