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Article

Ships decarbonization is an urgent technology and responsibility challenge that impacts global warming

Descarbonización de barcos es un reto de urgencia tecnológica y responsabilidad que impactan en el calentamiento global

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Abstract

Maritime transport generates 3% of global CO_2 emissions according to the GHG (Greenhouse Gases) report. The aim of this research was to analyze the decarbonization of ships through the technological migration from conventional fuels to alternative types for zero-emission purposes. On the other hand, shipping companies that modernize their fleets to zero emissions will have priority in the provision of services. However, those that do not have these assets will be penalized. A mixed analysis was carried out on the migration of technologies in zero-emission ships based on the quantification and estimation of statistical control variables, decision-making, modernization stages and technologies. The characterization of data obtained from each ship will determine the feasibility of applicable technologies to achieve zero emissions. The optimization of technology applied to each ship according to its use will be the subject of future work.

Objectives	Methodology	Contribution
Analyze the decarbonization of ships through the technological migration from conventional fuels to alternative types for zero-emission purposes.	This research had a mixed approach, applying both quantitative and qualitative technologies, using systematic processes, as well as records and estimated data.	The characterization of data obtained from each ship will determine the feasibility of applicable technologies to achieve zero emissions.

shipping industry carbon footprint, ships decarbonization, zero emissions ships

Resumen

El transporte marítimo genera 3% de las emisiones de CO_2 globales de acuerdo con el reporte GEI (Gases de Efecto Invernadero). El objetivo de esta investigación fue analizar la descarbonización de buques a través de la migración tecnológica de combustibles convencionales a tipo alternativos con fines de cero emisiones. Por otro lado, Las navieras que realicen la modernización de sus flotas a cero emisiones tendrán prioridad en el préstamo de servicios. Sin embargo, las que no cuenten con estos activos tendrán penalizaciones. Un análisis mixto fue realizado en la migración de tecnologías en barcos cero emisiones basado en la cuantificación y estimación de variables de control estadísticas, toma de decisiones, etapas de modernización y tecnologías. La caracterización de datos obtenidos de cada barco determinaran la factibilidad de tecnologías aplicables para lograr las cero emisiones. La optimización de tecnología aplicada a cada barco según su uso será motivo de trabajos futuros.

Objetivos	Metodología	Contribución
Analizar la descarbonización de buques a través de la migración tecnológica de combustibles convencionales a tipo alternativos con fines de cero emisiones.	Esta investigación tubo un enfoque mixto, aplicando tecnologías tanto cuantitativas como cualitativas, utilizando procesos sistemáticos, así como registros y datos estimados.	La caracterización de datos obtenidos de cada barco determinara la factibilidad de tecnologías aplicables para lograr las cero emisiones.

huella de carbono industria naviera, descarbonización de barcos, emisiones cero barcos

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Introduction

3% of global CO_2 emissions are produced by maritime transport according to the GHG (Greenhouse Gas) report. The IMO (International Maritime Organization) warns that failure to take decisions and measures to reduce this will result in an increase with major consequences for global warming. Decisions on the course to follow are governed by rules and regulations negotiated and agreed upon by the (IMO) and shipping companies with large assets in the maritime fleet industry and port companies. The initial proposal was to bet on the decarbonization of maritime transport and what this implies in deep waters and on land with objectives to be met in the short term 2025, medium term 2030 and long term 2050 to achieve zero emissions in the shipping fleet in transport, loading and unloading (Akgül, 2024 and Baştuğ et al., 2024).

The aim of this research was to analyze the decarbonization of ships through technological migration from conventional fuels to alternative types for zero-emission purposes; in addition, this transition is essential for achieving sustainability in maritime transport. The characterization of data obtained from each ship will determine the feasibility of applicable technologies to achieve zero emissions.

Nevertheless, the migration from conventional petroleum-derived fuels to zero-emission alternative fuels was the proposal with the greatest emphasis. The agreements of the organizations and companies involved decided to adopt alternative fuels with low or zero greenhouse gas emissions. Proposals on new technologies, logistics, change of travel rates, investments, execution times, penalties, economic support for modernization, among others, were the basis for focusing mainly on the source of pollution with the greatest impact: ships (Black et al., 2024 and Koilo, 2024)

How to achieve the decarbonization of port assets in line with the objectives of the IMO (International Maritime Organization)? in a sustainable manner and with a circular economy.

The renewal of engines, modernization and renewal of ship fleets must be accompanied by expert personnel in the design of ship engines, who can generate feasible and sustainable proposals for the sector to meet the 2025 aims. IMO representatives are negotiating support and financial aid to help developing countries have equal participation in the evolution and adaptation of maritime transport. However, they also warn that there will be no turning back and that delaying decarbonization would not be more costly due to its impact on climate change (Black et al., 2024 and Karvounis, et al., 2024).

With greater emissions to reduce in a shorter period with higher costs of dealing with pollution emergencies that generate uncertainty and increase implementation costs during transition times. The optimization of technology applied to each ship according to its use will be the subject of future work.

Research methodology

This research had a mixed approach, applying both quantitative and qualitative technologies, using systematic processes, as well as records and estimated data. The aim of this research was to analyze the decarbonization of ships through technological migration from conventional fuels to alternative types for zero-emission purposes. For this, the application of the quantitative method was relevant in the identification of control variables involved in previous studies such as; statistics, decision making, modernization stages and technologies.

