Alternative Fuels in Maritime Sector

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The current sulfur oxide (SOx), nitrogen oxide (NOx), and greenhouse gases (GHG) regulations have pressured international maritime transportation to adopt lower-emission fuels. Alternative fuels have received strong attention due to the fact they can be cleaner and environmentally friendly and, in some options, similar to the heavy fuel oil (HFO) and marine gas oil (MGO) used. The liquefied natural gas (LNG) is undoubtedly the main low carbon alternative with many ships already operating with this source in the world. Eighty-eight percent of the papers referred to LNG as an important source in the maritime sector for greenhouse gases (GHG) reduction. Hydrogen is one of the most cited options (16.2%). In a tank-to-wheel assessment, H_2 from fossil sources has nil GHG emissions, which can also be highly carbon-intensive when analyzed from a well-to-wheel perspective. Biodiesel is a renewable and low carbon source, which represented 14.5% of total mentions. This option, together with hydrotreated vegetable oil (HVO) (3.8%) and straight vegetable oil (SVO) (3.4%) are sources that can be blended into the current marine engines without further modification.

low carbon fuels greenhouse gases maritime transportation

1. Introduction

In past centuries the maritime sector has proved to be the most important means of transport of world goods, transporting more than 1 billion tons of products by sea worldwide, growing at an average rate of 3% per year since 1970 [1]. Although sea transportation is the best indicator of the world economic growth, the side effect has been the impact regarding the complexity of decarbonization measures.

Nowadays, maritime fossil fuel consumption accounts for around 2.2 million barrels of oil equivalent (MBOE), which represents almost 1000 million tons of equivalent carbon dioxide ($MtCO_2eq$), reflecting 3% of global emissions [2]. Moreover, the so-called bunker fuel has a very low quality, impacting high emissions of sulfur oxide (SOx), nitrogen oxide (NOx), and particulate matter (PM) [3][4].

The Sulfur Emission Control Areas (SECA) entered into force in 2015 to reduce the sulfur content from 4.5% to 0.1% in the Baltic Sea and American coast and 0.5% elsewhere in 2020. The NOx emission reduction regulations have also been in place since 2016 [5].

The demand for low emissions for such compounds triggered a trend toward cleaner fuels, as well as the concerns over the greenhouse gases (GHG) emission reductions, which have drawn the attention of governments worldwide.

Since 2011, the International Maritime Organization (IMO) has implemented a regulatory measure of energy efficiency requirements for all ships globally to reduce gas emissions from the shipping sector, through programs such as the Energy Efficiency Design Index Standards (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) [6][7][8][9]. However, several measures are still needed to achieve the target of 50% lower emissions by 2050 [9].

The International Energy Agency scenario proposed a number of activities that must enter into force immediately to meet the expected targets, which includes the use of alternative fuels.

2. Vessel Types and Current Fuels

2.1. Cargo Ship Classification and Propulsion

Nowadays, around 52,000 cargo ships transport goods across the world. They are bulk carriers, oil tankers, and container ships [10]. Marine diesel engines are fundamentally the same as that of road vehicles, yet they are commonly bigger and work with higher efficiency. About 75% of all marine diesel engines are four-stroke; notwithstanding, 75% of the introduced power is delivered by two-stroke engines [11][12]. All of these ships represent 500 GW of engine capacity [10], more than all installed renewable (428 GW) and fossil (365 GW) power in Europe [13].

There are essentially three categories of marine engines: slow speed, medium speed, and high-speed, normally classified in knots (15–25 knots) [10][14]. The category choice depends on the size, engine speed, and purpose. Moderate speed engines regularly function under 350 revolutions per minute (rpm) and have exceptionally low fuel utilization. As far as size is concerned, slow-speed engines are the largest engines on the planet that use heavy fuel oil (HFO) for ignition [11][15].

2.2. Marine Bunker Classification

Marine fuel can be classified as distillate, intermediate, and residual. The distillate classes are named marine gas oil (MGO) or marine distillate oil (MDO) which have different grades (DMA, DMB, DMX, DMZ). The letters “A”, “B”…“Z”, refer to the particular properties under the product specification, ISO 8217:2017 [16][17].

