LNG VERSUS CONVENTIONAL FUEL POWERED VESSELS: ENVIRONMENTAL IMPACT OF ROPAX SHIPS

ÁLVARO HERRERO-MARTÍNEZ
Grupo de I+D de Planificación y Gestión Oceánica y Costera, Cantabria (España), Universidad de Cantabria, Germán Gamazo nº 1, 39004 Santander, España
e-mail: alvaro.herreromartinez@unican.es (A.H.-M.) (Author for correspondence)

CARLOS GONZÁLEZ GUTIÉRREZ
Grupo de I+D de Planificación y Gestión Oceánica y Costera, Cantabria (España), Universidad de Cantabria, Germán Gamazo nº 1, 39004 Santander, España
e-mail: carlos.gonzalezgu@alumnos.unican.es (C.G.G.)

ANDRÉS ORTEGA-PIRIS
Grupo de I+D de Planificación y Gestión Oceánica y Costera, Cantabria (España), Universidad de Cantabria, Germán Gamazo nº 1, 39004 Santander, España
e-mail: andres.ortega@unican.es (A.O.-P.)

EMMA DIAZ-RUIZ-NAVAMUEL
Grupo de I+D de Planificación y Gestión Oceánica y Costera, Cantabria (España), Universidad de Cantabria, Germán Gamazo nº 1, 39004 Santander, España
e-mail: emma.diaz@unican.es (E.D.-R.-N.)

MIGUEL A. GUTIÉRREZ
Departamento de Tecnología, Facultad de Ciencias, Universidad Católica de Ávila, C/Canteros S/N, 05005 Ávila, España
e-mail: miguel.gutierrez@ucavila.es

ALFONSO-ISIDRO LÓPEZ-DÍAZ
Departamentos de Ingeniería Electrica, Electrónica y Automática, Escuela de Ingeniería Industrial y Aeroespacial, Universidad de Castilla-La Mancha, Avda, Calos III, SN, 45071 Toledo, España
e-mail: alfonso.lopez@uclm.es (A.-I.L.-D.)

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Abstract

Decarbonization and environmental respect have become pillars of European government policies. As a result and given that 80% of global freight transportation is carried out by ships, maritime transport emerges as one of the target sectors for these eco measures.

Numerous initiatives, projects, and new technologies focused on this field exist. This paper examines the potential reduction of CO2 emissions by using LNG as a fuel either in combination with or instead of conventional fuel on RO-Pax ships.

Taking advantage of the fact that we are facing a 'mature' technology already being applied in many ships. Emissions from a fleet of about 30 ships have been studied during the years 2019 to 2023 where progressively adding LNG powered vessels from 4 up to 11. Based on their annual consumptions' reports (HFO, MGO and LNG) total tons of polluted CO2 have been quantified together with the ratio tons of CO2 per sailed mile.

On the other hand, known daily burned marine fuels of one of those vessels sailing Balearic Islands-Mainland Spain route and due to high increase of gas prices during 2021 and beginning of 2022 (about

350%) a study was conducted: consuming LNG for 265 days whenever possible and avoiding this fuel for 143 days. Therefore, based on the same ship/route, a particular comparison of CO_2 emissions per nautical mile is obtained.

Finally, using above results, hypothetical study is carried out in which emissions are estimated based on the sailed miles during years 2017 to 2021: Potential emissions in case of LNG versus conventional fuel powered. The 5-year result shows about 17.08% potential reduction. Approximately 32700 tons of CO_2 only for 1 vessel highlighting the huge importance of the LNG powered vessels to reduce the environmental impact and the great importance of the investments on Research, Development and Innovation.

Introduction

The transportation of people and goods has been a cornerstone of international trade and a source of wealth for the countries and companies involved. From the beginning, rapid material delivery and transit time have been key goals in the pursuit of optimizing outcomes. The marine industry was developed in response to the need of minimizing the time spent to cover the distances from the starting point to the destination. Over time, sailing vessels, steamships, fossil fuel-powered ships etc. have emerged until achieving the specialization of the different types of ships that we can see these days, such as RoRo, bulk, tankers, general cargo, etc.