The characterization of data obtained from each ship will determine the feasibility of applicable technologies to achieve zero emissions. Pollution rates from ships in the global port supply chain identified that it is responsible for 3% of greenhouse gases, experiences of shipping and port personnel who identify the carbon footprint of ships and ports reported scientifically, were considered as the application of the qualitative method that allowed the possibility of obtaining results from the estimation of variables, which played an important role in decision making to understand the technological proposals to be implemented in ships, based on the modernization or renewal of zero-emission technologies.

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The operational data resulting from this investigation determined that the renewal of engines, modernization and renewal of ship fleets must be accompanied by personnel expert in the design of ship engines, who can generate feasible and sustainable proposals for the sector to meet the 2025 objectives. Finally, by the mixed method, an analysis of Control variables allows you to get involved in ¿How to achieve the decarbonisation of port assets in line with the objectives of the IMO (International Maritime Organisation)? in a sustainable manner and with a circular economy (Akgül, 2024 and Karvounis, et al., 2024)

Dual engines low emissions

Methanol is a sustainable alternative fuel that helps the marine industry to progressively reduce emissions, which is a key goal in decarbonization. If produced from renewable sources, it can reduce CO_2 emissions by up to 95% compared to conventional fuels. Green methanol would not add CO_2 to the atmosphere, which means that engines burning this fuel, when installed as a retrofit project on ships, will have carbon neutral emissions, helping shipping companies adapt to the changing energy landscape and environmental regulations. Ships currently have a flexible design adaptable to any engine and use methanol technologies on board as a source, either as pure fuel or blends in dual LNG-Methanol or Methanol-biofuel engines. (Akgül, 2024, Ammar & Seddiek, 2023, Bayraktar et al., 2023 and Dere, et al., 2024).

Sustainable marine boilers operate with MultiFlame burners and use a plate and box heat exchanger for fuel gasification providing thermal energy transmitted by hot engine water to efficiently utilize energy from LNG (Liquefied Natural Gas), LPG (Liquefied Petroleum Gas), Methanol and biofuels. (Xia et al., 2024).

Migration from conventional fuels to zero emissions

The keys to decarbonizing maritime transport are a challenge for the migration from conventional fuels to zero-emission fuels, such as hydrogen, ammonia and methanol.

Notwithstanding, when the production processes of these fuels are from a completely renewable source, they are called green and when in any of their processes they are derived from fossil fuels, they are assigned blue, gray and black colors, because, although they are zero-emissions when burned, a source derived from oil was involved in their production (Abeynaike & Barbenel, 2024).

The shipping industry uses internal combustion engines of the Otto, Diesel and Brayton cycles, with pure fuels and mixtures. However, by 2022 the ammonia engine has represented a technological challenge for adaptation in two- and four-stroke engines, with a net zero emissions scope. By 2023 the ammonia engine represents a functional technology that by 2024 will be installed in container ships in prototypes and in 2025 vessels with this technology will sail the seas in a commitment to the environment (Schwarzkopf, et al., 2023).

Hydrogen, Methanol and Ammonia, whether blue or green, will be the transport fuels of the future in the decarbonization of ships. An additional zero-emission alternative is electrification, provided that the electrical energy in its generation process comes from alternative energy sources or green sources. However, a transitional fuel is LNG (Liquefied Natural Gas), LPG (Liquefied Petroleum Gas) used in the dual cycle either with Hydrogen, Methanol and Ammonia (blue or green) or in a mixture with conventional fuels such as gasoline and diesel. One of the technological complications that currently limit the Otto, Diesel, Brayton thermodynamic cycles and their combinations is precisely the start-up at startup, which must be done with fossil fuels, because they are designed for this type of fuel. That is to say that engines, whether four-stroke, two-stroke or axial, once they have reached their nominal speed require a fuel migration system from conventional sources to zero-emission fuels once they are started, achieving their autonomy in the combustion of zero-emission fuels (Abeynaike & Barbenel, 2024).

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The IMO (International Maritime Organization) reported that tank-to-wake CO_2 emissions measurements have been the basis for mapping the carbon footprint behavior of ships, which has allowed it to identify, in conjunction with other organizations and other studies, that the impact of global maritime trade currently contributes around 3% of the international carbon footprint according to the World Economic Forum, with emissions amounting to 1,076 Mt (million tons) of CO_2. To ensure that by 2030 global warming does not exceed the 1.5 °C trajectory and that shipping activities continue to grow at the rate projected in recent years in the carbon footprint, it is certain that they will undermine the objectives according to the "Paris Agreement". To reduce greenhouse gas (GHG) emissions from international shipping, global measures must be adopted covering emissions of CO_2 (carbon dioxide), CH_4 (methane) and N_2O (nitrous oxide), but the latter two only from 2026 with the gradual implementation of measures on ships using green fuels until reaching the goal in 2050, according to the IMO objectives of zero-emission fleets.

The path of using Hydrogen, Methanol and Ammonia (blue or green) is a production technology known to the industry, mainly with applications for fertilizers, but not for supply as fuel. In Europe and Asia, by 2024, the requirements of some shipping companies that already use these zero-emission alternative fuels in a limited way in prototype ships are already at the stage of supplying maritime fleets. However, in the transition process, the costs of these zero-emission fuels are significantly more expensive than fossil fuels, which makes projects to produce green fuels difficult in a global supply chain. Investment decisions need to be made in companies that take risks in the fuel migration process when, at an early stage towards zero emissions in the shipping industry, demand is limited or non-existent in some developing countries (Baştuğ et al., 2024, and Kamran & Turzyński, 2024)

Zero-emission fuels: a challenge to current technologies in the shipping industry

Large-scale pure hydrogen in Denmark depends on a hydrogen pipeline connection to Germany to supply industrial Europe, but this infrastructure does not include the shipping industry.

