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DEPARTMENT OF MARITIME STUDIES

MSc in SHIPPING MANAGEMENT

ALTERNATIVE SOURCES OF ENERGY AS MARINE FUELS. ENVIRONMENTAL AND FINANCIAL EFFECTS. FUNCTIONAL IMPLEMENTATION AND SUSTAINABILITY.

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A Thesis

submitted in the Department of Maritime as a partial fulfillment of the requirements for the Master of Science degree in Shipping Management

Piraeus

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Finally, this endeavor would not have been possible without the generous support from all my friends for their constant trust and encouragement. Your friendship makes my life a wonderful experience.

‘’Μια αστραπή είναι η ζωή μας… μα προλαβαίνουμε ‘’ N.K.

CONTENTS

TABLES OF FIGURES

Figure 27: The container shipping deployment for the Russian Federation and Ukraine is decreasing. Deployment of container transport fleets in specific nations in TEU capacity

ABSTRACT

Today, climate change and the greenhouse effect have necessitated the replacement of existing energy sources with those that are less harmful to the environment. In Shipping, the ongoing development of technology, the rise in fuel prices, and the implementation of stronger rules on ship emissions have prompted many Maritime Companies to adopt natural gas and other renewable energy sources, which will be examined in greater detail. In addition, numerous examples of ships employing renewable or alternative energy sources will be provided to illustrate the rate of change in marine fuels. Due to the high volume of ship movements and the greater volume of goods they carry at a lower cost than other modes of transport, the development of more efficient types of energy leads to more environmentally friendly solutions. Finally, this thesis will also discuss how to optimize these alternative fuel sources from an economic and environmental standpoint.

Keywords: LNG; alternative fuels; sustainability; emissions; wind power; ammonia; LPG; hydrogen; methanol; CNG; emission reduction; energy-efficient shipping; renewable energy;

ΠΕΡΙΛΗΨΗ

Σήμερα, η κλιματική αλλαγή και το φαινόμενο του θερμοκηπίου έχουν επιβάλει την αντικατάσταση των υφιστάμενων πηγών ενέργειας με εκείνες που είναι λιγότερο επιβλαβείς για το περιβάλλον. Στη Ναυτιλία, η συνεχής ανάπτυξη της τεχνολογίας, η άνοδος των τιμών των καυσίμων και η εφαρμογή αυστηρότερων κανόνων για τις εκπομπές των πλοίων ώθησαν πολλές Ναυτιλιακές Εταιρείες να υιοθετήσουν φυσικό αέριο και άλλες ανανεώσιμες πηγές ενέργειας, οι οποίες θα εξεταστούν λεπτομερώς. Επιπλέον, θα παρασχεθούν διάφορα παραδείγματα πλοίων που χρησιμοποιούν ανανεώσιμες ή εναλλακτικές πηγές ενέργειας για να καταδειχθεί ο ρυθμός αλλαγής στα καύσιμα πλοίων. Λόγω του μεγάλου όγκου κινήσεων των πλοίων και του μεγαλύτερου όγκου εμπορευμάτων που μεταφέρουν με χαμηλότερο κόστος από άλλους τρόπους μεταφοράς, η ανάπτυξη πιο αποδοτικών τύπων ενέργειας οδηγεί σε πιο φιλικές προς το περιβάλλον λύσεις. Τέλος, αυτή η διπλωματική εργασία θα συζητήσει επίσης πώς να βελτιστοποιήσουμε αυτές τις εναλλακτικές πηγές καυσίμου από οικονομική και περιβαλλοντική άποψη.

Λέξεις Κλειδί: LNG; εναλλακτικά καύσιμα; βιωσιμότητα; εκπομπές αερίων; αιολική ενέργεια; αμμωνία; LPG; υδρογόνο; μεθανόλη; CNG; μείωση των εκπομπών; ενεργειακά αποδοτική ναυτιλία; ανανεώσιμη ενέργεια;

INTRODUCTION

The usage of fossil fuels, primarily heavy fuel oil (HFO) and marine gas oil, dominates seaborne transport, which accounts for about 80% of worldwide commerce volume [1,2]. There is a need to decrease the environmental and climate impact of shipping in the short and long term [[6], [7], [8] due to linked emissions of greenhouse gases (GHG), nitrogen oxides (NOx), and sulphur oxides (SOx) [[3], [4], [5].

In comparison to 2008, the latest International Maritime Organization (IMO) strategy intends to cut overall yearly GHG emissions from international shipping by at least 50% by 2050 [9]. To do this, they have set goals to reduce CO2-emissions by 40% by 2030 and 70% by 2050, as measured by the payload-distance freight metric, compared to 2008 [9]. By 2050, the EU wants to cut yearly CO2 emissions from shipping by at least 40% compared to 2005 [10].
To achieve these CO2 emission reductions, energy efficiency measures must be combined with the introduction of alternative marine fuels that emit less CO2 than conventional fuels [[11], [12], [13], [14]]. NOx, SOx (which are regulated in specific emission control regions), and particulate matter (PM) may also be reduced as a result [15].

Liquefied natural gas (LNG), methanol, hydrogen, wind and wave power, liquefied petroleum gas (LPG), compressed natural gas (CNG), ammonia and electricity are all feasible alternative maritime fuels. These fuels have different technical performance and other features, such as environmental impact, availability, cost, and infrastructure, all of which influence their potential for maritime propulsion. As a result, the shipping sector and policymakers must evaluate many criteria for a variety of options when choosing future maritime fuels [12,14,16,17].

There are studies in the literature that compare the economic and environmental performance of various marine fuels and propulsion methods (e.g., Refs. [[18], [19], [20], [21], [22], [23]]). Structured analyses that encompass a broad range of parameters are needed to better grasp the potential for alternative fuel options.

The goal of this study is to use a multi-criteria decision analysis approach to examine the prospects for ten different alternative fuels, for deep-sea shipping in 2030, while taking into account the influence of diverse stakeholder preferences. The study examines a few factors that influence the choice of marine fuel (covering economic and environmental aspects).

Our premise is that different shipping-related players' interests and values will result in varied rankings of alternative marine fuel sources. LNG is likely to be ranked high among fossil fuel-based alternatives by shipping industry actors due to pricing and supply-related advantages. It's less clear what to expect from renewable solutions because they all have advantages and disadvantages. Methanol has advantages in terms of economics and infrastructure, whereas hydrogen is attractive from a broad environmental standpoint.

New technologies for alternative energy sources have begun to set new environmental norms by lowering CO2 emissions, which are hazardous to the environment. Carbon is responsible for more than 80% of hazardous emissions in the atmosphere [27]. As a result, decarbonization is one of the most pressing environmental issues, and despite substantial improvements in energy efficiency in maritime transport, the shipping industry is responsible for almost 940 million tons of CO2 emissions into the atmosphere each year. Given the continual expansion of the worldwide fleet, it is easy to predict that these emissions will rise in the coming years [28].

Alternative fuels appear to be the sole option for the environment, and the European Union has already included their introduction in her White Paper on Transportation [29]. More specifically, the European Union produced a «Strategy for liquefied natural gas and gas storage» in 2016 in order to showcase the benefits and possibilities of LNG use to all Union members. Furthermore, in October 2014, the European Union's executive committee ordered 139 European ports to take sufficient action in order to provide LNG bunkering facilities until 2020 [30]. In addition, the International Maritime Organization (IMO) strengthened its efforts to regulate pollutant emissions by introducing new laws. The IMO, in particular, welcomed the International Convention for the Prevention of Pollution from Ships (MARPOL), which was also adopted. modifications to MARPOL Annex VI (Resolution MEPC.203 (62)) to reduce CO2 emissions by the implementation of an energy efficiency design index [27, 31].

This paper examines the potential for various types of fuels or technology investments to be used as marine fuels as well as the potential for environmental improvement. It also examines and evaluates these types of fuels in order to assess the new ecological equilibrium in accordance with established environmental and safety laws. In addition, the advantages and disadvantages of these type of fuel are discussed extensively. Last but not least, a financial evaluation of energy sources used as marine fuels is executed mentioning the impact of the war, as well as their possibility of being really viable and sustainable options to be adopted by the shipping industry.

1. ALTERNATIVE ENERGY RESOURCES

Alternative energy sources are needed when fossil energy sources become scarce and human energy demand rises. Renewable energy is an alternative energy source that reduces the greenhouse effect and is therefore environmentally friendly. Liquefied natural gas (LNG), solar energy, wind energy, hydrogen, ammonia, wave power, etc. are examples of renewable energy that have been demonstrated and exploited as an energy source.