Supported by significant technological advances, the risks of the maritime adventure have been notably reduced and, together with the large conveying capacity of ships, it has allowed maritime transportation to stand out as the means of transport used by over 80% of goods transported in the international trade (Unctad, 2023) [1].

Safety, speed and the specialization in the care and custody of the transported goods have been major concerns until the end of the last century when sustainability started to be discussed following the Brundtland Report (United Nations, 1987) [2]. In this report, the concept of sustainable development is defined as the process to `satisfy the needs of the present generations without compromising the possibilities of the ones in the future in order to meet their own needs'. Since then, the reduction of the pollutant emission and greenhouse gases have gradually arisen to become a central goal for governments and international organizations. The continuous growth of the maritime industry (Unctad, 2023) [1] makes that the efforts undertaken so far have only achieved to stop the overall CO_2 emissions to the atmosphere approximately 3% of total emissions (IMO, 2020) [3] (Olmer et al., 2017) [4] but a greater commitment by all parties is needed to reduce the total amount. According to Mikova (Mikova et al., 2019) [5] it is insufficient when it comes to the legislation implemented by each country but it must be a coordinated action by all governments and they must include all private and public entities.

In the maritime field, several regulations have been enacted with the aim of mitigating the CO_2 emission from ships to the atmosphere. At an international level, IMO is the specialized agency of the United Nations responsible for the regulating the international maritime transportation. OMI, in July 2023, published the revised strategy of decarbonization which has as its objective to significantly reduce the GHG emissions of the international maritime transportation. The new goals include a 20% reduction in emissions by 2030, a 70% reduction by 2040 (in comparison to 2008 levels) and a final goal of achieving net-zero emission by 2050. At a European level, The European Green Deal (Commission, 2019) [6] provides a roadmap to develop the necessary measures and policies with the aim of reducing GHG and achieving climate neutrality by 2050 by reducing 55% in 2030 compared to 1990 data.

IMO has been developing and implementing a new legislative framework aimed at reducing atmospheric emissions by means of the Annex VI of the MARPOL Convention, which came into force on May 19, 2005.

Annex VI specifically focuses on the ODS emissions (Ozone Depleting Substances) SO_x, NO_x and CO_2. The specific regulations about CO_2 emissions outlined in MARPOL´s Annex VI include the implementation of EEDI (Engergy Efficiency design index) (Ančić et al., 2018) [7] in the new vessels constructions, which promotes the use of more energy-efficient engines and equipment when building ships to make them less polluting; and the creation the SEEMP (Ship Energy Efficiency Management Plan), which is a plan for shipowners and operators to improve the energy efficiency of vessels. Both came into force on January 1, 2013. In October 2016, the OMI established the obligatory requirements for ships to record and report their fuel consumption in the MEPC 70 meeting (MEPC.278(70)) (MARPOL, 2016) [8], as well as the obligation to create a plan in which ship operators specify how they are going to carry out such recording and reporting. This plan is known as SEEMP II. In 2021, the OMI adopted a new set of technical an operational measures (MEPC.328(76) resolution) (MARPOL, 2021) [9], which includes the calculation of the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), both of which came into force in January 1, 2023. Under the EEXI framework, all existing vessels with a gross tonnage of 400 or higher are required to calculate the EEXI obtained, which reflects the vessel's "technical" or "design" efficiency. All vessels must achieve a "required EEXI" equivalent to the EEDI required by 2022. The CII reflects the vessels' operational efficiency, using IMO's DCS (Data Collection System) and SEEMP consumption data (Barreiro et al., 2022) [10]. It is mandatory for vessels with a gross tonnage of 500GT or more. Annual operational values are compared with the required ones, with reductions between 2023 and 2026. In order to help companies achieve the CII required, the creation of SEEMP III is necessary. It is a mandatory and specific document for each ship which outlines the plan to improve the CII and, therefore, the operational energy efficiency of the ship over the next three years.