Entrepreneurs say we have not seen a buyer willing to pay the price to produce methanol or ammonia, some projects may make sense, but we are talking about scale to transition the shipping industry to scale with low-emission fuels, we need the market to be open and evolve.

The IMO (International Maritime Organization) has set the objectives of decarbonization migration from 2023 to 2030 and zero-emission decarbonization for the entire shipping industry by 2050. The shipping industries are willing to carry out the migration aligned with the IMO objectives in a gradual and cooperative manner, but they warn that the introduction of a tax on carbon-intensive marine fuels in 2025 is not in agreement and that the application of this will increase import prices globally and generate shortages in the transition stage. The shipping companies are leaning towards gradual moderate modernization for at least the next decade and propose that once there is a significant penalty in the carbon price for fossil fuels, that will be when the demand for green fuels will really begin to activate with full life cycle fuel standards.

The IMO warns that, without regulation, we cannot realistically expect a deep decarbonization of maritime transport nevertheless, this must comply with specific objectives in terms of time, form, execution, and penalties. But there is one thing we must not forget: today we do not pay when we pollute. Is that fair or not? Low-carbon fuels, such as LNG and LPG, are currently used as bridging fuels at 1.2% in marine fleets in different configurations, so setting a carbon price to drive decarbonization in a tax on fossil fuels in the shipping industry will help investment in promoting green technologies in the shipping sector and will be an incentive for maritime transport owners to engage in modernization. The panorama must be seen under the expectation (“It is an opportunity rather than a threat”) that there are currently many processes in which shipowners and operators are optimizing as much as they can; that is something very positive and should not be underestimated. These improvements will be even greater when we have carbon penalties incentivizing fleet owners to modernize and commit to sustainability.

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The IMO continues to stand by its stated goals and decision on a short-term carbon tax for the shipping sector by 2025, stating that we will all be the owners of the problems unless we manage to find alternative solutions. Shipping companies, based on their scale and profits, are equally committed to complying with the regulations and standards established in the mutual agreements, fulfilling their rights and obligations (Akgül, 2024 and Xia et al., 2024).

The short-term decarbonization objectives establish that 5% of the world fleet must operate with low or zero-emission fuels by 2030. The world fleet must use 28 to 30 Mt (million tons) of Hydrogen, Methanol, Ammonia in its mobility and the demand for green or blue fuels by the energy sector must be covered with port or on-board supply centers depending on the technology implemented on the ship. In a previous evaluation of the short-term 2025 objectives, significant investments in ship modernization and green fuel loading centers were reported with logarithmic ascent, which implies that the objectives can be met.

The medium-term objectives in the decarbonization of the shipping industry committed to reducing the carbon footprint of its transport operations by 25% by 2030, if this proves technically feasible in the modernized pilot fleet in the first stage assessed in 2025. The feasibility assessment by the shipping companies will be under constant evaluation against the parameters pre-established with the fleet before modernization.

The ammonia engine started in 2019 with the preparation of infrastructure, supply and safety systems both on the engine and on site., the engine was modified, with a cylinder prepared to burn ammonia. The engineers benefited from experience in dual-fuel engines: technical changes to the injection equipment and engine control software. On 03 July 2023, the full-scale two-stroke marine engine with ammonia was finally developed: the first successful test of the ammonia engine. The focus in 2024 is on engine performance, pilot oil energy fraction, ignition and various emission categories. International marine engine and system companies are developing technologies for two-stroke engines using pure ammonia as fuel and dual-stroke engines using fuel mixtures to reduce emissions to zero.

These were adapted during 2023 and tested in 2024, as they leverage previous technologies, generating a technological adaptation that can be quickly implemented by engine technologists, considering that the ammonia-burning engine system did not exist as such. The first ammonia engine is expected to be installed on a ship in 2025. Onboard safety technologies and measures to ensure that the crew of an ammonia-fuelled ship can work safely include ammonia sensors, system ventilation, double-walled pipes and special measures such as water screens to completely contain ammonia in the event of a leak. A challenge to be met in line with the short-term objectives of decarbonizing the shipping industry (Ammar & Seddiek, 2023, Chin Law, et al., 2024, Dere, et al., 2024 and Schwarzkopf, et al., 2023).

The potential for the ammonia-fueled two-stroke engine with a tipping point in net zero CO_2 maritime transport during combustion is huge, with the engine aiming to reduce the greenhouse gas footprint by more than 95% compared to a standard diesel engine. The expectation for ammonia is very high and it will become the preferred fuel for maritime transport by 2050 with the lowest production cost of all green fuels. Ammonia is a slow-burning fuel, so the slow-cycle two-stroke diesel engine is ideal for burning it. The ammonia-fueled engine is very flexible and will be applied in a first stage to Ro-Ro (roll on-roll off) vessels, container ships, and tankers. The next stage will be to characterize the operating curves and verify the engine emissions for patenting and commercial use. On the other hand, technologies for the generation of blue and green ammonia on board are being developed in parallel, involving the combination of systems in the supply of ammonia, which will reduce the size of the storage tanks, being used as cargo space, optimizing zero-emission, sustainable and sustainable development ships that at the end of their useful life will be reused through the 9 Rs of the circular economy. Dual-fuel ammonia engines are currently at (Technology Readiness Levels) TRL4, with the technology validated in a test engine configuration, but are expected to reach TRL 9 around 2025 (Ammar & Seddiek, 2023, Dere, et al., 2024, Melideo & Desideri, 2024 and Schwarzkopf, et al., 2023).