The intermediate fuel oil (IFO) is divided into grades 180 and 380, these numbers correspond to the maximum kinematic viscosity of the residual fuel, in square millimeters per second (mm^2/s) at 50 °C [17].

Residual fuels, also called residual marine fuels (RMA, RMB, RMD, RME, RMG, RMK) or heavy fuel oil (HFO), in particular, are of very low quality, lower cost, and are the most used, and in different grades [17]. As the distillate class, the letter refers to their properties under International Organization for Standardization (ISO) 8217:2017 [17].

2.3. International Shipping Emissions

Most CO_2 emissions from international shipping are produced by bulk carriers, container ships, and oil tankers (15%, 18%, and 11% of the total shipping emissions, respectively). The high emissions of these vessels are directly connected with the long journeys for delivering their cargo across seas and continents [10][18].

The share of consumption by fuel type is 72% of HFO, 26% of marine gas oil, and 2% of LNG [10][19]. The main concern of HFO consumed by the shipping sector is the sulfur content estimated at 13% of the world’s sulfur emissions [10][20]. SOx emissions contribute to several environmental problems, such as acidification of the water and soil, and human health issues [10][21].

The new regulations already in force imposed by Annex VI of the IMO have limited the sulfur content in Emission Control Areas (ECA) (0.1%) (0.1% m/m) and non-ECA areas (0.5% m/m), replacing the HFO with MGO or LNG [10]. The ECA areas are comprised of the Baltic Sea, North Sea, East and West coasts of the United States, and the Caribbean Sea within a distance of 200 nautical miles [22], while non-ECA areas represent the rest of the world.

Concerning NOx emissions, Tier I came into force in 2000 with standards ranging from approximately 10 to 17 g/kWh, according to speed engines, Tier 2 (in 2011) fostered 20% NOx reduction below Tier 1, and Tier 3 standards applied to the NOx Emission Control Area (NECA) (The same regions of ECA areas as sulfur control) for engines installed after 1 January 2016, with 80% NOx reduction below Tier 1 [23]. Regulation 13 of Marpol Annex VI stipulates that the emission control for all ship engines is designed for powers above 130 kilowatts (kW) [24]. Although regulations regarding SOx and NOx are stricter, the CO_2 emission reduction measures are still weak and insufficient.

The International Renewable Energy Agency (IRENA) [25] recently published a report projecting the fuel demand in the shipping sector in 7.9–12.4 EJ by 2050, listing the most relevant contributing factors: global economic growth, economic growth in emerging markets, shift toward cleaner cooking fuels, strong growth in the petrochemical sector, regional trade agreements, and cleaner energy transition.

2.4. Maritime Sector and CO_2 Emissions

CO_2 emissions in the maritime sector are forecast to reach values two-fold higher than current levels by 2050. This scenario raised IMO concerns to plan effective measures against the uncontrolled emissions of the sector. The 72nd Marine Environment Protection Committee (MEPC) resolution of the IMO set the goal of reducing emissions by half in the next three decades [22].

3. Alternative Fuels in Maritime Sector

Biodiesel

Biodiesel is highlighted as the main option to replace HFO and MGO due to the fact they have similar properties [26][27][28][29]. However, their sustainability depends on the feedstock used, which might increase problems associated with competition for land, food/feed production, and indirect land use.

In the studies by Lin (2013) [30], the biodiesel blend stood out as an important source of reducing the sulfur content when applied up to 20%, in line with the current specifications. However, the author did not mention GHG emissions.

In another publication by Lin (2013) [31], the author raised concerns about the main obstacles to introducing biodiesel into the maritime sector, such as high production to meet maritime demand, high feedstock cost, and lack of standards for biodiesel applied to marine engines. To overcome some barriers the author put forward some strategies.