At a regional level, in response to the deregulation of the maritime transport regarding atmospheric emissions, the European Parliament decided to take action regarding those vessels operating in European waters. In absence of data on CO2 ships' emissions, it was concluded that a robust system for monitoring, reporting and verification (MRV) of the CO2 emissions from maritime transport is a previous requisite for any regulatory measure or establishment of efficiency standards, whether it is applied to the UE or globally. In 2018, the law which makes all ships over 500GT that operate in European waters report the CO2 emissions while traveling between, from or to European ports came into force. From these data that the maritime operators have been reporting throughout the years, on January 1, 2024, the maritime transport was included in the European Union Emissions Trading System (EU ETS), in which ships with a gross tonnage over 5000GT operating in European waters will gradually be required to pay for their CO2 emission allowances.

The last measure from the European Union that affects the maritime transport is the so called "FuelEU Maritime". This is an initiative focused on promoting the use of cleaner and more sustainable marine fuels, as well as promoting the transition to more environmentally friendly technologies and practices in the maritime transport. This regulation will come into force on January 1, 2025.

On the other hand and, taking into consideration the seriousness of the situation, apart from the political and legislative actions to decarbonize the maritime transport, there are other types of technical and operational measures on which both researchers and shipping companies have been working hard.

-Design: Hull shapes (Lindstad et al., 2016) [11], Hydrodynamic Appendages, Air lubrication (8%) (Fotopoulos & Margaris, 2020) [12], Paints (H. Wang & Lutsey, 2013) [13], Heat recovery systems , OPS (Iris & Lam, 2019) [14], etc.

-Machinery and propulsion: Engine power, Efficiency in new engines, higher performance propellers, use of batteries, fuel cells (McKinlay et al., 2021) [15] etc.

-Alternative fuels (Taljegard et al., 2014) [16] : HFO with scrubbers, LNG (Thomson et al., 2015) [17], methanol, ammonia (Hoegh, 2024) [18], Hydrogen, Biofuels, FAME-HVO, synthetic fuels, Nuclear, etc.

-Alternative sources of energy: rotor sail, suction sail, wind sail (Tillig et al., 2015) [19] (WalleniusWilhelmsen, 2022) [20], Kite, , etc.

-Operational measures (Beşikçi et al., 2016)[21] : speed reduction (S. Wang & Meng, 2012) [22], optimization in the loading capacity, routing optimization (Psaraftis & Kontovas, 2016) [23]: tides, weather forecasting, alternative routes, scheduled hull cleaning (Adland et al., 2018) [24], optimal trip trimming, etc.

As it may be expected, none of these measures by itself is the only solution but, as Bouman says (Bouman et al, 2017) [25], it is necessary to combine them to achieve the challenging goals established by 2050

Study case – LNG ROPAX

All the decarbonization measures proposed above have advantages and disadvantages, so there is no universal solution. Instead, each shipowner must conduct an individual study of their needs and possibilities and then choose from the different existing options.

Decarbonization in the maritime sector is a field of study too broad to be covered in just one publication. Various studies demonstrate that emission from conventional combustion engines are one of the causes of global warming and they are linked to health-damaging diseases (Quaranta et al., 2012) [26] (Sorte et al., 2019) [27] (Tian et al., 2013) [28] (Sasha Khomenko et al, 2021) [29]. For this reason, and due to the potential impact on the population centers near the ports, this article focuses on a case of study of liner ROPAX ships operating between the islands and the Iberian Peninsula, using LNG as propulsion fuel (Dobrota et al., 2013) [30] . The transportation of people, its frequency and regularity make these vessels a perfect candidate for study, given their direct impact on society.

LNG is made of various gases where methane (CH4) is the main element (from 85% to 96%) (Government, 2024) [31] (Fernández et al., 2017) [32]. According to EMSA (European Maritime Safety Agency) (EMSA, 2017) [33] it can reduce CO2 emission by 25/30% whereas NOx may reduce it by 40/80%. Sox and PM are almost eliminated (between 90% and 100%). These real percentages may depend on the engine efficiency, the quality of the LNG, the percentage of 'pilot fuel' used and other factors which will be discussed below.

Spain imports approximately 99% of its gas from 10 different countries. 58% comes through gas pipelines in gaseous form, while the remaining 42% comes in liquid form via maritime routes and it is received at regasification plants before being injected into the national distribution system. Besides, Spain has storage facilities that account for 37% of the total European capacity, making it a crucial player in the future of the international sector and ensuring an easy access to the product to supply it to the ships. (Government, 2024) [31]. Accordingly, the EU has already foreseen the availability of LNG supply at the major maritime ports by 2025. The supply can be carried out in three different ways: Truck to Ship (TTS), Ship to ship (STS) or Port to ship (PTS), depending on the available equipment and facilities.