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Ammonia is a commodity frequently traded primarily for use as a fertilizer, and the infrastructure for its storage and transportation is available in many places. Green ammonia is produced by combining nitrogen extracted from the air and hydrogen separated from the water molecule using renewable electricity. Safety is paramount, due to the toxicity and pungent smell of ammonia. Burning ammonia carries the risk of emitting N_2O (Nitrous Oxide), "laughing gas" which is a very potent greenhouse gas. To avoid this, engine combustion mixture regulation parameters must be set to very low levels of laughing gas emissions (Kamran & Turzyński, 2024).

Green fuels will be more expensive than conventional ones, at least initially. Therefore, the industry needs global regulation, a CO_2 tax or some other kind of offset method to cover the additional costs. The IMO will not publish concrete measures to reach that goal until 2027 – too late in an industry where the average lifespan of a ship is 25 to 30 years.

For ships, ammonia has a slightly higher emissions reduction potential and at a lower cost than methanol.

Dual-fuel methanol engines have already reached a Technology Readiness Level (TRL 9), meaning that the system has been tested in an operational environment. The FCM Methanol is a low-flashpoint fuel supply system (LFSS) capable of supplying methanol within the flow, pressure, temperature and filtration parameters specified by the engine manufacturer (Ammar & Seddiek, 2023, Bayraktar et al., 2023 and Karatuğ, et al., 2023).

Since green fuels are not yet available in sufficient quantities, ESD (Electrostatic Discharge) is considered promising as it offers emission reduction, high-efficiency propellers, wind-assisted propulsion, air lubrication systems, exhaust gas recirculation and speed optimization. CO_2 emissions can be reduced by using ESD by 30% for container ships, 45% for bulk carriers, 50% for tankers and 60% for LNG carriers.

Around 1,900 ships with two-stroke engines and up to 900 ships with four-stroke engines are currently eligible for conversion and could save more than 97 Mt (million tons) of carbon dioxide (CO_2) emissions annually if they run on green fuels. To meet the demand for ship engine modernization, shipyards, ships and specialist personnel who will carry out the conversions are already preparing in close collaboration. Conversions to be considered viable should cost less than 25% of the value of a new vessel to be considered commercially viable for the sector. Prices for single-fuel engines will range from 12 to 60 million dollars per vessel, depending on whether it is a retrofit or a new engine change, according to the average established by European and Asian shipyards. This has generated pressure on shipping companies who seek financial support to carry out the modernization. The segments of modernization of 2-stroke engines with Hydrogen, Methanol and Ammonia (blue or green), LPG (Liquefied Petroleum Gas) with dual arrangements will satisfy the market of bulk carriers, container ships, Ro-Ro, tankers and LNG. However, four-stroke dual-fuel engines with diesel/methanol, diesel/LNG (Liquefied Natural Gas), diesel/LPG (Liquefied Petroleum Gas) etc. It is more oriented towards cruise ships and cargo ships, such as ferries. (Karatuğ, et al., 2023 and Lu, et al., 2023).

Other options such as electrification or switching to mono-fuel engines such as Hydrogen, Methanol, Ammonia (blue or green) and synthetic natural gas (SNG) are options to consider for zero-emission vessels from the economic perspective that modernizing or changing the engine is cheaper than building a new ship.

Emissions certification rates for maritime transport

The Environmental Ship Index (ESI) identifies ocean-going vessels that perform better in reducing emissions to air than required by current International Maritime Organization (IMO) emissions standards. It assesses the amount of nitrogen oxide (NOX) and Sulphur oxide (SOX) a ship releases and includes a reporting scheme on the ship's greenhouse gas emissions. The ESI is a good indicator of the environmental performance of ocean-going vessels and will help identify cleaner ships overall and achieve their sustainability goals.

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Under the Maritime Regulation (MRV), shipping companies must buy and surrender (use) allowances from the (European Union Emissions Trading Scheme) EU ETS for every tonne of CO_2 (or CO_2 equivalent) emissions reported under the EU ETS system. It is up to shipping company authorities to surrender allowances by 2025: for 40% of their emissions reported in 2024; 2026: for 70% of their emissions reported in 2025; 2027 onwards: for 100% of their emissions reported. These rules were adopted on 16 May 2023 and entered into force on 5 June 2023 (Christodoulou & Cullinane, 2024, Melideo & Desideri, 2024 and Xia et al., 2024).

From 1 January 2018, large ships over 5 000 gross tonnes loading or unloading cargo or passengers in ports in the European Economic Area (EEA) must monitor and report related greenhouse gas (GHG) emissions (currently only CO_2 emissions, but also nitrous oxide and methane emissions from 1 January 2024). Monitoring, reporting and verification (MRV) of the information must be carried out in accordance with the 'Maritime MRV Regulation'.

Carbon dioxide (CO_2) emissions are projected to increase by 130% by 2050, this threshold is likely to be reached by 2040, or sooner, if emissions are not reduced leading to increasing risks of extreme heatwaves, droughts and floods. Implementing the policies outlined in the IMO targets will reduce this temperature increase by between 2.4 and 2.6°C by 2100.