According to the International Energy Agency's (IEA) annual report, renewable energy capacity would be reduced by 13% in 2020 compared to 2019. Due to supply chain problems, social distancing norms and lockdown measures, and growing finance challenges, construction activities have been delayed. Other considerations, such as financing new energy projects during the covid-19 outbreak, are related to persistent policy instability and uncertain market trends. [32]

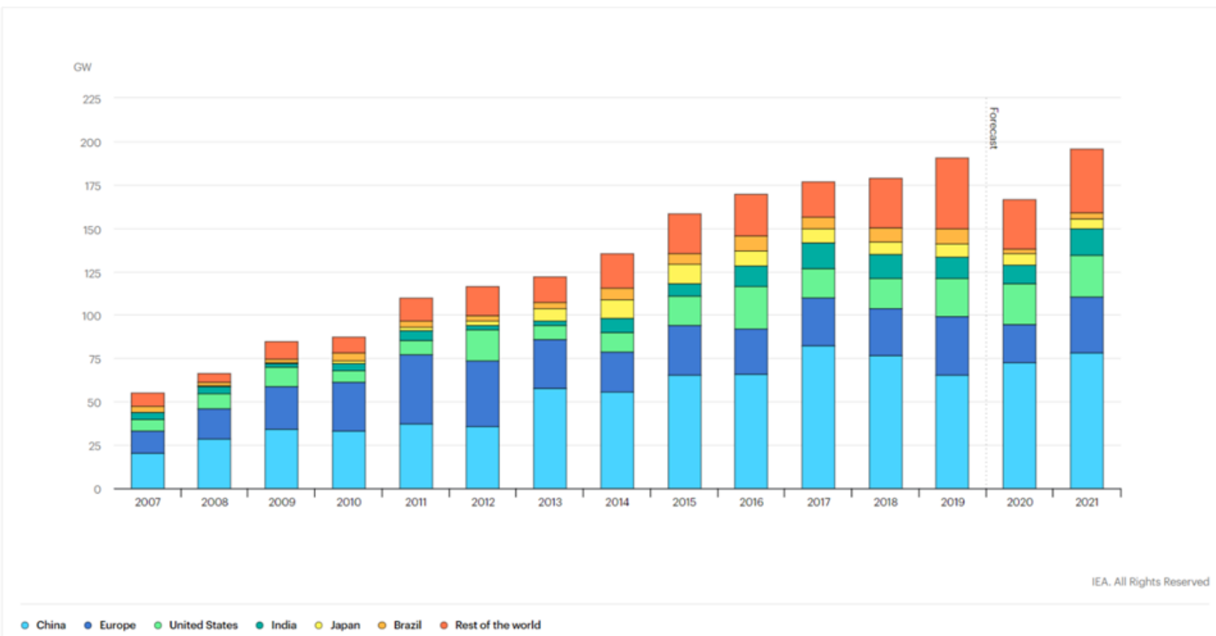

Figure 1. Renewable electricity capacity additions, 2007-2021, updated IEA forecast

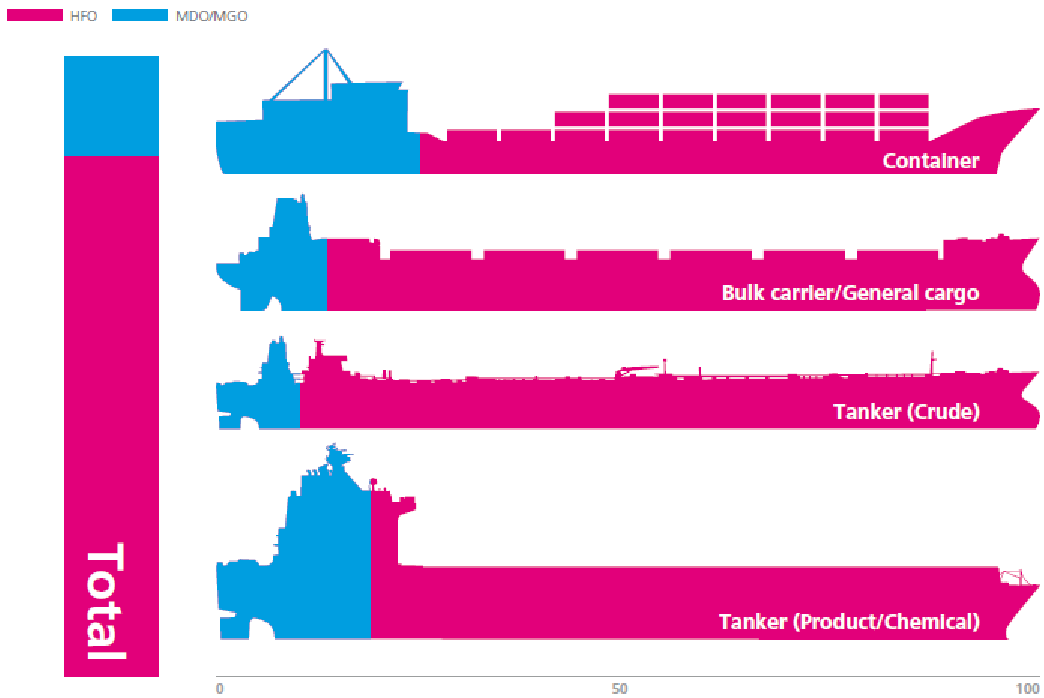

Figure 2. Marine Fuel Mix 2010

China, Europe, the United States, and India will see substantial capacity increases for electrical energy sources from renewable energy in 2020 and 2021. The renewable energy sources that will be prioritized include wind and solar PV.

In all, combined capacity growth in 2020 and 2021 has been revised downward by over 10%. The movement of this revision is based on the use of technology and national policies. Solar PV was used during Covid-19. The expansion of initiatives in Europe, China, and the United States has slowed by 36%. In terms of wind, the prediction for project decline in 2020 and 2021 has been updated, with the most notable changes being in the energy sector. Europe, China, and the United States have all contributed. Meanwhile, new renewable alternative energy sources are being developed. Wind and solar energy can be used to improve power or as the primary power source for ships.

1.1 ALTERNATIVE ENERGY RESOURCES AS MARINE FUELS

The current state of maritime transportation relies primarily on HFO fuel, according to MDO/global MGO's marine fuel trend 2030 [14]. It depicts the fuel consumption scenarios for different types of ships, such as tankers (crude/chemical/products), bulk carriers/cargos, and containerships. The use of HFO fuel is higher than that of MDO/MGO.

A comparison of alternative and conventional marine fuels is frequently a matter of interpretation and point of view. As a result, alternative marine fuels will become the goal of ecologically friendly fuels in the near future. Methanol, hydrogen, LNG, ammonia, wind energy, electric power, etc. are examples of alternative fuels.

The Bulk Carrier/General Cargo ship used LNG as a source of sustainable energy in 2015. HFO is still commonly employed across ship types, even if the ratio of container ships has fallen from 2010 to 2020. The goal is to create hydrogen-powered ships by 2025. The usage of fossil fuels by HFO and MDO is still considerable in 2030. With the IMO's tightening of GHG standards, it's envisaged that all types of ships will use clean energy like hydrogen and methanol to boost the percentage of clean energy. [33]

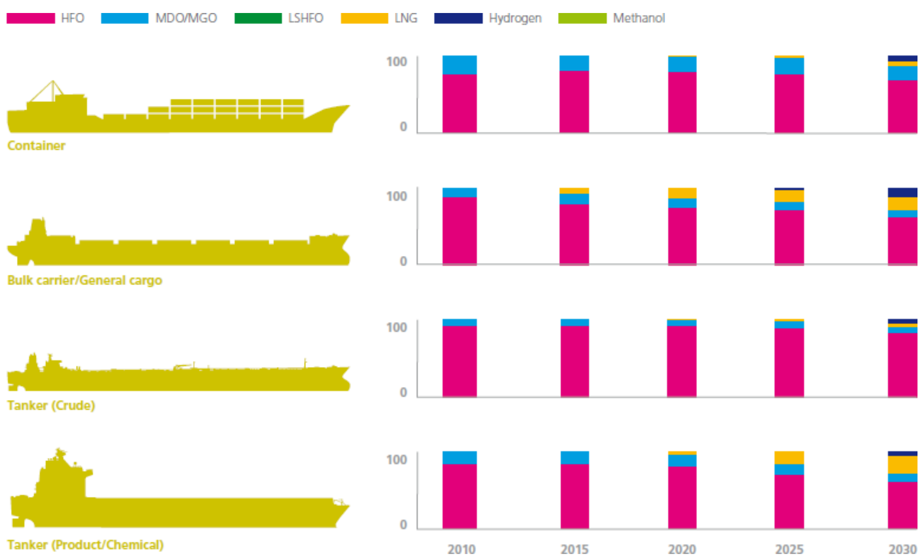

Figure 3. Containership, bulk carrier/general cargo, tanker (crude) and tanker (product/chemical) fleet fuel mix (%)

1.2 LIQUEFIED NATURAL GAS (LNG)

The United States is presently the largest natural gas producer in the world. Natural gas is primarily utilized for heating and electricity generation in the United States, accounting for almost one-third of the nation's primary energy consumption. While the majority of natural gas in the United States is transmitted by pipeline in gaseous form, the international market for natural gas has led to the usage of LNG, or natural gas in liquid form.