From the technical point of view, LNG has been used for years as propulsion fuel of methane ships to take advantage of BOG (boil-off gas) when they do not have re-liquifying gas plants (Chang et al., 2008) [34].

It is a colorless and odorless gas, which is non-toxic but it is inflammable and it is stored in liquid state at a temperature below -163ºC (Dobrota et al., 2013) [30]. It occupies a volume 1.8 times that of the MGO so the autonomy of the vessels that consume this type of fuel may be limited or the space dedicated to its storage will need to be increased while maintaining the necessary temperature.

Safety is a fundamental aspect in the use of LNG and the regulations of construction and measures to avoid leaks are very well defined. It is mandatory to install double wall pipes. There are strict requirements in the quality of the materials, characteristics and the situation of the tanks, leak detectors, ventilation and other requirements of the legislations that are explicitly included in the IGF code (IMO, 2015) [35]. Both dual engines and boilers can be prepared to burn diesel or gas from the ships' launch but modifications in the existing engines can be also made to adapt them to the new fuel. In the fleet where the study has been conducted both situations can be found.

Taking into account that the maritime propulsion from the use of LNG has been a mature technology for years and well known in this field, this study is aimed to quantify the reduction in CO2 emission for gas propelled ROPAX versus FO fossil combustion conventional ones. It should be noted that, together with the gas, dual engines require the injection of a 'pilot fuel' in the combustion chamber. The percentage of the combination may vary but it ranges from 1.5% and 3% depending on the load of the engine (from 10 to 100% respectively) (MAN Diesel & Turbo, 2014) [36] (Dobrota et al., 2013) [30].

Methodolody

1. Context and introduction
2. Study of emissions of the entire fleet
3. Specific study case
4. Discussion

1 CONTEXT AND INTRODUCTION

Given the repercussion of the ship emissions in ports and to for the further conclusions of the study published about the potential impact of the OPS (Herrero et al., 2022) [37] in which one of the conclusions raises the frequency as a key factor and highlights RORO sectors, Ferry and cruises as optimal to get to the decarbonization at the highest positions, this paper seeks to go deeper into the topic.

As a general rule, ports are located near urban centers and ROPAX, as they transport both people and goods, they are characterized by covering medium and short distances and having high frequency and presence in their base ports. For this reason, the reducing emissions from this type of vessels has positive consequences in the quality of life of people living in their areas of influence. These maritime services, taking into account the interruption while COVID, were used between 2019 and 2023 by 19.5 million people, being this traffic between the Iberian Peninsula, the Balearic Islands, Ceuta and Melilla; 78% of this in 2023. Insular ports such as Menorca, Mallorca, Ibiza, Ceuta, etc. or those in mainland like Barcelona, Valencia, Denia, Motril, Malaga, etc. could be benefited if emissions were reduced. Therefore, it is in these ports where the need for public-private collaboration to promote decarbonization and boost investments should be more evident. So, since 2019, and thanks to this collaboration, LNG-powered vessels have been introduced from the initial 4 to the 11 ones projected by 2024. The objective is the quantitative study of the CO2 emissions in regular line ROPAX ships propelled by LNG versus conventional ships.

One of the potential challenges for the private investment and the commitment to use LNG is the volatility of prices. Following the COVID19 pandemic and exacerbated by the Russian invasion of Ukraine, this issue becomes evident making European states diversify their suppliers minimizing the dependencies they had in previous years. The increase in gas prices, reaching 350% higher from the beginning of 2021 to September of the same year (ElEconomista, 2021) [38] makes the shipping companies take a step back, despite their substantial investments, and rely on conventional fuels to keep the viability of their services. This situation allows the authors to conduct a specific study case comparing the emissions of one of the vessels under 2 real scenarios, having as the only variable the type of fuel used. LNG versus conventional fossil fuels.

According to Maragkogianni, there are two approaches to quantify the CO2 emissions from vessels: (Maragkogianni et al., 2016) [39]

- Top-Down': used to calculate global emissions and entire fleets on taking into account their fuel consumption.

