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THE TRANSITION TO ALTERNATIVE FUELS IN THE MARITIME SECTOR IN THE CONTEXT OF DECARBONIZATION. OPPORTUNITIES AND CONSTRAINTS

Alternative fuels can facilitate the green transition of the maritime sector over time, but there are constraints regarding the production capacity for the existing demand and the need to re-engineer the ships. This paper aims to analyze the types of alternative fuels currently available compatible with the maritime sector and the advantages and disadvantages they come with as well as the forecast of their use over time. In the context of current alternative technologies available the alternative fuels analyzed in this paper are bio-fuels, electrofuels like e-hydrogen, e-ammonia and e-methanol, and electricity. The most reliable alternative solutions to conventional fuels in the maritime sector are concluded to be ammonia and hydrogen, while biofuels and renewable energy technologies are additionally used. The main challenges regarding the use of these fuels relate to infrastructure, safety, personnel training, costs and storage.

Keywords: Decarbonisation; maritime sector; carbon neutral fuels; marine fuels; alternative fuels; electro fuels; biofuels

1. Introduction

In the context of climate change and pressures to limit global temperature to 1.5°C, and by 2030 to reduce greenhouse gases (GHG) emissions by 55% comparing 1990's levels and also by 2050 for Europe to become carbon neutral, there are many efforts to pursue in order to meet all these goals [1]. The maritime sector is not excluded from these regulations.

At the moment, the natural actions and anthropic activities are the main factors for the generation of greenhouse gases emissions into the atmosphere. The accumulation of this gasses forms the carbon footprint that is mainly responsible for the climate change (Fig. 1).

However, sea transport is the most efficient mode of transport and accounts for 80% of global transport, prompt action must be taken. One of the solutions for the ecological transition is the

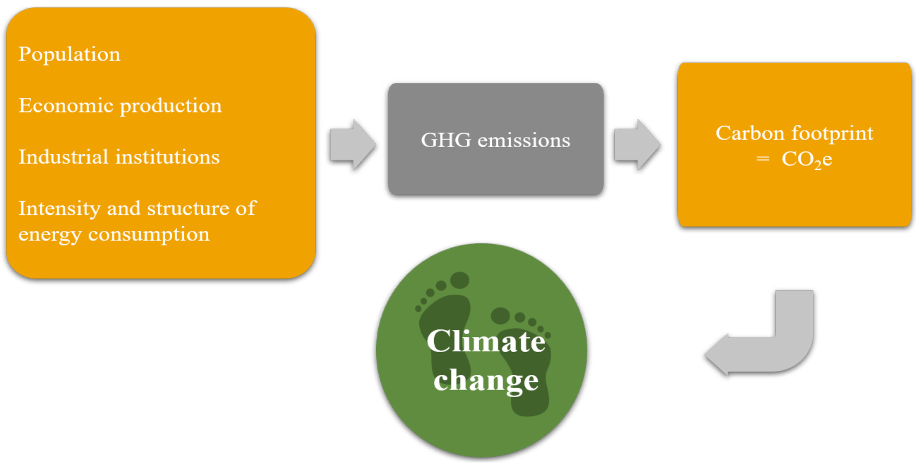

Fig. 1. Main factors for GHG emissions

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transition to alternative fuels (more precisely to carbon neutral fuels) [2]. In order to carry out this work, the main regulations and official documents were analyzed together with the global objectives regarding the prevention of global warming:

– Paris Agreement – 1.5°C scenarios;
– The 2030 Agenda for Sustainable Development;
– The renewed sustainable finance strategy;
– Fit for 55 – European Green Deal;
– Emission Trading System EU ETS;
– European Climate Law 2021;
– GHG Protocol;
– 2023 IMO Strategy on Reduction of GHG Emissions from Ships;
– The European Scientific Advisory Board on Climate Change;
– ISO 14064-1:2018 (Part 1);
– IPCC (Intergovernmental Panel on Climate Change) A6.