Liquefied natural gas is natural gas that has been cooled to a liquid state, roughly -260 degrees Fahrenheit, for transport and storage (LNG). The volume of liquid natural gas is 600 times that of natural gas in its gaseous state. This approach enables the transmission of natural gas to places without pipes. When pipeline transmission is not practicable, natural gas is transported over long distances by liquefying it. Liquefied natural gas (LNG) transports natural gas to distant markets that cannot be connected to pipelines. As a dense liquid, natural gas may be delivered in specialized tankers to terminals around the globe. At these terminals, the LNG is converted to a gaseous state before being piped to distribution companies, industrial users, and power plants. [34]

In the near future, the maritime industry is likely to enhance its usage of LNG as a marine fuel [29]. Natural gas is regarded as one of the most important alternative sources of energy for humanity [35] among many types of fuels. Liquefied Natural Gas (LNG) as a fuel, in particular, is regarded as one of the most promising energy alternatives for the future [36].

LNG is a cleaner energy than HFO and MDO, emitting significantly less SO_2 and NO_x but significantly more CH_4 [37]. It is a mixture of gases that is liquefied by reducing its temperature below its boiling point. Methane makes up around 87–99 mole percent of LNG, with the remainder consisting of propane, ethane, and 19 other heavier hydrocarbons, depending on the LNG source [38, 39]. For example, LNG imported from Belgium includes 90% methane and 10% ethane by mass (by mass) [40] ethane At -164 C degrees [41], LNG has a lower calorific value of 21 MJ/L and a higher calorific value of 24 MJ/L. Natural gas is refrigerated to -162 degrees Celsius at atmospheric pressure to make LNG, making it a cryogenic fluid [42, 43]. The major component of natural gas, methane, is chilled below its boiling point during liquefaction. Simultaneously, oxygen, carbon dioxide, water, hydrocarbons, and certain sulphur compounds are either removed or reduced to some amount [44]. Natural gas requires 600 times the volume of LNG to provide the same amount of energy at atmospheric conditions [45]. Furthermore, when exposed to an unconfined environment, both LNG and its vapor will neither create fire or explode [46]. LNG is a type of natural gas that is non-toxic, non-corrosive, colorless, odorless, safe, and clean [47, 48]. LNG isn't harmful; but, in order to ignite it, it must first be dissolved and then combined with air in the right proportions [49]. Furthermore, the CO_2 emissions from LNG's life cycle are 18% lower than those from a gasoline vehicle model [50]. These advantages position LNG as a viable transportation fuel.

In comparison to pipeline gases, LNG is also more efficient and accessible for transportation [41,47,51]. LNG that has been cleaned and condensed can be carried safely across the ocean [52]. To handle the low temperature of LNG during shipping, specially built double-hulled ships are employed [45].

1.3 COMPRESSED NATURAL GAS (CNG)

Compressed natural gas (CNG) is a gasoline-based fuel gas mostly made up of methane (CH_4) that has been compressed to less than 1% of its original volume at regular atmospheric pressure. It's kept and delivered in rigid containers with a pressure of 20–25 MPa (2,900–3,600 psi), commonly in cylindrical or spherical shapes, at a pressure of

20–25 MPa (2,900–3,600 psi).

When compared to the other fuels, CNG creates fewer harmful gases. Natural gas is less dangerous than other fuels in the event of a leak since it is lighter than air and disperses quickly when discharged.

CNG sea transportation is a relatively new concept in gas shipping, almost 50 years after the introduction of liquefied natural gas (LNG). The first CNG carrier was built and tested in the late 1960s, but the project was shelved due to the ship's expensive capital cost and the low gas prices at the time. The means of transportation is now being pursued with zeal, and CNG shipping is on the verge of being commercially viable.

The technique has a wide range of commercial applications in major natural gas markets throughout the world. Following classification society approvals for ship design and CNG containment system technology, several maritime CNG projects are presently in the works. Two CNG technology companies have established manufacturing facilities for their gas containment tanks, with one of them now in operation.

CNG maritime technology is well suited to onshore and offshore reserves that can't be generated because a pipeline solution is too expensive or because LNG is too expensive. Between pipelines and LNG, CNG occupies a market niche. CNG projects are easier to implement than LNG projects. CNG shipping can also be used to swiftly monetize stranded gas sources and provide a temporary solution, establishing a market history that can eventually be used to support a pipeline or LNG transport. [53]

1.4 LIQUEFIED PETROLEUM GAS (LPG)

By definition, liquefied petroleum gas (LPG) is any liquid mixture of propane and butane. To attain appropriate saturation, pressure, and temperature characteristics, certain mixes of butane and propane are employed.

Propane has a boiling point of –42°C and is gaseous at room temperature. By adding mild pressure (8.4 bar at 20°C), it can be handled as a liquid. Butane comes in two different forms: n-butane and isobutane, with boiling points of –0.5°C and –12°C, respectively. Both isomers can be liquefied at lower pressures than propane because they have greater boiling temperatures. Propane tanks for land-based storage have safety valves to maintain the pressure below 25 bar. Due to the lower volumetric energy density of LPG and volume inefficiencies in Ctype tanks, LPG fuel tanks are 2-3 times bigger than oil tanks (similar as for LNG).

LPG is produced as a by-product of oil and gas production or as a by-product of oil refineries. LPG can also be made from renewable sources, such as as a by-product of the manufacturing of renewable diesel.

LPG can be used in three different ways as a ship fuel: in a two-stroke diesel engine, a four-stroke lean-burn Otto-cycle engine, or a gas turbine. Currently, just one type of two-stroke diesel engine, the MAN ME-LGI series, is commercially available. A Wärtsilä four-stroke engine was installed for stationary power generation in 2017. (34SG series). To maintain a safe knock margin, this engine had to be derated. Wärtsilä's alternative technique needs the installation of a gas reformer, which mixes LPG and steam with CO2 and hydrogen to produce methane. This combination can then be used without derating in a standard gas or dual-fuel engine. [54]

As a result, using LPG as a viable alternative fuel for today's gas and CNG/LNG-fueled marine engines, the appropriate "equation" can be based on the US HD5 standard, which has a low sulfur content (percent by volume): 93 percent minimum, butane 3.5 percent maximum, propene/propylene 3% maximum, other olefins 0.5 percent maximum, sulfur 50 ppm maximum (Limit embraced in numerous nations). Filtered (not contaminated by plasticizers, rust particulates, sodium dioxide, water, or other soil), such LPG composition can guarantee more than 101 Octane and could be a brilliant fuel for marine engine manufacturers to adopt as a solid fuel for the next generation of high productivity, extremely low emission engines.

In 2015, global LPG production reached 284 million tonnes, equivalent to around 310 million tons of oil in terms of energy content, and is growing at a rate of about 2% per year. In comparison, the International Maritime Organization (IMO) estimated that the shipping sector consumed 307 million tons of fuel on average between 2010 and 2012. North America and the Middle East have seen major increases in production. The considerable increase in shale gas output in recent years can be attributed to North America's production boom, which has turned the US into a net exporter of LPG since 2012. [55]

1.5 HYDROGEN AND FUEL CELLS

Hydrogen is the clear frontrunner among the different clean fuel alternatives now being tested. A research conducted by the Global Maritime Forum in March 2021 looked at 106 projects aimed at achieving zero emissions in maritime shipping around the world, and found that roughly half of them relied on hydrogen as a low-carbon fuel source. The relative ease with which existing ships can be retrofitted with hydrogen fuel cells is a fundamental advantage of hydrogen over other fuel choices. (For a more detailed examination of its benefits, see Q3.) With minor improvements to fuel capacity or operations, hydrogen fuel may replace 43% of voyages between the United States and China without any alterations.

Hydrogen-powered ferries and smaller cargo vessels have been tested in the United States, Belgium, France, and Norway. Royal Dutch Shell, the world's largest oil company, has invested in a number of hydrogen production projects in Europe and

China, claiming that hydrogen is "advantaged over other prospective zero-emissions fuels for transport."

Non-hydrogen liquid fuels, such as biofuel, have also piqued business attention, but they are less developed than hydrogen. Maersk, for example, operated a carbon-neutral ship in 2019 that went from Rotterdam to Shanghai and back on a 20% biofuel blend.