The Energy Efficiency Design Index for Existing Ships (EEXI) and Carbon Intensity Index scheme implemented from 2023 measures their structural efficiency in terms of energy efficiency level per capacity mile and would reduce fleet CO_2 by 2030 by 0.7 – 1.3%. Meeting this EEXI, which follows the IMO's zero-emissions targets for 2050, will not be a problem for relatively new green ships. However, for older ships, this may not be cost-effective and could lead to increased scrapping (Pivetta, et al., 2024 and Sahraie, et al., 2024)

Reducing the carbon footprint: a commitment between ports and shipping companies

From 2030, the IMO has established within its objectives that island-type, wet and dry ports must provide ships that set sail in their port facilities with a connection to a land-based electricity supply for stays of more than two hours, which will promote the decarbonization of maritime transport with responsible environmental behavior. In addition to providing climate alignment, loan portfolios to the shipping industry, charterers and operators, chartering activities, global ship climate alignment, chartering, clean energy in accordance with the agreements made by the International Chamber of Shipping, International Association of Ports, Ministerial of Clean Energy, public-private platform for the energy sector, maritime value chains to promote the consumption of green fuels in port (bunkering) in support of the global energy transition 2050 (Zhang, et al., 2024).

Fuel costs represent a significant portion of ship operating costs and will determine freight rates. Transitioning to cleaner fuels may be more expensive and increase these costs. In December 2022, ultra-low sulfur fuel oil was $635 per metric ton, heavy fuel oil was around $515. Green hydrogen was $2,500 per metric ton, ammonia cost $1,239 per metric ton (fuel oil) and methanol was around $1,400 per ton. The final costs of chartering low- or zero-carbon vessels will be more expensive during transition periods, however the IMO will generate decarbonization certifications that compensate for the prioritization of the use of vessels that have this certification, making compliant vessels have more work to do and although non-certified vessels will be able to offer lower charter prices, their income to ports will be limited and they will be fined for non-compliance, placing them in the position of responsibility and compliance sooner or later (Pivetta, et al., 2024 and Zhang, et al., 2024).

The maritime fleet currently uses different fuels with a share of alternative fuels of 1.2% with the following distribution: diesel, 98.8%, batteries and hybrid system (diesel-electric cycle) 29.4%, LNG 68.4%, Methanol 0.8% and LPG 1.4%.

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However, it is intended that the pending portfolio for 2025 will be covered with a greater share of alternative fuels with 21.1% with the following arrangement: diesel, 78.9%, batteries and hybrid system (diesel-electric cycle) 39.9%, LNG 52.1%, Methanol 3.4%, LPG 5.5% and hydrogen 0.3%.

The design of new ships and engines must be done now to allow the deployment of zero carbon emissions. Modernization, engine change or ship change should be evaluated, remembering that the average useful life of ships is 25 to 30 years and considering that by 2050 they will be in working condition (IRENA, 2021). Shipowners must decide or pose challenges to shipowners, which complicates their investment decisions. Capacity and fleet renewal regulations will not come into force until 2027. The demand for a new fleet of ships during the last three decades grew by around 4.8%. However, for the period 2023-2027 a decline is projected with a growth rate of 2.5 during the period (McKenney, T. A., 2024).

Fuels in the shipping industry; with supply in port or on board

Fuels based on their origin or production process can be considered grey, black and brown, those generated from fossil fuels. “Blue”, direct carbon capture and storage from air is considered “Green”; electrolysis renewable energy. Green fuels include those produced by biomass, alternative fuels, biofuels and advanced fuels.

E-fuels (synthetic fuels), Methanol and Ammonia; electrolysis Water and electricity Hydrogen (electrolytic); natural gas extraction gaseous energy Methane (natural gas); Biogas production agricultural waste Biogas; biogas upgrading Biogas Methane (bio), CO_2; Steam methane reforming Methane and water Synthesis gas; Synagas Syngas Pressure Swing Absorption Hydrogen (blue or bio) and CO_2; Nitrogen separation (PSA or cryo) Air Nitrogen and oxygen (and other traces); Haber Bosch process Nitrogen, hydrogen and thermal energy Ammonia; Carbon capture (industrial) Fuel gas CO_2; Carbon capture (air) Air and electricity CO_2; Sabatier process CO_2 and hydrogen Methane (synthetic) and oxygen; Methane liquefaction Methane (natural gas, bio) and electricity LCH_4 (liquid methane).

Hydrogen liquefaction Hydrogen and electricity LH_2 (liquid hydrogen); Ammonia liquefaction Ammonia and electricity LNH_3 (ammonia); Liquid biofuels Residues, oils and crops Hydrotreated vegetable oil, fatty acids; Methanol synthesis CO_2 and hydrogen Methanol (synthetic); Fischer-Tropsch Hydrogen and CO_2 Blue crude, e-diesel; Hydrogen ICE (internal hydrogen; combustion engine) Hydrogen Water (+nitrogen oxides); Hydrogen fuel cell Hydrogen Water; Methane ICE Methane (+diesel) CO_2+ NOx + CH_4 (methane); Methanol ICE Methanol (+diesel) CO_2+ NOx; Ammonia ICE Ammonia + diesel CO_2+ NOx + NH_4 (ammonium) + N_2O; (Nitrous oxide); Diesel ICE Diesel CO_2+ Nox

Without new emission control measures, emissions could reach up to 1,500 Mt in 2050, an increase of 50%, the IMO approved a program to reduce greenhouse gases (GHG) by at least 50% by 2050, committing to establish at least six green maritime corridors between two or more ports worldwide by 2025, and more green maritime corridors will be included by 2030 to decarbonize the shipping industry by 2050.