Moreover, in order to analyze the most relevant recently published articles on this topic, a synthesis of the literature in the field was made through Clarivate Analytics Web of Science (WoS) platform. The analysis was carried out by searching for keywords using the "topic" section. The keywords used in the "topic" section were: "marine fuels", "alternative fuels" and "carbon neutral", the selected period was the last 5 years, more precisely 2019-2023. 15 relevant articles were identified and analyzed.

Being a highly debated topic, the technologies and solutions for reducing greenhouse gas emissions from the consumption of marine fuel are numerous and constantly updated, therefore it is important that studies in this field are constantly carried out in order to discover the most reliable method or technology. The paper discusses the main types of alternative fuels to conventional ones in the maritime field.

2. Conventional marine fuels

To discuss alternatives to conventional fuels, it is necessary to understand conventional fuels and the impact their use has on the environment in order to identify the need to use cleaner solutions. There are two categories of marine fuels: crude oil and fuel oil. The most typical marine fuels are represented by: fossil fuel oils and gas oils as heavy fuel oil (HFO), marine gas oil (MGO) and marine diesel oil (MDO) as being a mixture between HFO and MGO. In 2021, more than 93% of vessels at sea ran on these fuels [2]. Studies show that current marine fuels are great contributors to global warming due to the emissions generated during their use rating 13% of Sulphur oxides and 2.6% of CO_2 emissions caused by humans. For example, heavy fuel oil is around 86% carbon, which means it emits around 3.15 tonnes of CO_2 per tonne of fuel consumed [3].

The main emissions and particles that are currently analyzed as being generated during the combustion of marine fuels are CO_2 emissions, nitrogen oxides and sulphur oxides and particulate matter [4]. Current alternative fuels are created to decrease the amounts of these elements. However, it is quite a controversial topic, given the long and complex path from the production of a fuel to its final use [5].

An important aspect to consider when evaluating a fuel is the consideration of the emissions generated from the entire life cycle of that fuel and not only the emissions generated at the time of its use on board. Because it can be seen that some alternative fuels, although they emit less GHG than conventional ones, they can emit a larger amount of GHG in upstream activities, such as during production, transport, etc. [6].

3. Alternative fuels

The choice of an alternative fuel over a conventional one must be the result of a laborious analysis based on several evaluation criteria. However, it is quite difficult to convince shipowners to use alternative fuels when they go on the premise of "the fuel that fulfils regulations at lowest price" [7]. And rightfully so. The new solutions also come with many challenges, from the adaptation of ships to new technologies and fuels, to investments in building new ships, to the adaptation of transport and fuel supply conditions, which also involves the adaptation of port facilities to the restrictions imposed by the use of such fuels, until the training of personnel specialized in the handling and interaction with these alternative fuels. That is why the alternative fuels come with many opportunities but also with constraints [8].

Current alternative technologies [2] available:

– Solid oxide fuel cell – devices which convert chemical energy into electrical energy and heat that does not involve direct combustion as happens in internal combustion engines. The advantages of these devices are increased conversion efficiency compared to conventional systems, relatively easy maintenance, flexible design [9].
– Liquefied hydrogen – hydrogen is carbon free (if it is produced from renewable energy) and is one of the most energy efficient fuels, it is much more energy efficient than diesel [10].
– Wind-assisted propulsion systems – technology that uses the power of the wind to propel the ship [11].
– Air lubrication systems – technology that involves reducing the ship's frictional resistance by injecting air along the bottom of the ship [12].
– Onboard carbon capture and storage – technology that involves the capture of CO_2 emissions from the ship's exhaust gases, which are then stored on board the ship until it reaches the port where they are unloaded [13].
– Nuclear propulsion – propulsion provided by the heat from onboard nuclear reactor [14].

In the context of these alternative technologies which are widely debated within the report [2], the alternative fuels (TABLE 1) considered in this study are:

– Biofuels;
– Electro-fuels;
– Electricity.