- Bottom-up': based on the activity and focused on calculating the specific emissions on operating hours, installed power, working system, etc.

  In this study, the Top-Down approach will be used since we know the fleet's annual fuel consumption.

2 STUDY OF EMISSIONS OF THE ENTIRE FLEET

All the sustainability reports published annually by the studied shipping company from 2019 to 2023 have been taken into account to conduct this research. The miles sailed, except for 2020 which, due to COVID experienced a significant decrease, have been increasing. (Table1)

%sailed miles compared to previous year		-24,94%	14,21%	14,31%	17,30%
	2.019	**2.020**	**2.021**	**2.022**	**2.023**
Miles	1.622.430	1.217.832	1.390.920	1.590.007	1.865.000
Gasoil (m3)	89.785	65.236	79.790	103.266	91.314
HFO (t)	150.736	77.882	72.565	136.733	150.499
LNG (kWh)	24.592.371	511.825.077	698.531.771	36.936.760	388.258.000

Table 1 - Source: authors

Considering the data form the previous table regarding the fuel consumption for the different fuels, the goal is to obtain the tons of CO_2 emitted into the atmosphere by each of them:

MDO

Consumption provided in cubic meters.

$$CO2\ (tons) = M3 \cdot D \cdot EF(MDO) \qquad [1]$$

According to Fourth IMO GHG Study – July 2020 (IMO, 2020) [3]:

M3 – The shipping company provides the consumption in cubic meters.
D – Density - MDO - 0.895 tons/m3
EF(MDO) – Emission Factor 3.206 tons of CO2 per consumed ton of Gasoil

HFO

Consumption provided in tons

$$CO2\ (tons) = Tons(fuel) \cdot EF\ (FUEL) \qquad [2]$$

According to Fourth IMO GHG Study – July 2020 (IMO, 2020) [3]:

Tons(fuel) – tons that the shipping company publishes.
EF (fuel) – Emission Factor 3.114 tons of CO2 per consumed ton of HFO

LNG

Consumption provided in kWh

$$CO2\ (tons) = (kWh/Ed) \cdot EF\ (LNG) \qquad [3]$$

According to Fourth IMO GHG Study – July 2020 (IMO, 2020) [3]:

kWh – consumption that the shipping company publishes
EF – Emission Factor 2.750 tons of CO2 per consumed ton of LNG
Ed – Energy Density – 48000 KJ per kilo of LNG
1Kwh= 3,6MJ = 3600 KJ KJ = 1Kwh/3600

48000 KJ/kg = 48000/3600 Kwh/kg = 13.333 Kwh/kg
13.333 Kwh/kg = 13,333 Kwh/ton

Once we have the tons of CO_2 emissions of each type of fuel, the total amount of tons emitted to the atmosphere per year is calculated.

Furthermore, in order to make a comparative among the years of the study, we also calculate the ratio of CO_2 tons per nautical mile sailed.

Ratio TCO_2/mile = total CO_2 tons polluted / total sailed miles [4]

T CO2	2.019	2.020	2.021	2.022	2.023
Gasoil (t)	257.626	187.188	228.948	296.307	262.014
HFO (t)	469.392	242.524	225.967	425.786	468.653
LNG (t)	5.072	105.564	144.072	7.618	80.078
Tons of CO2	**732.090**	**535.276**	**598.986**	**729.712**	**810.745**
Ratio tCO2/mile	0,451	0,440	0,431	0,459	0,435
total CO2 % compared to previous year		-26,88%	11,90%	21,82%	11,10%

Table 2 - Source: authors

3 SPECIFIC STUDY CASE

Due to the need of the shipping company to stop the LNG consumption because of the increase of its cost, the opportunity to conduct this study arises. The situation is ideal to compare real consumption under these circumstances. The regular line ROPAX vessel studied has the following characteristics:

Built	2002
Retrofit LNG	2020
Lenght Overall	186.25
Beam	25.6
GT	24409
Engine	MAN 9L51/60DF
Cargo capacity	
Passenger	1000
Vehicles	481