The fuels of ships maneuvering for 2040 are expected to be 420.6 Mt, 79.1% more than consumed during 2020. Container ships use “heavy fuel oil” (HFO) during cruising and “marine gas oil” (MDO) during maneuvers and berthing. HFO = 40200 kJ kg^{-1}, MDO = 42700 kJ kg^{-1}, short term (now to 2030), medium term (2031-2040) and future long term (2041-2050). The focus of the industry should be on promoting clean hydrogen-based ZEFs and incentivizing their widespread adoption, to align with the Global Maritime Forum (GMF) transition strategy. Currently, ammonia, methanol and hydrogen are derived from natural gas feedstocks. Clean hydrogen-based production for maritime applications is currently limited to demonstration projects. In addition to clean hydrogen, methanol production will require CO_2, which can be obtained from industrial point sources or through DAC (direct air capture) technologies. Clean hydrogen production facilities and carbon capture technologies must be of sufficient industrial scale to advance ZEF production. The largest Danish clean methanol plant in Europe in northern Sweden is due to start operations in 2025. It is expected to supply 50,000 tonnes of clean methanol annually.

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Around 30 ships were identified as running on methanol during 2023 and the world's first clean methanol-powered container ship will start operating by the end of the year. Liquid hydrogen and ammonia engines are still in development and are expected to be deployed on ships after 2025 (Lu, et al., 2023 and Zhang, et al., 2024).

Fueling and onboard storage technologies for methanol, ammonia and liquid hydrogen must advance beyond the prototype stage. ZEF (Zero Emission Ferry) accounts for less than 1% globally. Investments of USD 0.8 to 2.1 trillion will be needed by 2050. Production of 160 MTPA (million tonnes per annum) of green liquid hydrogen and around 130 MTPA of CO_2 feedstock will require investment of USD 0.6 to 1.9 trillion. If industrial CO_2 is not located at point sources adjacent to ZEF production facilities, an infrastructure will have to be established with investments of USD 10 to 23 billion. ZEF (Zero Emission Ferry) stations must be supported by a fueling infrastructure with an investment of USD 132 to 176 billion and accelerate the implementation of FAME (Fatty Acid Methyl Ester Biofuels). Fleet operators have committed that 5% of deep-sea shipping and 10% of ship-based freight volume will be powered by ZEF (ISO 14083 standard, EEXI), with an estimated investment of USD 450 billion by 2030. The International Chamber of Shipping (ICS) submitted a Fund and Reward proposal to the IMO for shipowners to make mandatory contributions per tonne of CO_2 emitted to create a new IMO fund to be operational in 2024. Scalable Zero Emission Fuels (SZEF) account for 5% of fuels for international shipping by 2030.

At least 20 G20 countries and 10 developing countries have public services, financing mechanisms and the direct use of green hydrogen (H_2) through fuel cells (FC) and internal systems. Internal combustion engines (ICE) are an option, for short voyages. Green H_2 costs range from 66-154 USD/MWh and from 2030, the price is expected to be regulated at 32-100 USD/MWh. For renewable Methanol, biomethanol, renewable e-methanol: e-methanol 107-145 USD/MWh, Renewable Ammonia: e-Ammonia 67-114 USD/MWh (Tu, et al., 2024).

In 2050, the production of around 46 million tonnes of green H_2 is forecast, of which 73% will be needed for e-ammonia production, 17% for e-methanol and 10% will be used directly as liquid hydrogen via FC or flared via ICE. Renewable ammonia will be the basis of decarbonization with 43% blended, around 183 Mt transient blue ammonia; IRENA Ammonia is achieved through four key indirect electrification advanced biofuels; The most advanced commercial and bunkering ports are; Singapore (~22%), Fujairah (UAE) (~8%) and Rotterdam (Netherlands) (~6%). Most critical are Panama Canal, Strait of Malacca and Suez Canal (Dere, et al., 2024 and Hui, et al., 2024).

The implementation of energy efficiency mechanisms in ships that reduce the carbon footprint are; voyage performance management through Information and Communication Technologies (ICT), just-in-time arrival (JIT), speed optimization, route planning, autopilot software, smart devices for energy consumption savings, trim, draft and ballast optimization, reduction of energy demand on board of all machinery and equipment, continuous analysis of operating curves through software, total scheduled maintenance TPM (hull roughness, propeller, corrosion, contamination, mechanisms, engine, auxiliary systems), load, structural weight, bulb design, hydrodynamics and aerodynamics, design optimization (waterline, bow and settina shoulder, stern body, wave mitigation devices, propeller), propulsion improvement, balance tank flows, boundary layer systems as a means of levitation and lubrication reducing hull friction, hybrid auxiliary power generation systems fuel cells (FC) (Chin Law, et al., 2024 and McKenney, T. A., 2024).

There are 200 LNG bunkering ports in Europe and Asia. LNG must be stored under cryogenic conditions, is considered highly dangerous and requires safety and handling precautions. LNG has 26% more CO_2 than fuel oil. These loading ports will be displaced in less than 20 years by methane, ammonia and hydrogen bunkering ports. (Pivetta, et al., 2024).

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Renewable energy fuels have current market costs; HFO $41/MWh, LNG $19/MWh, advanced biofuels $72/MWh, fatty acid methyl ester (FAME) biodiesel $238/MWh, hydrotreated vegetable oils (HVO) such as methanol from lignocellulosic biomass $25/MWh to $176/MWh, green H_2 via fuel cells (FC), internal combustion engines (ICE) and e-fuels $66 to $154/MWh, and are expected to reach costs from 2030 of $32 to $100/MWh (Tu, et al., 2024).

Results Discussion

Renewable methanol, i.e. bio methanol and renewable e-methanol, requires few modifications to the ICE engine and can provide significant carbon emission reductions compared to conventional fuels. The renewable e-fuels, methanol and ammonia, are the most promising fuels.