TABLE 1

Alternative fuels considered in the present paper

Alternative fuel		Description
Biofuels		liquid fuels and blending components produced from biomass materials [15-18]
Electro-fuels	e-hydrogen [22,23]	fuels in gas or liquid form that are produced from renewable energy [20,21]
	e-ammonia [25]	
	e-methanol [27]	
Electricity		Electricity produced from renewable sources, stored in batteries [29]

3.1. Biofuels

They are liquid fuels and blending components produced from biomass materials (agriculture, forestry, etc.).

The main pros and cons [15,16] identified for biofuels as an alternative fuel choice are:

- Advantages:
  - They have the ability to be used in existing engine systems and this doesn't imply big modifications, thus low capital expenditures would be needed;
  - They represent a possible option for deep-sea shipping but more for short-sea shipping as fishing vessels, offshore energy production supporting vessels, tugs, etc.
  - They are sulphur free and therefore they do not emit Sulphur Oxides (SOx) [17];
  - They emit lower quantities of NOx, but a recalibration of the engine towards low NOx modes would be required.
- Disadvantages:
  - Today, the cost of biofuels are very high comparing to the price of conventional fuels. They can be two or three times higher. However, the price may be partially compensated in the context of Fit-for-55 package adoption;
  - They offer uncertainty regarding covering the demand of this type of fuel in the near or far future because this implies the availability of biomass. Currently the biomass used to produce the biofuels is biomass from crops which has limitations [18];
  - The choice of other biomass sources, like algae or waste and residues will be necessary to ensure the supply of more sustainable or fully sustainable biofuels and this involves advanced processes.

Ships that run exclusively on biofuels are still relatively rare compared to those that use dual-fuel engines (which can run on both conventional and biofuels). Danish shipping company Maersk has launched several initiatives to use biofuels on its ships. In a pilot project, Maersk used a biofuel based on vegetable oils to power its commercial vessels, thereby reducing CO_2 emissions [19].

3.2. Electro-fuels

The electro-fuels are the fuels in gas or liquid form that are produced from renewable energy (solar, wind power, etc.) The electro-fuels discussed in this paper are Hydrogen, Ammonia and Methanol [20,21]:

– **e-hydrogen (H_2)**

The adoption of hydrogen in shipping is on the rise due to its ability to achieve near-zero emissions when derived from renewable or nuclear energy sources [22]. It can be utilized in fuel cells to produce electricity for electric motors, or it can be combusted in internal combustion engines, either in its pure form or mixed with diesel. Despite its environmental advantages, hydrogen does come with certain challenges, such as its low volumetric energy density. This characteristic requires energy-intensive processes like liquefaction and cryogenic storage, leading to considerable energy losses and elevated costs. Furthermore, there are concerns related to non-CO_2 greenhouse gases, such as NOx, as well as the necessity for cautious handling of hydrogen due to its explosive nature and its tendency to make materials brittle [23]. Neo Orbis is a hydrogen-powered ship of Port of Amsterdam that will be launched in 2025. It uses for propulsion hydrogen in a solid form, as sodium borohydride ($NaBH_4$) and it is the first ship that will sail on this substance. The ship is battery-powered, silent, and fully emission-free. The hydrogen gas will be produced by a brand-new extractor [24].

– **e-ammonia (NH_3)**

Ammonia presents a viable alternative to hydrogen in engines as it does not generate direct CO_2 emissions when burned. It offers several benefits compared to pure hydrogen, including the ability to be stored as a liquid at –33°C or at ambient temperature under high pressure (10 bar), as well as a higher volumetric energy density than liquid hydrogen. Ammonia is non-explosive and can utilize storage tanks similar to those for liquefied petroleum gas (LPG). However, it is highly toxic to humans and harmful to the environment. While ammonia can serve as a hydrogen carrier by undergoing an upstream process to release hydrogen on ships, this method reduces overall energy efficiency, making its direct use more practical. Additionally, burning ammonia results in only water and nitrogen as by-products, significantly decreasing total CO_2 emissions [25]. Through a 15-year agreement with Yara Clean Ammonia, North Sea Container Line, and Yara International, CMB.TECH announced the order of the world's first ammonia-powered container vessel. Specifically, Qingdao Yangfan Shipbuilding will construct the 1.400 TEU ice-class container ship, which will be called Yara Eyde. The Yara Eyde is anticipated to be delivered by the middle of 2026 and will be the first container ship fueled by ammonia in history. It will serve routes between Norway and Germany and run on clean ammonia [26].