The most prevalent element in the universe is hydrogen. Pure hydrogen (H2), on the other hand, is rather rare on Earth. It can be present in both water (H2O) and organic substances such as methane (CH4). Pure hydrogen gas, which is commonly employed in chemical synthesis and crude oil refining, is created artificially, mainly from fossil fuels like methane in carbon-intensive procedures. Each year, the manufacturing of hydrogen generates 830 million metric tons of CO2, which is higher than Germany's entire CO2 emissions in 2017. Future low-carbon hydrogen will most likely be made from water using electrolysis, which produces almost no carbon emissions.

Depending on the carbon intensity of the production process, hydrogen is classified into three types:

Steam reforming is used to create gray hydrogen from fossil sources. Gray hydrogen accounts for 95 percent of the 70 million metric tons of hydrogen produced each year, with natural gas accounting for over 70% of gray hydrogen production (mostly methane). Gray hydrogen produces about 10 kilograms of CO2 each kilogram of hydrogen produced, putting it in between natural gas and coal in terms of carbon footprint.

Steam reforming is used to make blue hydrogen, however the facilities are upgraded with carbon capture, utilization, and storage (CCUS) technology. Blue hydrogen plants may absorb 50–90% of CO2 emissions, yielding around 2–5 kg CO2 per kg H2 produced, depending on the technology and fossil fuel utilized. The blue hydrogen facility in Port Arthur, Texas, for example, absorbs about 60% of CO2 produced during production.

Electrolysis, which uses electricity to divide water into hydrogen and oxygen, produces green hydrogen. Green hydrogen is the only form of hydrogen with a nearly carbon-free production process since electrolysis does not produce CO2. Electrolysis with electricity supplied from renewable sources (solar or wind power) produces less than 5% of gray hydrogen's CO2 emissions (non-zero due to emissions generated during transportation and electricity generation). Although this method of manufacturing is not new—alkaline electrolysis has been in use for over a century—the expenses of producing green hydrogen are much higher than those of producing blue or gray hydrogen. The only sustainable and mass-produced fuel source for the marine sector is hydrogen produced by electrolysis using renewable energy.

Hydrogen gas can be stored and transferred in fuel tanks once it has been produced. However, because hydrogen has a low energy density, it must be compressed and chilled greatly, similar to how methane is compressed to generate liquefied natural gas (LNG). [56]

Hydrogen's potential lies in its utilization in fuel cells. The development of hydrogen fuel cells has made substantial progress and piqued the interest of a wide range of industries, including cruise ships, passenger ships, and offshore supply vessels.

Fuel cell technology is based on electrochemical reactions that directly convert the energy of a fuel into electricity. It requires the use of a fuel, such as LNG, biofuel, or hydrogen, as well as an oxidizing agent. A hybrid propulsion system with an internal combustion engine and a fuel cell can be placed on board. Alternatively, the ship's electricity needs can be fulfilled using fuel cells.

In the operation of a fuel cell, the concept of catalysis is extremely significant. The fuel cell is an electrochemical mechanism that converts energy into hydrogen and oxygen in water while also providing electricity and heat. Constant flow is used to create electricity. Figure 4 depicts a section of a conventional fuel cell, which will be examined in greater detail further down.

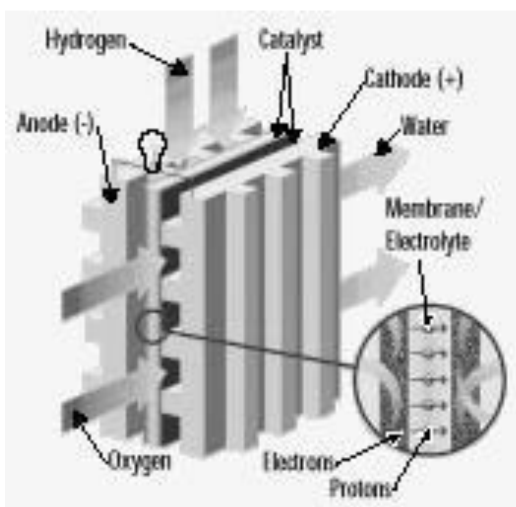

Figure 4. Section of a typical fuel cell

The fuel and the oxidizing agent, for example, are both gases or liquids in the form of a solution. Figure 5 depicts the basic principle of operation of fuel cells, which refers to the simplest, most classic, most efficient, and most developed element today, H2 / O2.

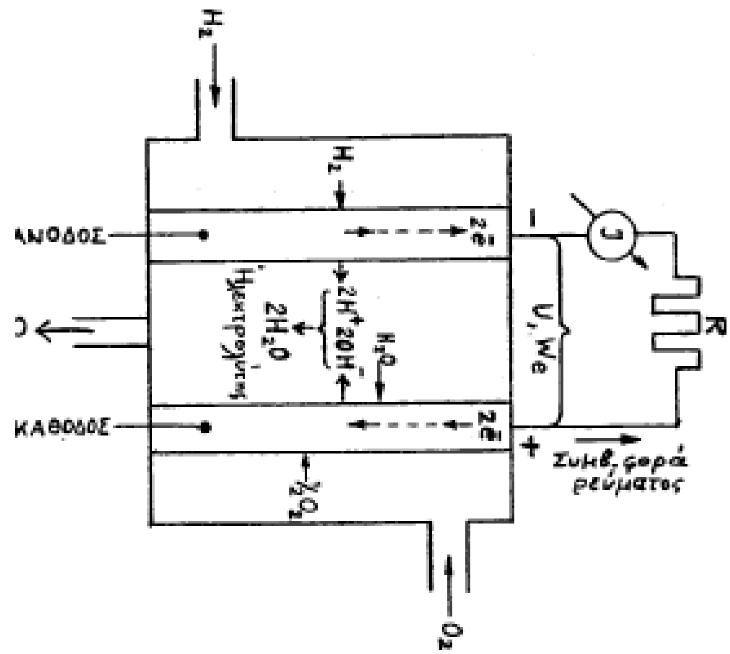

Figure 5. The fundamentals of fuel cell operation

H2 is introduced to a steady flow from one side and comes into contact with the anode inside the pores of which the oxidation of H2 occurs through the use of a suitable highly active catalyst. The two electrons released in the anode pass through the "consumer" (i.e., an "electronic conductor") R, to which they provide useful electricity, to the descent (electrode +), where they are absorbed in the region, receiving "reduction" of O2 there, once again in the presence of a suitable active Catalyst. The cathode's hydroxyl ions go via the Alkaline Electrolyte (typically KOH concentration) to the anode, where they combine with hydrogen ions to generate water. The created H2O is continually extracted from the cell, ensuring that the electrolyte density is not changed. The latter must always have excellent ion conductivity, as the KOH solution in OH- does, and poor conductivity in electrons, whose circulation between anode and cathode is limited to the external circuit. It should also prevent their diffusion reagents from passing through.

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The electrodes, which are the site of electrochemical reactions and current data gathering, are a significant part of the element. As a result, they must meet a variety of stringent criteria. The elements also work with other reagents (which are currently in varying levels of research and success), such as Methane, Methanol, Hydrazine, other hydrocarbons, Ammonia, and so on, with O2 or air, based on this concept. However, the events that occur in these are highly complicated, revealing a wide range of issues.

The costs of both investment and operation are still substantial. The cost of a fuel cell, for example, is claimed to be 2-3 times greater than the cost of a conventional engine. There are currently programs testing the use of fuel cells in ships.

The Alsterwasser, a 100-person passenger ship, was constructed for use in inland waterway transportation by the Zemships (Zero Emissions Ships) initiative in 2008, and a number of other small ferries and riverboats followed. The Zemships, later called the FCS Alsterwasser, were the world's first fuel cell-powered ships. It was fueled by two hydrogen fuel cells, each with a 48kW capacity. The ship was in operation in Hamburg until the end of 2013, when the cost of operating a hydrogen supply infrastructure rendered it obsolete. A ship powered by a hive 330kW fuel tank successfully tested aboard the Viking Lady offshore boat in 2012 as part of the FellowSHIP project, working for over 7000 hours. This was the first fuel cell unit to operate aboard a commerce ship, with a 44.5 percent electricity efficiency (including internal combustion) and zero NOx, SOx, or suspended particle emissions. When the thermal reset is turned on, the total fuel efficiency rises to 55%, but there is still potential for improvement.