Table 3 - Source: authors

In 2021, the period from January 1 to September 24 LNG is used as propulsion fuel. From that moment, the vessel is instructed the opposite and it starts to use HFO in its engines. The fact that it is the same vessel, the same engine, characteristics, etc. allow us to obtain the real fuel consumption data to compare emissions in the two scenarios we are analyzing. Since we have the real data up to February 27, 2022, the emissions for three periods are calculated:

1- LNG consumption period

2- Conventional consumption period

3- 2021 Period

	Initial date	final date	days	Miles
Period Burning LNG	01/01/2021	24/09/2021	265	78995,8
Period avoiding LNG	27/09/2021	17/02/2022	143	31331,6
Year 2021	01/01/2021	31/12/2021	364	97968,4

Table 4 - Source: authors

Once known the periods shown in table 4 and using the data obtained from the books of the vessel and reported to EMSA (EMSA, 2024) [40], in accordance with Article 21 of EU Regulation EU 2015/757, which determines the obligation of registering, reporting and verifying the CO2 emissions of the maritime transport (Council of the European Union, 2015) [41], the CO2 emission produced by the vessel are calculated for each type of fuel and the total amount.

If the amount of CO2 tons is dived by the nautical miles sailed, the Ton CO2/mile ratio can be obtained, enabling the annual estimation of the studied vessel according to the proposed objective: LNG Vs Conventional fuel

	Tons LNG	Tons HFO	Tons MDO	Tons CO2LNG	Tons CO2FO	Tons CO2MDO	Total tons CO2	Ton CO2/mile
Period Burning LNG	6869,20	2515,40	803,17	18890,30	7833,96	2574,97	29299,23	0,3709
Period avoiding LNG	89,55	4150,25	262,59	246,27	12925,54	841,87	14013,68	0,4473
Year 2021	6930,60	4964,14	971,52	19059,15	15460,32	3114,70	37634,17	0,3841

Table 5 - Source: authors

Thus, once known the annual distance sailed by the ship, the annual emissions are obtained based on the two scenarios by multiplying them by the CO2 ton per mile ratio. By subtracting the emissions calculated for one and other scenario, we obtain the emissions that could have been avoided if the vessel had used LNG at all times in comparison to the emissions in case of not having this possibility.

	2017	2018	2019	2020	2021	TOTAL
Sailed miles	88198,00	98066,70	94853,20	49678,50	97968,40	428764,80
LNG consumed	32712,29	36372,56	35180,68	18425,56	36336,10	159027,19
Consumed conventional fuel	39448,30	43862,27	42424,97	22219,69	43818,30	191773,53
Difference	**6736,00**	**7489,71**	**7244,29**	**3794,13**	**7482,20**	**32746,33**

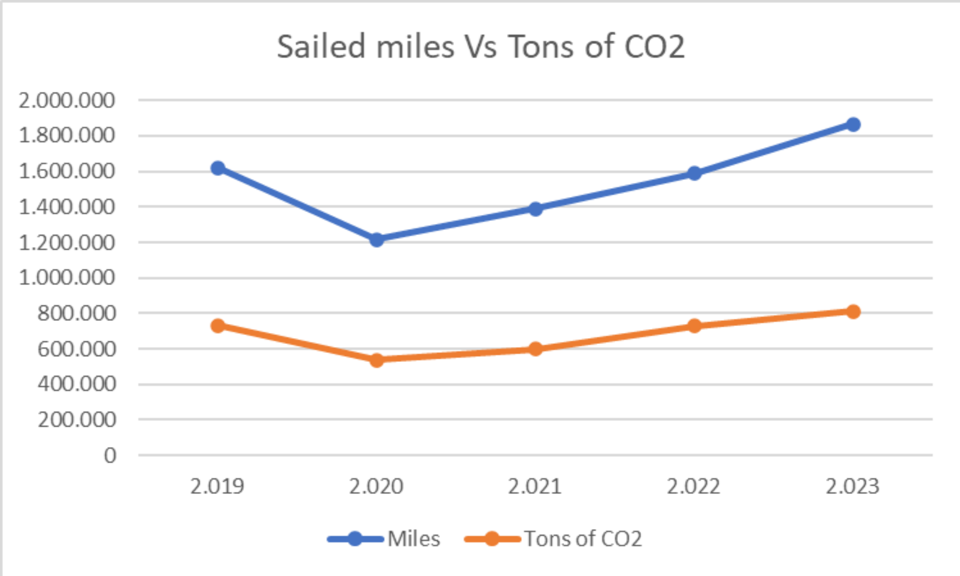
Table 6 - Source: authors

Therefore, and in view of the obtained results, it turns out that the emissions saving capacity of the LNG powered vessel instead of conventional fuels is 32,746 tons of CO2. A reduction in CO2 emissions of 17.08%.