– **e-methanol (CH_3OH)**

Methanol is a simple alcohol in liquid form at the ambient temperature. It serves dual purposes, functioning as both a combustion fuel and a source for fuel cells that generate electricity. Key advantages of methanol include its biodegradability, lower environmental impact, and reduced toxicity to marine ecosystems in cases of spillage, particularly when compared to traditional fuels [27].

The methanol market is experiencing growth, with a promising focus on „e-methanol," sourced from renewable materials. However, concerns exist regarding the conventional production methods for methanol, which typically rely on natural gas and coal, leading to increased greenhouse gas emissions. As a disadvantage of its use, it is highly flammable and currently many times more expensive than conventional fuel. Currently, it is available through existing infrastructure in more than 100 ports worldwide. The Swedish ferry business Stena Line and the UK classification society Lloyd's Register (LR) will collaborate on a project to convert two rapid roll-on/roll-off (RoRo) ships to run on methanol. The ships will be put into service in late 2025 after being constructed at Weihai, China, by Stena RoRo. According to Stena Line, the ships' design also includes features that guarantee they will stay up to date with emerging technologies. These include plans for battery operation, electrification preparations, and the ability to connect to shore power facilities should they become available [28].

3.3. Electricity

The deep-sea shipping industry faces significant challenges in transitioning from traditional fuel to electric power. While electric propulsion could reduce reliance on fossil fuels, it requires substantial battery capacity, which takes up valuable cargo space and adds considerable weight to the vessel. Additionally, charging electric ships can be time-consuming and demands large amounts of power, posing logistical hurdles for long-distance voyages. However, hybrid systems, combining internal combustion engines with battery power, may offer a more efficient solution for vessels with fluctuating loads, such as tugboats and dredgers. These systems enable better load management and can incorporate fuel cells powered by hydrogen, allowing for efficient energy use and the needed battery support for rapid demand changes [29].

Currently, there are no large ships that operate exclusively on electricity over long distances, due to the technical limitations of electrical energy storage technologies (batteries), which do not yet allow sufficient autonomy for large ships.

Ellen is a large electric ferry that operates between the ports of Aerø Island, Denmark. It is one of the largest electric ships in the world. Ellen is approximately 80 meters long and can carry 200 passengers and 30 vehicles. It is powered exclusively by electric batteries and has a range of approximately 22 miles (35 kilometers) on a single charge [30]. Ampere is another electric ferry, operating on a route in Norway, and is considered the first fully electric passenger and vehicle transport ship. It has a capacity of 120 vehicles and 360 passengers, and its batteries allow the ship to operate over short distances, between two ports that are only 5 kilometers apart [31]. The main challenges of large electric ships are the limited range, battery capacity and charging infrastructure.

4. Opportunities and constraints

Hydrogen-based fuels offer significant potential for the shipping industry. Nevertheless, there is a substantial shortfall between the projected production of low-carbon hydrogen and the levels necessary to meet the targets outlined in 1.5°C scenarios [20].

When it comes to the production of e-fuels, the current output is limited by a shortage of renewable electricity generation facilities specifically designed for this purpose. To establish a sufficient number of these plants quickly and affordably, the industry will need to receive adequate incentives [3].

As e-fuels gain traction, heightened competition among various sectors may result in elevated costs for an extended period. There are several challenges currently faced by most carbon-neutral fuels, including higher capital investments, restricted availability of fuel, insufficient global bunkering infrastructure, the necessity for additional crew training, elevated fuel prices, and increased demands for onboard storage space [32].