"WorldWise Marine" collaborated with Dutch trailer operators Iskes and Smit to develop the "Hydrogen Hybrid Harbor Tug" (HHHT). This is a 50-ton trailer with fuel cells and hydrogen stored at a pressure of 430 pounds per square inch. The innovation is found in the fact that fuel cells combined with batteries provide enough power to operate the trailer in standby mode, which accounts for 85% of its operating time. When the trailer has to carry out a mission, diesel is used. "When compared to a traditional trailer, we can achieve a 98% decrease in sulfur and nitrogen oxide emissions, as well as a 30% reduction in overall carbon emissions," stated Michiel Wijsmuller, CEO of Offshore Ship Designers.

Figure 6. Hydrogen Hybrid Harbor Tug (HHHT): Hybrid trailer

In 2012, Germanischer Lloyd unveiled design concepts for a zero-emission Scandlines ferry capable of transporting 1500 people and 1000TEU of cargo at a service speed of 15 knots, powered by liquid hydrogen and a technology that combines fuel cells and batteries. Nonetheless, with practically all present commercial production options based on fossil fuels, the practicality of hydrogen production is a crucial issue. Electrolysis of seawater will be used to produce sustainable hydrogen using energy sources such as surplus electricity from offshore wind farms, various types of onshore renewable energy sources, or aboard wind turbines. [57]

1.6 METHANOL

Methanol as a marine fuel is becoming more viable in the quest for a cleaner, more sustainable fuel mix in shipping, and it is providing the experience needed to build tougher marine fuel regulations. It is produced from natural gas has been shown to minimize NOx and SOx emissions, and shipping can significantly cut its greenhouse gas emissions by creating methanol from renewable sources. So far, 12 methanol-powered ships have been put into service, with another ten on the way. Its availability is being significantly scaled up in terms of infrastructure, onboard applications, and installations, according to research.

Methanol can be created from a range of renewable sources, such as biomass or electrolysis powered by renewable energy and assisted by carbon capture technology, because natural gas is the major feedstock in methanol synthesis. As a result, methanol is a strong contender for a future in which ships is powered entirely by renewable fuels.

Either production process, when blended into conventional methanol in increasing proportions, might lower the carbon footprint of its usage as a marine fuel by a significant amount.

Methanol is attracting more interest from owners of oceangoing vessels, shortsea carriers, ferries, cruise ships, and inland canal vessels due to its capacity to cut CO2 emissions and comply with IMO2020 rules.

There is also the expertise of the offshore support vessel and platform supply vessel fleets handling methanol for the offshore industry, which can be used as reference points for wider use of methanol as a bunker fuel. Methanol is a widely traded commodity with a global distribution network that might be used to assist maritime fuel bunkering with ease. The liquid nature of methanol gives it an advantage over other gas fuels, allowing existing infrastructure to be repurposed to incorporate engines and vessels with simple retrofits.

At room temperature and pressure, methanol is a colorless liquid with a distinctive unpleasant odor. It boasts the highest hydrogen-to-carbon ratio of any liquid fuel, a ratio that could reduce CO_2 emissions from combustion when compared to traditional fuel oils. This alternative energy resource, when utilized as a primary fuel, can cut CO_2 emissions by roughly 10%. Methanol, on the other hand, has the potential to be a carbon-neutral fuel in the future provided it is generated sustainably using biomass/biogas or renewable power.

The liquid nature of methanol gives it an advantage over other gas fuels, allowing existing infrastructure to be repurposed to incorporate engines and vessels with simple retrofits.

Installing LNG tanks is more difficult than retrofitting a vessel's tanks from conventional fuel oil, ballast, or slop to contain liquid methanol fuel. Methanol is also much easier and less expensive to store on board than gas. Methanol's low energy content is one of its drawbacks as an alternative fuel. It has a specific energy of 19,700 kJ/kg, which is significantly lower than LNG and other liquid fuels. Methanol takes 2.54 times the storage volume of conventional fuels for the same energy content, making it less appealing for use by smaller ships. To store enough energy for longer deep sea travel, using fuels like methanol would necessitate major redesign, such as bigger fuel tanks.

Methanol has a lower environmental impact than traditional hydrocarbon fuels since it dissolves well in water and only very high concentrations cause deadly circumstances or any change in local marine life. Methanol is abundant in the ocean, where it is naturally created by phytoplankton and rapidly digested by bacteria microorganisms, allowing it to enter and support the food chain. [58]

1.7 AMMONIA

Ammonia is a nitrogen-hydrogen chemical with the formula NH_3. It has half the energy density of bunker fuels and becomes liquid at -33 degrees Celsius, so it doesn't need to be stored in high-pressure or cryogenic tanks. Because ammonia is difficult to burn, specialized internal combustion engines are being developed now and will be available in 2024. Green and blue hydrogen are promising feedstocks for zero-carbon ammonia bunkering onshore and offshore before being combusted by onboard engines. [60]

Currently, the fertiliser sector consumes 80% of all ammonia produced. However, as the maritime industry is under pressure to decarbonize and move away from dependency on fossil fuels, ammonia is emerging as a viable option. If 30% of the world's shipping shifted to ammonia as a fuel, current production would have to roughly treble. Up-scaling offers hurdles, but there is an even greater one for ammonia production to be carbon free, which will come at a cost; however, this also presents a chance for both industries to decrease their carbon footprint and collaborate.

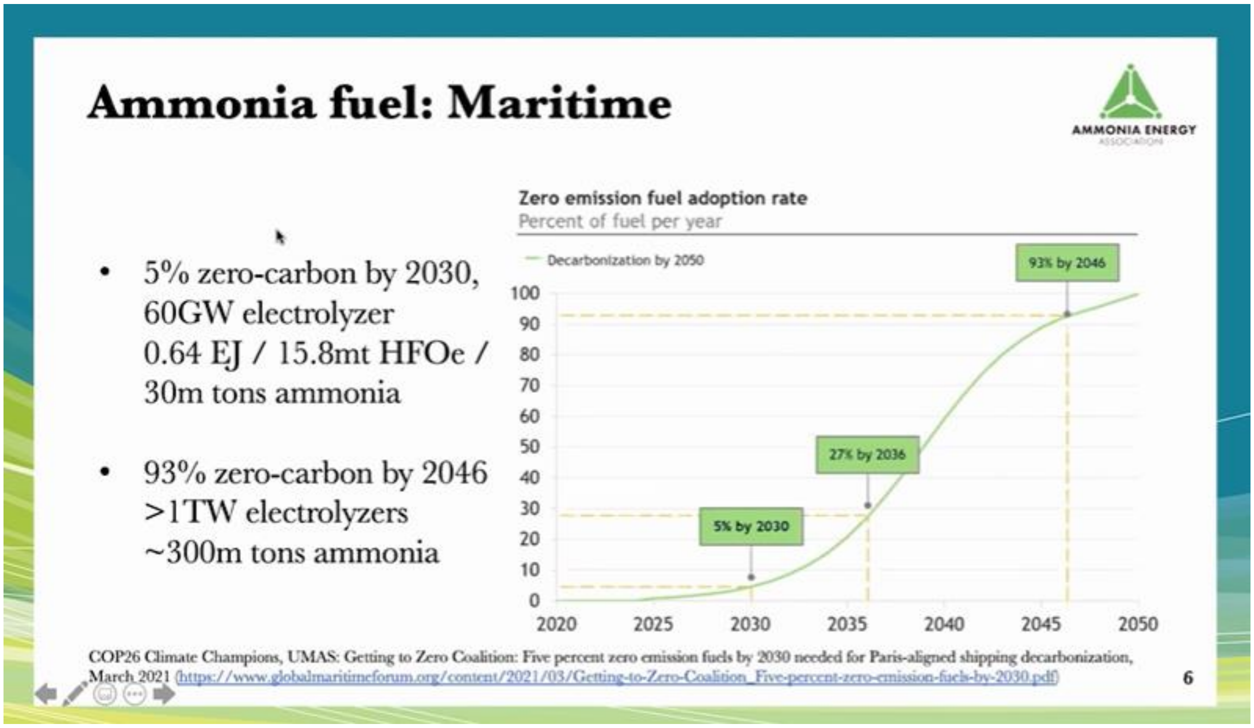

Figure 7. Zero emission fuel adaption rate

Governments have set ambitious greenhouse gas (GHG) reduction targets for the coming decades. Every industry, including shipping, will be impacted as we transition from fossil fuels to renewable energy. Targets are being turned into regulations by regulators like the International Maritime Organization (IMO) and the European Union. As carbon dioxide (CO2) regulation becomes more stringent, it is evident that no one fuel will be able to meet all of shipping's zero-carbon requirements. Shipowners will equip ships with the fuel that is best suited to the ship's kind, route, and cargo in the future. [60]

Ammonia will very certainly always be generated where energy is abundant and costs are cheap. With the new renewable energy environment, new ammonia facilities can be built in regions where fossil feedstock was not possible. This means that ammonia can be generated in new areas with abundant renewable energy sources, such as Australia's solar and wind resources and Iceland's geothermal and wind resources. The overall economics of these green ammonia factories will be heavily influenced by the capacity factor. If a combination of renewables can bring capacity close to 100%, some places will benefit.