4 DISCUSSION

After numerous calculation exercises and considering the results, it becomes evident that there is a need to obtain individual data from more vessels of the fleet to draw reliable conclusion which allow the generalization and extrapolation of these findings to the entire studied fleet. The different characteristics of over 30 ships and the numerous factors that affect the consumption open the door to future research. Some of these factors being size, age, type of vessel (fast ferries, new smart vessels, electric propulsions vessels) routes, propeller and hull conditions, working times (in port, sailing, maneuvering) speed, engine load, ship loaded condition (loaded, ballast) etc.

On the other hand, a conclusive result the studies conducted is that the decarbonization measures implemented between 2019 and 2023 do mitigate or reduce the CO2 emissions per nautical mile sailed. As it can be seen in Graphic 1, the slope of CO2 emissions tends towards horizontal whereas the that of the nautical miles travelled continues to increase. It is expected that the implementation of new measures continues and that curve of emissions ends up with a downward trend to achieve the objective.



Graphic 1 - Source: authors

Despite the reduction percentages estimated by EMSA due to the use LNG (20/30%) the result of the study indicates that it is 17.08%, falling short of what it was expected. It is worth noting that this is a very substantial reduction percentage since it stems from the emissions of the main engine, being this the primary focus of pollution.

This deviation from previous publications may be justified due to operational complexities the vessel, with many variables listed above, such as port entries and departures (maneuvering) along with continuous and prolonged periods of onshore consumption (this vessel is not equipped with OPS), which makes this ship keep its engines running during dock stays, increasing the fuel consumption without increasing the nautical miles sailed.

Even though it is not the focus of this paper, it is important to highlight the importance of the proper combustion of methane by reducing the methane slip or CH4 `leak´(Ushakov et al., 2019) [42] to the atmosphere to achieve the objective of reducing greenhouse gas emissions It is worth noting that the CO2 equivalent (over 100 years) of CH4 is 28 times higher than that of CO2 (Shine, 2009)[43].

Finally, in the discussion of this article, we would like to leave the door open to future research to continue with this line of work, based on the possibility that engines and vessels prepared for the consumption of LNG can easily increase the reduction of CO2 emissions into the atmosphere by using Bio-methane or other types of synthetic fuels. In such scenario, the reduction potential of emissions of the existing facilities onboard could multiply the environmental advantages.

5 CONCLUSIONS

The following conclusions can be drawn from the data and results obtained in this study:

1. From the economic perspective, the price difference between LNG and conventional fuels will be the key for the success of this as a propulsion fuel. To be environmentally sustainable, it is necessary to be economically sustainable.

2. Control on LNG supply and not depending on just a few suppliers would mitigate price volatility favoring private entities' interest.

3. Given that consumption of LNG is viable for newly constructed vessels but also the reinstalling the engines of the existing ones, the increase of supply points of this fuel is key to quickly implement it in all types of ships.

4. It is a mature and well-known technology. It is not a recent or novel development, so its implementation does not pose significant uncertainties.

5. It is not a toxic product, but it must be stored in liquid state and at very low temperatures. The technical requirements are approved and known by Classification Societies, shipyards, ports, etc. That is to say that there is already a comprehensive regulatory guidance.

6. It is evident that LNG is a fuel with great potential to reduce CO2 emissions into the atmosphere.

7. Depending on how vessels operate, the percentage of reduction of the LNG can vary from the 17% observed in the studied ROPAX vessel to the 30% that EMSA claims.

8. Using LNG in ROPAX vessel is not sufficient to achieve the goal of zero emissions in this sector by 2050.

9. The combination of different technologies is necessary to achieve the imposed decarbonization goals.

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