While the advantages of electric propulsion are persuasive for shorter journeys and certain applications, the challenges and expenses associated with batteries suggest that this technology will likely remain a niche solution within the broader shipping sector, particularly for deep-sea operations. Future bioenergy and ammonia shipments could potentially match current levels of coal and gas transport [33].

Currently, the adoption of hydrogen or ammonia in shipping is at an early stage of technological readiness. More pilot programs and research are essential to accurately assess the viability of these fuels in practical applications. Although bioenergy utilization is expected to expand in line with 1.5°C scenarios, it must adhere to stringent sustainability criteria. Furthermore, there is a discrepancy between the projects currently in planning and the level of ambition needed. Over the past decade, biofuels have experienced a growth rate of 5% annually; however, to achieve the necessary outcomes for the 1.5°C scenarios by 2030, the growth rate for sustainable biofuels must rise to between 7% and 18% per year [34].

In the decarbonization efforts of the maritime sector, it is important not to overlook the carbon footprint generated at the port level (Fig. 2).

Berth operations play a significant role in escalating the overall carbon footprint of the logistics chain, necessitating substantial investment and time for a successful transition [35].

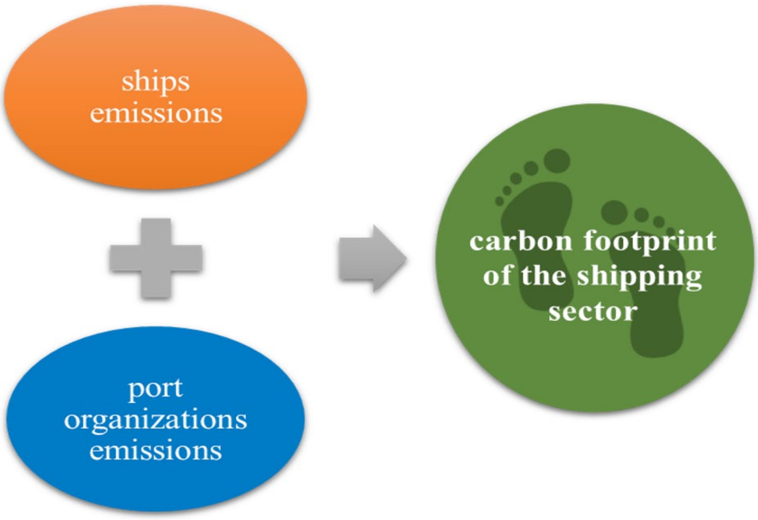

Fig. 2. Carbon footprint of the shipping sector

5. Forecast of alternative fuels use in the future

A projection by DNV [2] outlines the anticipated changes in the fuel mix for maritime transport up to 2050 as it can be seen in Fig. 3. It predicts that by that year, low and/or zero-emission fuels will constitute 84% of the total mix. Ammonia is projected to lead this category with a 36% share, followed by biofuels at 25%, and e-fuels at 19%. Additionally, electricity is expected to account for at least 4%.

The shift towards alternative fuels in the maritime sector will depend on several factors, including the accessibility of advanced biofuels and an adequate supply of renewable hydrogen for e-fuel production.

6. Conclusions

The maritime sector faces both challenges and opportunities in its transition to greener operations. Emerging technologies in biofuels, electro-fuels, and blue fuels are anticipated to meet new production standards, paving the way for the decarbonization of shipping activities. Despite these advancements, shipping remains central to logistics, with the potential for future bioenergy and ammonia shipments to rival current coal and gas transport levels [36].

Implementing safe operational practices is crucial, especially in addressing the new safety concerns associated with bunkering operations, which will require comprehensive training for involved personnel. Initially, the adoption of alternative fuels may necessitate more frequent inspections and maintenance compared to traditional fuels, alongside ongoing training for crews to handle these new systems effectively.

The design of vessels is likely to undergo significant changes as energy-efficient technologies and carbon-neutral fuels are integrated, potentially transforming both ship design and operation. While electric propulsion offers advantages for short trips, its widespread use in deep-sea shipping may be hindered by the limitations and expenses of battery technology.