This alternative source of fuel is a good hydrogen carrier and a good energy storage medium. Depending on tank capacity, it can be compressed and stored as a liquid in either atmospheric or pressurized tanks. The tank pressure is approaching atmosphere and the temperature is -33°C when stored in huge quantities over 10,000 tons. The tank pressure is a few bar in quantities between 100 and 1,000 tons, while the temperature is still around 0°C. Ammonia is commonly stored at ambient temperature and up to 20bar in tanks with capacities less than 100 tons. Ammonia has been recognized as a carbon-free fuel that can also serve as a good energy storage medium. It has a 12.7MJ/l energy density. [61]

The high volumetric energy density of contemporary fossil-based fuels is one of their main selling points. Most alternative fuels can't compete, which means they'd take up valuable cargo room onboard a ship. Because ammonia's volumetric energy density is similar to that of methanol and higher than that of hydrogen, onboard storage is viable, albeit not as compact as today's heavy fuel oil (HFO).

In addition, ammonia was selected as one of the top three fuels with potential for 2050 in a recent poll of shipping sector stakeholders conducted by Lloyd's List - the marine journal – and LR. According to the survey, ammonia usage is expected to increase to 7% of gasoline by 2030 and 20% by 2050. Ammonia is also a key component of various national decarbonization plans. Japan, for example, intends to increase ammonia fuel consumption to three million tonnes per year by 2030. We examine the potential of ammonia as a transportation fuel, focusing on how it could cut or eliminate CO2 emissions, the primary greenhouse gas linked with fossil fuels. [60]

1.8 ELECTRIC POWER

1.8.1 ELECTRIC-HYBRID SHIPS

Electric propulsion is the method of propulsion in which the ship's axles move directly (or less frequently via gearboxes) from electric motors, as opposed to diesel, gas turbines, or steam turbines. Numerous ship applications with varying speed profiles, such as supply vessels, manufacturing vessels, drilling ships, tankers, icebreakers, battleships, and cruise ships, can benefit from electrical propulsion systems. In general, electric propulsion may show to be the optimal option for the following application categories:

a. Vessels with significant propulsion needs (eg. drilling vessels).

c. Vessels with powerful auxiliary equipment.

c. Vessels with significant variations in propulsion power.

d. Vessels having numerous high-speed, non-reversible engines.

f. Submarines in general.

Diesel engines, gas turbines, and steam turbines are still present in propulsion systems, but instead of directly moving the propeller axle system, they move electric generators, which have the effect to power the electric propulsion motors, which are referred to as "prime movers" in the literature. The propulsion installation augmented with a control system for its operation, i.e. the reservation-start, the modulation of speed, and the change in rotational direction of electric motors.

In the late 19th century, Russia and Germany conducted experimental electrical applications for propulsion in which the electric propulsion engine was directly powered by battery packs. Passenger ship firms began utilizing the first generation of electric propulsion around 1920 as a result of intense competition for a reduction in transatlantic trip performance. The large ships' propulsion power requirements were then met by turbine-electric systems.

Figure 8. The S/S Normandie utilized an electric propulsion system and was the first ship to cross the Atlantic Ocean at speeds over 30 knots.

Modern electric motors were powered by steam generators, and the frequency of the generators determined the rotational speed. In normal operation, the generators powered each propulsion engine separately; but, for lower speed travel, two engines might be powered by a single generator. The arrival of diesel engines in the middle of the 20th century heralded the end of steam turbine technology and electric propulsion, at least until the 1980s.

With the evolution of power electronics technology and notably electric motor driving systems, electric propulsion systems have returned. The second generation of electric propulsion utilized rectifiers (E.R. / S.R.) for the control of propulsion machines S.R., circa 1970, and ER/ER converters for engine control in 1980. The propulsion system is currently powered by a robust network with continuous voltage and frequency. By controlling the speed of fixed motors, fixed-pitch propellers are regulated (FPP).

Although these solutions were initially applied to specific types of ships such as research vessels and icebreakers, since 1975 they have been applied to cruise ships, tankers, etc. (Queen Elizabeth II, Fantasy, Princess). In diesel propulsion with direct drive, the thrust is controlled by a hydraulic system that varies the pitch of the propellers. These are referred to as controllable pitch propellers (CPPs). Since the 1990s, the introduction of azimuth propellers (Figure 9) has been a highly successful innovation, providing ships with more maneuverability, easier transit through areas of high mobility, and the potential of dynamic placement positioning (DP).

Figure 9. Azimuth propeller of the icebreaker "Vitus Bering."

Based on this, the electric motor is installed within a submerged outer blade pod with a very short propeller shaft, or the propeller is directly attached to the engine (Figure 10). The outer sheath may be rotated 360 degrees freely, providing the ship with agility and movement, while the propeller is fixed in place. Exterior housings replace traditional rudders, and the boat's overall hydrodynamic performance improves.

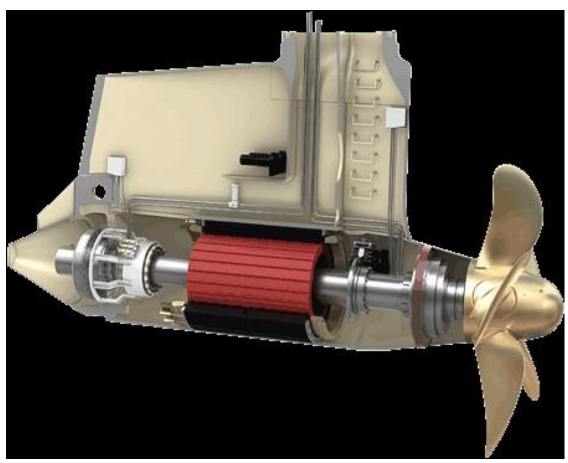

Figure 10. Azimuth thrusting system (interior)

Particularly when it comes to warships, electric propulsion is the most common option for submarine operation. To exploit the potential benefits of electric propulsion, additional subsystem research and refinement are necessary due to the increased requirements and stricter specifications of navies compared to merchant ships (in terms of space limits and propulsion system requirements).

Electric propellers can be engineered for extremely high efficiency over their whole speed and power range, unlike conventional diesel engines, which have a clearly defined performance peak around their normal point of operation. A ship with variable speed will be able to run with great efficiency across its operational range by selecting the best number of generators to meet the intended power demand. For a traditional diesel propulsion system, usage outside of its nominal mode will significantly reduce its efficiency.

It should also be mentioned that the selection of a ship's propulsion system allows for greater flexibility in the design and selection of subsystems, as well as their propulsion and electrical installation layouts. In any event, it is important to note that electric engines are the sole viable option for auxiliary propulsion (i.e., the side propulsion system mechanisms that improve the propulsion capability of ships, especially in ports) by deploying mostly high-power induction motors (0.5-2.5 MW).

1.8.2 COLD IRONING

As previously mentioned, ship-related emissions are not distributed evenly, but are instead concentrated along coastlines and waterways. A ship's stay at the berth and afterwards in the port can be as long as the duration of the voyage. Numerous studies imply that each trip can be separated into three distinct phases. The separation is determined by the ship's operation in the given circumstance. The three specific categories are a) sailing, b) handling, and c) mooring. The distinction is a result of the differences in fuel consumption and gaseous emission composition exhibited by each condition. Due to their proximity to the mainland, the final two scenarios are emphasized because they have direct effects on the population. The ships are stationary, and when they are stationary in open waters, they emit gaseous pollution. This is due to the requirement for both the production of power and steam for various on-board uses.