However, ammonia is more attractive, due to its zero carbon emissions. On the other hand, green H_2 produced from renewable energy through the electrolysis process, is the only viable alternative shipping fuel, as it produces net zero life cycle emissions. Each alternative fuel has advantages and disadvantages in terms of physical characteristics such as calorific value, density, temperature, pressure that contrast with respect to their feasibility characteristics for use as fuel.

Liquid green H_2 stands out, then MGO similar to Methanol and Ammonia, followed by LNG similar to liquid H_2. Internal combustion engines (ICE) for cargo ships with high torque and power requirements require high calorific value from the fuels supplied; to conserve it they require fuels with similar or higher calorific value.

If it is replaced by fuels with lower calorific value, the power can be compromised, causing the ship's structures to be lightened or the load to be reduced. However, for cargo ships this can be a weapon against them, because reducing the weight of their structure with light, high-strength materials can make them more expensive and the amount of cargo in global trends does not turn in the direction of reduction, on the contrary, to increase, making them more profitable in their services.

Therefore, although Ammonia and Hydrogen are emerging as the two winning fuels in their green state, Ammonia is feasible for ferries and ships with less weight. On the other hand, the fuel that has all the possibilities and the winner in terms of power is the green liquid H_2 (1 bar at -283°C and 120 MJ/Kg) and compressed (700 bar at 20°C and 120 MJ/Kg) due to its technical characteristics and adaptability to internal combustion engines of the Diesel cycle.

The application of hydrogen as a fuel in Diesel cycle engines is feasible if the quantity of liquid or compressed H_2 supplied to the engine is regulated, which, depending on the injection temperature, determines the supply pressure before the explosion. For this, the injection system must be regulated through intelligent closed-loop systems with feedback signals, with solenoid valves and high-frequency injector systems that regulate the supply based on the pressure. An overpressure in the engine heads can generate a destructive explosion of the same, because within the internal combustion chamber certain pressures can be supported that can vary depending on the design of the engine that the manufacturer applied in its manufacture varying by model, year, materials among others, so it is necessary to know the maximum pressure that the engine supports in the combustion zone in order to supply hydrogen intelligently without exceeding those pressures so that the operation can be carried out without the heads exploding due to overpressure until the fracture (Agarwala, 2024, McKenney, T. A., 2024 and Wang et al., 2024).

The process of adapting liquid or compressed H_2 to diesel engines and not to Otto cycle engines is precisely that diesel engines have a more robust construction that allows them to withstand pressure in better conditions, but not for what Hydrogen produces at burning pressure. Hydrogen auto ignites between 536 to 585 °C. However, the temperatures in the combustion chambers in an ICE engine are 1960 to 2200 °C, for this reason Diesel engines are a functional option if they are regulated in the injection systems considering that this is directly proportional to the temperature of the ignition zone (Agarwala, 2024).

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Diesel engines, although they are a limited option and can work, do NOT represent a viable option for use with hydrogen, because as a technology they require specialized systems for regulating pressures in the ignition zone, which represents danger and a large amount of investment. So why is there an interest in wanting to apply fuels such as ammonia or liquid or compressed hydrogen in both cases green? This is because 95% of the international fleet of ships use diesel engines as a means of propulsion and to modernize them to zero emissions, the adaptation of the existing systems in the fleet is proposed to improve these emission conditions. But incorporating fuels such as LNG, LPG, Methane and green ammonia due to their pressures in the combustion chamber do not represent a problem and provide advantages in reducing emissions, the only problem is to regulate the fuel input intelligently to keep the engine stable according to its operating curves. For compressed H_2, the problem is twofold, apart from regulating the fuel inlet to provide stability to the engine, now the combustion chamber pressures must be regulated so as not to reach its breaking point due to overpressure. Engine tests require testing times based on their performance and safety, which must be followed before implementing modifications that have not been fully evaluated. It is true that we are in a race for zero emissions and that it is urgent to modify the shipping fleet, but a hasty administrative decision can cause engineering decisions to achieve these objectives to claim lives and great losses of ships that explode on the high seas, even worse in port areas where they intend to generate fuel loads from green H_2 plants inside the port, causing highly dangerous chain explosions (Wang et al., 2024).

The migration of engines with zero-emission fuels is the reason for identifying existing technologies in this article and based on experiences and work in the research group in the area of different types of engines, it is stated that the Brayton cycle or gas turbine for high-pressure fuels is already well studied simply because it is an axial machine with higher compression ratios than those of the Otto and Diesel cycles (ICE), therefore the approach mainly for container ships, bulk carriers and Ro-Ro is to replace the engines of their ships that can still fulfill part of the service life with gas turbines with speed reduction systems that use hydrogen as a zero-emission fuel.

This proposal is within the proven technologies and even offers something better "the use of the Brayton cycle that uses nuclear as an energy source", which is also within the alternative energy sources mainly tested in the military industry. All this means that fleet modernizations can be done with LNG, Methane and Ammonia, with Diesel cycle engines so that from 2024 when this article is being written to 2030 the decarbonization objectives in ships can be met. But the large shipbuilders must redirect their designs in these 26 years towards replacing the Diesel engine with gas turbines with gearbox systems that use green H_2 as an energy source or nuclear to achieve a sustainable and sustainable shipping industry that complies with decarbonization by 2050 (Agarwala, 2024, Karvounis, et al., 2024, Melideo & Desideri, 2024 and Xia et al., 2024).