- establishing a standardized marine-grade biodiesel
- comprehensive field testing of the biodiesel blend in maritime transportation
- enhancing price competitiveness of marine-grade biodiesel by reducing manufacturing costs
- expanding the use of biodiesel in marine diesel engines by reducing feedstock costs
- applying suitable methods or technologies to improve the low-temperature fluidity of biodiesel blends
- reducing biodiesel costs by generating additional income from the production of purified glycerol for use in cosmetics, pharmaceuticals, and other relevant industries.

LNG

The LNG has been pointed out as the best fossil option to replace HFO and MGO, with 30% less GHG emissions and free from SO_X and NO_X [32]. The first LNG vessel was built in 2000, but there are currently 55 worldwide. Their activities are more concentrated in Europe (57%) and North America (38%) due to the ECA regulations [10].

Methanol

Methanol has emerged as a cleaner alternative source, with seven methanol ships operating to date. The emissions can be reduced to 99% SO_X, 60% NO_X, 95% PM, and 25% CO_2, in line with ECA regulations [10][33]. However, methanol is obtained from fossil sources mainly from natural gas through catalytic hydrogenation.

Bio-methanol can be obtained from gasification and Fischer–Tropsch conversion. There are plenty of studies on bio-methanol production. Nevertheless, there is a lack of information in the current literature. Some studies are modestly mentioning it as a promising source, albeit only in the long run [4], due to the fact that conversion technologies are still highly expensive in comparison with consolidated routes of biofuels and fossil marine fuel.

Pyrolysis Oil

Pyrolysis oil has been considered as a substitute alternative to HFO in the maritime sector and can be burned directly in low and medium-speed combustion engines. Moreover, it is compatible with the current diesel infrastructure [10]. Some experts suggested upgrading processing of bio-pyrolysis oil might be made in the current refinery infrastructure. However, the possibility of using pyrolysis oil in the maritime sector comes up against some specifications [4].

Pyrolysis oil has some negative characteristics, such as acidity, low calorific power 17–23 gigajoule per tonne (GJ/t) of fuel, which is about half of the HFO. It cannot be stored for a long time due to phase separation, the amount of water can reach around 30%, and the stage of development of the transformation route is also very low [4]. Due to all of the constraints mentioned above, pyrolysis oil can be used as a substitute, albeit with many restrictions, and the lack of testing for use in ship engines makes its use impossible at the moment. The disadvantages cited before can probably explain the small number of studies, i.e., 5.1% of all studies mentioned.

Fischer-Tropsch Diesel

Although Fischer–Tropsch diesel is derived from old technology, mostly used in World War 2 by the German army and in South Africa in the 1950s during the Apartheid embargo [34][35], FT-diesel derived from biomass still lacks technology that made it highly expensive with a long way to go as far as research and development (R&D) is concerned to become feasible. Only 4.3% of the mentions in the present study cited this as an alternative source to be used in the maritime sector.

Hydrogen

Fuel cells operating with hydrogen have been widely discussed among experts from industry and academy due to indirect GHG emissions [36]. Hydrogen is an energy carrier capable of being produced from renewable resources through electrolysis of natural gas reforming or biomass gasification [10][32].

Hydrogen represents the second-highest rate of mentions (16.2%) by the authors as a potential source for the maritime sector. Currently, there are a few projects of hydrogen fuel cell ships operating in the world, including a civilian ship called Viking Lady that has been retrofitted with an LNG internal combustion engine (ICE) with the support of fuel cells that use methanol or hydrogen [10][37].

One of the bottlenecks in the storage capacity of hydrogen is the pressure of the storage tanks (under 700 PSA) [10].

Another negative point is that hydrogen may not be transported under the International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code). Thus, the nations which want to operate with this source must enter into an international agreement [32][38]

High investment costs in production and infrastructure are the major barriers to hydrogen implementation on international maritime cargo ships. The current retail cost of hydrogen is 1.5–6 times higher than conventional HFO, thus making use of this resource unfeasible [10][39].