The terms COLD-IRONING and Shore-to-Ship power supply are virtually equivalent. This deactivation of all internal combustion engines of the vessel gave the procedure the name "cold" since, in addition to eliminating its emissions, it lowers the boat's temperature. During the ship's stay in port, an offshore energy source is given to meet the ship's power needs:

- Loading and Unloading
- Supply
- Lighting
- Air-Conditioning
- Heating
- Additional shipboard electronic systems

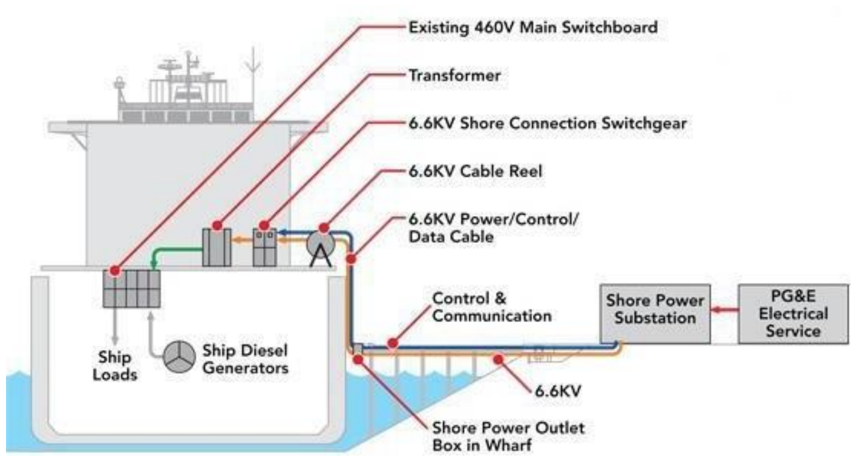

Figure 11. A presentation of an installation for the land-based energy supply of the ship. source: APL GGC Cold-Ironing Project

The ships are constructed with the electrical components necessary to receive power from a terrestrial power plant. Essentially, the ship's primary power supply system is linked to the land system via the power plant - panel located in the ship's accommodation, typically on the Main Deck. It is primarily utilized for the ship's tanking when it comes to the ship's provisioning. The inability to cool the generators during the tanking time prevents them from operating and generating power.

Adopting such a procedure has a major positive impact on ports and ships alike. Turning off the ship's generators is equivalent to achieving zero emissions. This factor and the fact that onshore power plants do not need to be near to the port are sufficient to improve the surrounding environment.

During anchoring in the port, 90% reductions in CO_2, SO_4, NO_x, and PM emissions are possible. On the contrary, the overall emissions rely on the energy mix of the country's electricity generation. If it is based on energy sources such as lignite, then the port's pollution emissions are reduced as they are transferred to the location where electricity is generated. In contrast, if energy production relies on alternative energy sources such as photovoltaics, wind turbines, and hydropower, then overall emissions are lowered. Additionally, land-based energy helps lessen port noise.

The process is now automated because it is routine. It is remarkable that there is a unique mechanism that discloses the socket, as well as a rope that passes through the socket and a winch that raises the hefty cable and makes the connection. [62], [63]

Figure 12. Connecting the ship to the ground network using an automated procedure.

1.8.3 BATTERY-SUPPLIED ELECTRICITY

The Zerocat and the Ar Vag Tredan are examples of battery-powered ships. The first, owned by Siemens and the winner of the 2014 SMM Ship of the Year award, is a newly constructed ferry that can carry up to 120 automobiles and up to 360 passengers for short (20-minute) excursions utilizing lithium-ion batteries that require only 10 minutes to recharge. The catamaran Zerocat was commissioned in 2015 and operates off the west coast of Norway, where the batteries are recharged by renewable energy from a hydroelectric facility. With this energy source, as with the other ones, there is no pollution at all, as the ship is propelled solely by batteries that will be charged in specific ports. Since fuel is free, the usage of batteries considerably cuts the ship's running expenses. However, it is probable that the ship will not be able to go long distances, as is the case with oil-powered vessels, because the batteries will need to be recharged at the nearest port, which should have the necessary infrastructure. As a result, this type of marketing will provide the impetus for ports to install battery charging ports, so enhancing the economic and social life of the port and creating employment opportunities for human potential. [64]

1.9 WIND POWER

Wind energy is the energy derived through the use of the wind. It makes a significant contribution to the solution of the electricity generation problem. Wind itself is formed as a result of the temperature changes in the airflow that creates barometric differences. If the temperature in two consecutive places is not the same, the colder region's air pressure will be greater than the hottest, causing a gaseous mass to move from the colder to the hottest zone. Wind energy is used for a variety of purposes, including generation of power and water pumping. The machines in question are wind turbines, which are mostly utilized in wind farms.

It is a gentle form of energy that falls under the category of "clean sources," or those that do not emit or produce pollution. There are no greenhouse gases or other pollutants released, and the environmental impact is minimal when compared to traditional power plants. Wind energy is currently the most inexpensive of all the mild energy sources available. It provides energy independence and security to small and developing countries by serving as an alternative to oil. The equipment is simple to manufacture and maintain and has a long life cycle, enhancing energy independence and security. Depending on the weather, wind energy can be used on ships with varied degrees of efficiency.

Sails dominated the high seas prior to the invention of the steam engines, enabling relatively small ships with considerable crews. The main source of early ships relied on the usage of wind energy via sails from antiquity until two centuries ago. In any case, wind is a well-understood, widely available, although with some variations, renewable energy source.

Sailing boats are still used today, but primarily for recreational purposes. When you consider that there are ships with a total weight of 250,000 DWT, such as ULCC tankers (Ultra Large Crude Carrier), it's easy to see why sailing isn't a viable option. In addition to size restrictions and high-speed requirements, modern commercial vessels are unable to deploy sails due to ergonomic concerns. They have, nevertheless, made numerous attempts to integrate and employ sails on cargo ships.

Current initiatives include the adoption of a variety of renewable energy technologies, aimed at a variety of ship types ranging from tiny to major freight carriers, as both main and auxiliary propulsion machines. Soft sails, static sails, rotors, kite sails, and wind turbines are all examples of wind-powered propulsion. It's also important to make sure that onshore wind installations don't interfere with the ship's operations.

1.9.1 SOFT SAILS

Despite the fact that sails were originally the only means of propulsion, they are still considered an intriguing manner of supplementing power. Traditional soft sails are an established, proven technology that can directly exploit the wind's propelling force. Traditional sails, on the other hand, impose bending moments on the boat, resulting in the ship tilting. Extra endurance concerns may need reaching the tissue to the keel, and the existence of tissue and connection may have a substantial impact on cargo management.

Technological advancements in the super yacht and racing yacht industries can be applied into industrial application. Sails can be employed as a primary or auxiliary propulsion system, and they can be retrofitted into existing ships or integrated into new building designs. In optimum weather conditions, fuel savings from employing sails can reach 15% at 15 mph and 44% at 10 knots. [65] Dykstra / Fair Greenheart, B9 Shipping, and Ecoliner Transport are the market leaders (Figure 13).

Figure 13. From left to right. (top) 1. Dykstra / Fair Transport Ecoliner, 2. Seagate Delta Wing Sails, 3. Greenheart, 4. B9 Shipping, (bottom)

The last two designs use Dyna-Rig systems (which have been successfully used on the Maltese Falcon super yacht) that function and operate automatically from the deck, making it easier to take advantage of the wind, keeping crew sizes similar to fossil fuel vessels, and allowing cargo loading and unloading to become easier. The cargo ship Greenheart is a more traditional design. Seagate, an inventive Italian business, has designed folding deltoid wing sails that can be retrofitted to existing ships (Ro-Ro, container ships, car carriers). There are also a variety of kit designs that can be employed on small-scale trucks and catamarans for local use, particularly on islands, or as auxiliary propulsion systems on a wide range of existing small-scale conventional motor boats.

1.9.2 SOLID SAILS

Solid Sails, which are effectively stiff "wings" in a rotating mast, have a fin-shaped design that provides more thrust with less resistance than traditional sails. Fuel savings of up to 21% for tankers, 8.5% for ferries, and 20% for cargo ships (PCTC) can be gained by utilizing these sails. [66] The initial Japanese attempts in the 1980s offered several types of fixed sails. Walker Wingsail, which was erected at 6500 dwt Ashington in 1986, is one of them. The testing at the time did not reveal significant savings in resources, and several technological challenges to this technique have yet to be solved. Figure 14 also shows the 16,000 dwt tanker Shin Aitoku Maru and the 26,000 dwt bulk / log transport Usuki Pioneer, both from that period. [67]

Figure 14. 16,000 dwt tanker Shin Aitoku Maru (top) and 26,000 dwt bulk / log carrier Usuki Pioneer (bottom)

The Danish Ministry of Environment and Energy funded a study in 1995 by a consultant from the Company Naval Architects and Marine Engineers that examined the potential for commercial ships using sails to aid them. Thus, between 1995 and 1999, a plan for a merchant ship of 200 meters and 50,000 tons, dubbed "Modern Windship," was produced, the image of which is given below.