Ammonia and green hydrogen

To obtain green ammonia, products such as water (H_2O) and air (21% oxygen, 78% nitrogen, 0.89% noble gases, 0.1% water, water vapor; 1% at sea level and 0.4% in the entire atmosphere and small amounts of other gases) are used. Both water and air are a renewable source of power. When water is exposed to an electrolysis process, the bonds in O2 and H are separated, while on the other hand, air is exposed to nitrogen production, separating O_2 and N_2 mainly. The H_2 and N_2 obtained through the Haber Bosch process, obtain ammonia (NH_3), considered green due to its renewable sources (Abeynaike & Barbenel, 2024, Agarwala, 2024 and Inal, et al., 2024).

Japan and South Korea have devoted significant R&D to developing engines that use ammonia as a power source by the method of electro-reduction of nitrogen to ammonia and are considered green with scalability and infrastructure. The global ammonia industry produces approximately 180 Mt of ammonia per year, 80% of which is used by the agricultural sector for fertilizers. Current ammonia production takes place in eastern China, Europe, southwest Asia and North America. China produces 32% of ammonia from coal, while natural gas is used in the rest of the world.

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South Korea and Japan are developing technologies to use ammonia as a fuel and forecast a large use of H_2. By 2030, renewable ammonia is projected to account for about 183 Mt of ammonia per year compared to 17 Mt of ammonia per year currently produced. Some countries have the infrastructure to produce renewable H_2 and ammonia, such as Morocco, Australia, Chile, Denmark, the Netherlands, New Zealand, which use solar, wind or a combination of renewable energy sources (Abeynaike & Barbenel, 2024, Hui, et al., 2024 and Nerheim, et al., 2024).

The world's first ammonia-powered container ship November 30, 2023, the vessel, named Yara Eyde, will be the first to sail the emission-free shipping route between Norway and Germany and will operate between Oslo, Porsgrunn, Hamburg and Bremerhaven from 2026 in anticipation of critical 2030 climate targets. internal combustion engine (ICE) that uses ammonia (NH_3) and hydrogen H_2 as fuel in gas turbines, towards a cleaner and more sustainable energy future (Nerheim, et al., 2024). Hydrogen-fueled gas turbines will need to be regulated in their operating parameters and be able to provide combustion stability, flame dynamics and controlled combustion process. Onboard hydrogen production has been shown to be a cost-effective alternative and eliminates the need for a large hydrogen storage tank. However, it requires the installation of intensive waste heat recovery networks and additional unit operations, such as high-temperature steam generators, steam turbines, reformers and blue and green hydrogen systems, and onboard blue hydrogen production could be a cost-effective alternative (Chin Law, et al., 2024, Kamran & Turzyński, 2024, Karvounis, et al., 2024 and Lu, et al., 2023).

Conclusions

The objectives set out in common agreement between the international shipping sector and the IMO (International Maritime Organization) in the decarbonization of ships to zero emissions by 2050 will be carried out in stages. To reduce the carbon footprint of both ships and ports, the primary objective has been set to migrate from conventional fuels to environmentally friendly alternative fuels.

Some of these fuels are considered transitional fuels with reduced CO_2 emissions, such as LPG, GNS, LNG and Methanol in a dual cycle with diesel. However, to achieve zero emissions towards the 2050 objectives, Hydrogen and Ammonia (green) are in descending order of importance. These fuels, as they do not come from regulated sources of alternative origin, can be classified as blue and although their degree of production is minimal, they cannot be considered zero emissions, but in large mass production they represent great potential for the shipping industry and even on board.

In the analysis in accordance with the objectives of this research, it is identified that to achieve the decarbonization of ships by 2050 with zero emissions, a future based on green hydrogen is required as a promising technology applied to gas turbines driving ships, towards a cleaner and more sustainable energy future. On the other hand, it has been shown that the production of (blue) hydrogen on board is a cost-effective alternative, eliminating the need for a large hydrogen storage tank on the ship and reducing explosiveness in supply ports, also being a sustainable alternative. And, finally, is the gas turbine as a driving source for ships with nuclear energy.

If the useful life of ships is 25 years by 2050, the eradication of dual engines by manufacturers and shipping companies must be present. According to this, investing in a modernization of a dual ICE will be a very short-term decision, which is why it is considered a transition investment. Therefore, to be competitive and meet the IMO's zero-emissions targets, ship production from 2030 onwards must use hydrogen or green ammonia gas turbines as a power source.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

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Authors' Contribution

The contribution of each researcher in each of the points developed in this research, was defined based on:

Flores-Cruz, Luis Antonio: Contributed to the project idea, research method and technique, about to develop all the project.

Cruz-Gómez, Marco Antonio: He supported the design of the field instrument. He also contributed to the writing of the article.

Correa-Nieto, Marco Antonio: Contributed to the research design, the type of research, the approach, the method and the writing of the article.

Mejía-Pérez, José Alfredo: Resarched multiple papers and information about the topic.

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Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
EEA	European Economic Area
ESI	Environmental Ship Index
EU ETS	European Union Emissions Trading Scheme
FC	Fuel Cells
FAME	Fatty Acid Methyl Ester
GHG	Greenhouse Gas
GMF	Global Maritime Forum
H_2	Hydrogen
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oils
ICE	Internal Combustion Engine
ICS	International Chamber of Shipping
IMO	International Maritime Organization
ISO	International Organization for Standardization
LH_2	Liquid hydrogen
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
Mt	Million tons
MTPA	Million Tonnes Per Annum
MWh	Megawatt-hour
N_2O	Nitrous oxide
NH_3	Ammonia
NOx	Nitrogen Oxides
SNG	Synthetic Natural Gas
SZEF	Scalable Zero Emission Fuels
TPM	Total Scheduled Maintenance
USD	United States Dollar
ZEF	Zero Emission Ferry

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