Ammonia

Recently, ammonia (NH_3) has been widely discussed as an alternative fuel due to the fact that it does not have direct CO_2 emissions [40]. It is capable of being used in internal combustion engines (ICE) or fuel cells [41][42][43]. However, ammonia is mostly produced from fossil sources.

Studies on international shipping have assessed the possibility of using hydrogen combined with ammonia as a potential source of 70% CO_2 emission reduction by 2035 [43][44]. While Hansson et al. (2020) developed a scenario of carbon neutrality for Danish maritime cargo until 2050 [45][46]. Nevertheless, Hanssson et al. (2020) mentioned some factors that must be considered, such as safety distribution and development of fuel cells [46].

HVO, SVO and Ethanol

Hydrotreated vegetable oil (HVO), straight vegetable oil (SVO), and bioethanol are mentioned as the main biofuel options in the short and medium-term with 3.8%, 3.4%, and 3.4% mentions, respectively. These biofuels are already commercialized on a large scale and can use the current marine fossil fuel infrastructure. However, there are sustainability concerns for HVO, SVO, and bioethanol in their large-scale production feedstock, needing considerable croplands area sizes which can constrain deforestation in some regions, compete with food and feed production and road transport, which already use this fuel source [47].

GHG Impacts

International shipping is the most problematic sector to apply any policy or regulation due to the fact that the oceans are international areas and each region is governed by individual rules. Moreover, there is strong resistance to new options for the decarbonization of the sector.

The current big merchant ships are designed to use liquid fossil fuels only in their engines. Including alternative fuels as an option could balance the emissions [10][48]. Nevertheless, a carbon footprint assessment of those cleaner sources must take into account measuring other powerful gases, such as methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, which must be included to assess their direct or indirect global warming potential (GWP) on a temporal scale [48].

Conventional biofuels, such as SVO, biodiesel, and HVO, have considerably lower GHG impacts and could certainly reduce the problems associated with their use. However, the main concern is the feedstock (food and feed) and CO_2 emissions of direct and indirect use on land [10].

Abbreviations

€	Euros
BAU	Business-as-usual
Bio-LNG	Bio liquefied natural gas
Bio-SNG	Bio synthetic natural gas
CO_2	Carbon dioxide
CH_4	Methane
DMA	Destilate marine oil A
DMB	Destilate marine oil B
DMX	Distillate marine oil X
DMZ	Distillate marine oil Z
EEDI	Energy Efficiency Design Index

FT-diesel	Fischer–Tropsch diesel
gCO_2eq	Gram of equivalent carbon dioxide
GHG	Greenhouse gases
GHG	Greenhouse gases
GJ	Gigajoule
GW	Gigawatt
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IEA	International Energy Agency
IFO	Intermediate fuel oil
IGC	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IRENA	International Renewable Energy Agency
IMF	Intermediate marine fuel
IMO	International Maritime Organization
ISO	International Organization for Standardization
kWh	Kilowatt-hour
LNG	Liquified natural gas
Marpol	International Convention for the Prevention of Pollution from Ships
MBOE	Million barrel of oil equivalent
MCDA	Multi-criteria decision analysis
MDO	Marine distillate oil
LNG	Liquified natural gas
MBOE	Million Barrel of Oil Equivalent
MCDA	multi-criteria decision analysis
MDO	Marine distillate oil
$MtCO_2eq$	Million tons of equivalent carbon dioxide
N_2O	Nitrous oxide
RMA	Residue marine oil A
RMB	Residual marine oil B
RMD	Residual marine oil D
RME	Residual marine oil E
RMF	Residue marine Fuel
RMG	Residual marine oil G
RMK	Residual marine oil K
RPM	Revolution per minute
RQ	Research question
s	Second
SECA	Sulfur Emissions Control Area

SEEMP	Ship Energy Efficiency Management Plan
SOx	Sulfur oxide
SVO	Straight vegetable oil
SSP	Shared socio-economic pathway
t	Tonne
TEU	Twenty equivalent units
USA	United States of America
USD	US Dollar
WoS	Web of Science

D.; ISBN

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