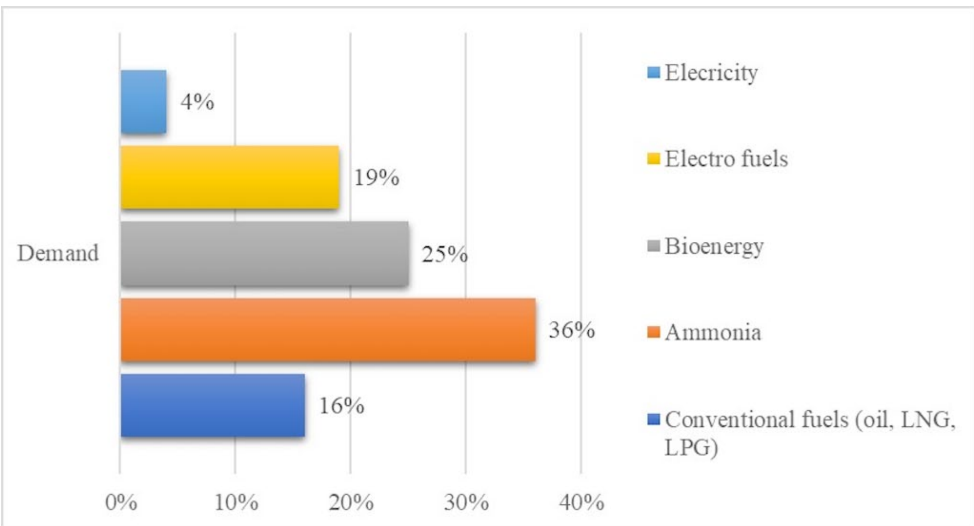

Fig. 3. Expected demand for fuels in the maritime sector in 2050 [2]

A successful transition to greener practices demands coordinated efforts at both the vessel and port levels, particularly through the establishment of designated green shipping corridors. These corridors will create a collaborative environment involving various stakeholders, including cargo owners, charterers, port authorities, and energy suppliers. Although more than 25 green shipping corridor initiatives have been proposed, they are mostly in the early planning stages and face challenges such as inconsistent fuel prices, logistical issues, and the need for unified stakeholder cooperation.

The most reliable alternatives to conventional fuels in the maritime sector are ammonia and hydrogen, while biofuels and renewable energy technologies are being used additionally. However, each of these solutions comes with technological, economic and logistical challenges that must be overcome to become a fully scalable alternative to traditional marine fuels.

Projects and research in the field of electric shipping are constantly expanding and larger electric ships capable of operating over longer distances will appear, in parallel with the development of battery technologies and fast-charging infrastructure.

While there are medium-sized electric ships, such as ferries and passenger ships for short distances, there are currently no large commercial ships that operate exclusively on electric power over long distances. However, technological developments continue to progress, and the use of electric power in shipping could become a more widespread option in the future.

Relying solely on zero-carbon fuels is impractical given the high demand, indicating that achieving net-zero emissions will also require rapid developments in carbon capture technologies and the other alternative technologies. Achieving net-zero emissions involves balancing emissions with those captured, highlighting the importance of innovative strategies for managing emissions in the maritime sector.

The purpose of the paper was to conduct a pros and cons analysis of currently available alternative fuels that are compatible with maritime transport in the context of existing alternative technologies that are widely debated in other reports by stakeholders in the field.

Future studies that can build on this paper can address the costs associated with the transition and the economic implications for companies in the maritime sector.

The limitations of this study are represented by the existence of a small number of previous studies on the advantages and disadvantages associated with these fuels compared to each other since they all present advantages and disadvantages, but it cannot be presented which of the disadvantages are greater or have greater implications, as well as in the case of the advantages. Therefore, a future cost analysis could quantify both qualitatively and quantitatively the implications of the transition to each of the fuels discussed in this paper [37], which could subsequently contribute to the decision-making processes for maritime companies.

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