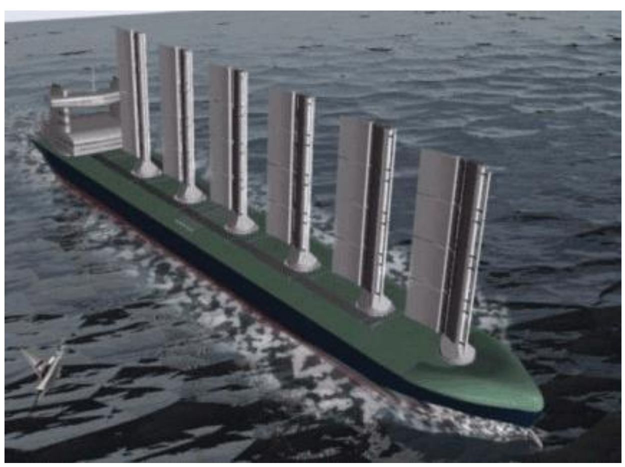

Figure 15. Modern Windship

The usage of sails found to be typically uneconomical on standard product delivery routes, according to the study's findings. When compared to ordinary ships, commerce ships of the same size, have an increased cost of around 10%. The findings revealed that simply lowering a traditional ship's waist speed by one knot, a 25% reduction in fuel usage can be accomplished. On days with more air, though, adding sail equipment might save an additional three tonnes of fuel per 24 hours. This equates to 10% - 15% of total gasoline use.

Sail Log, a German business, looked into using 20,000 m2 sails on a 50,000 dwt Panamax bulker. The company chose traditional square sails because it is well known that they can perform well. Long bulk freight routes (where quick service is not required) have been recognized by Sail Log as being better suited for use as sails for assistance or even full utilization. According to the business, the operational costs of a bulk cargo ship equipped with an autonomous sail assist system might be 22% lower than those of a ship powered by diesel. It should be noted, however, that the figures vary greatly depending on the source.

Large ships (e.g., the UT Wind Challenger and the EffShip project, which use rigid sails and telescoping masts) are among the current suggestions. Oceanfoil, a British firm, has investigated the use of wing sails and has a new patent for a redesigned and better concept that has been available for purchase since early 2015. Figure 16 depicts the above-mentioned examples of how this technology can be used.

Figure 16. Solid sails. Left UT Wind Challenge, right Oceanfoil

The racing yacht and boat industry have adapted promising new commercial designs pioneered by Propelwind. To power port ferries, OCIUS Technology Ltd, an Australian business, employs floating sails paired with solar panels. OCIUS has just patented a new type of static sail that can fold to accommodate different wind conditions. This technology, according to the business, will be applicable on current ships of all sizes. The Norwegian LadeAS with The Vindskip's original design is a hybrid merchant ship with a primary propulsion engine that runs on LNG and an aerodynamic hull that works as a huge sail.

1.9.3 ROTORS

Flettner rotors, also known as motors, are vertically revolving rotors mounted on the ship that transform wind energy into propulsion in a direction perpendicular to the wind, utilizing the Magnus Phenomenon, which occurs when air flows over a rotating roller. This means that the ship will benefit from the additional boost, resulting in lower fuel use. An average fuel savings of 1,023 tons per year has been projected for a Supramax truck (55,000 tonnes dwt) fitted with a system of four wind engines (with a rotor height of 20 meters and a rotor diameter of 2.3 meters) that spends 246 days at sea every year. Other types of ships, each day and per rotor of the same size, have similar reduction possibilities. [68]

It was originally confirmed on a variety of ships in the 1920s, including the 3000 dwt Barbara. Until the early 1980s, when legendary oceanographer Capt. Jacques Cousteau and his team unveiled the Turbosail in the investigation of their yacht Alcyone, this technology had been mostly overlooked. The conclusions of a rigorous investigation of 75 energy-powered platform winds, supported by considerable testing, were released in 1985 by an American business called Windship Corporation, indicating that the rotors had by far the largest development dynamics.

Enercon began testing the 12800 dwt E-Ship 1 in 2010, which had four Flettner rotors powered by exhaust from the main conventional engine. Despite the fact that much of the deck surface is used, bulkers and VLCC class tankers are being actively evaluated for conversion. Flettner-type rotors are now used in recent prototype designs. Figure 17 depicts ships with Flettner rotors as auxiliary propulsion.

Figure 17. Ships using Flettner rotors. On the left, Cousteau's Alcione and E-Ship 1 on the right.

1.9.4 KITE SAILS

The towing kite (figure 18) is a new wind energy technology that is tied to the ship's bow with a cable and can be adjusted to an appropriate height to maximize the usage of strong winds at sea. The masts and sails of a container take up a lot of room on the deck. Because the containers cranes must maneuver around the masts, loading and unloading is more challenging. To limit storage loss, the corporations have developed taller towers, some of which are over 100 meters tall. However, the Panama Canal limits mast heights at 60 meters, and collapsible tissues are expensive to manufacture, operate, and maintain. The expense of equipping a merchant ship with a variety of masts as well as strengthening the hull and deck, is believed to be over 10 million euros. As a result, it will take at least 15 years to recoup the initial investment.

The goal of using a kite tow is to lessen or eliminate the aforementioned concerns while taking advantage of the strongest winds available at higher altitudes (up to 300m) than the sails can reach due to the lack of resistance from the sea and land surfaces. The "aerial sails" take up no deck space, need minimal adaptation, may be stowed under bridges and retracted when not in use, and can be retrofitted onto existing ships. They can be removed for repair and then reinstalled on another ship. The installation can be done at a yard or in any port with the right equipment and cranes. During installation, which takes one to two weeks, the ship can stay in the water.

When compared to standard wind propulsion systems, this technology produces much more propulsive energy per square meter. This is due to the ship's technical capabilities resulting from the ship's spatial separation from the aerial sail that tows it. The aforesaid factors lower their equipment sails' initial capital and running expenses while enhancing energy efficiency. A towing kite on the bow of a ship, like a traditional sail and mast, reduces the inclination of the ship caused by heavy winds. However, the above technologies should only be used as a supplement and should never be utilized to replace large ships' propulsion and power generation systems.

With the help of a telescopic web, the towing kite may be lifted and folded. This enables the eagle to grow swiftly and effectively to the appropriate height and position in regard to the wind, allowing the ship to reach the fastest potential speed. The entire process of growing and folding the eagle takes around 15-20 minutes. The Eagle can only lift and act correctly when the wind is strong enough; otherwise, it will not be able to operate well and provide the ship with the necessary propulsion. Because the fabric is synthetic, it is wind and rain resistant.

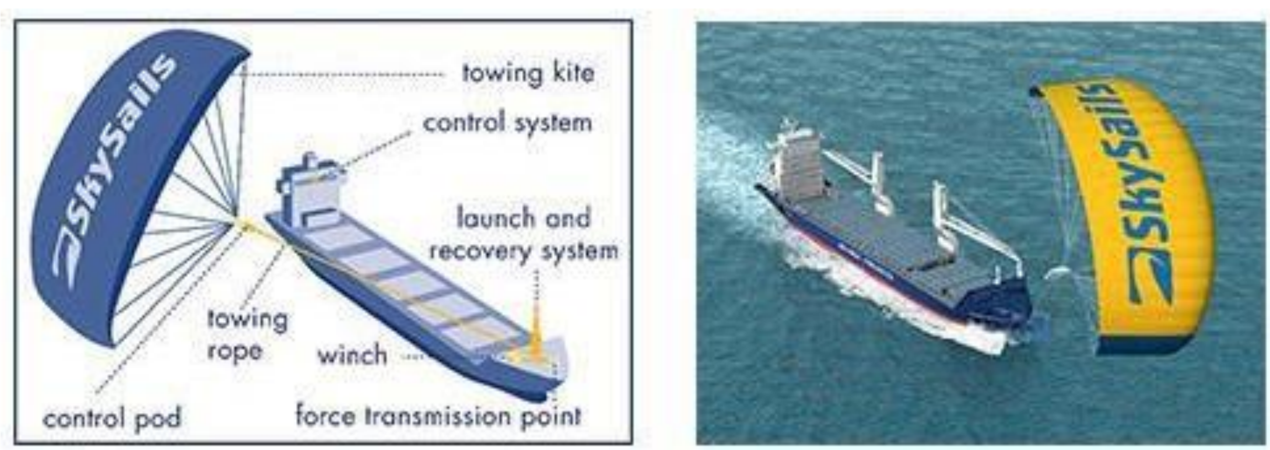

Figure 18. Typical example of a towing kite

Towing kites differ from other wind energy ideas in that they leave a minimal footprint during installation, making the conversion process very simple. Installing a towing kite on an existing ship is not difficult or expensive, but it does require complex launch, recovery, and control systems. A control panel on the bridge makes it simple to run the system. The operation of launching and hoisting is semi-automatic, requiring only a few actions from the deck bow crew. [69]

Kites aboard ships can reduce energy usage by 10-35% each ship, depending on the route and wind conditions. The power a kite can produce is determined by its surface. A 160-square-meter kite surface equals 600 kW, whereas a 5,000-square-meter kite surface equals 19,200 kW. The maximum length of a ship on which a kite can be mounted is 30 meters. The investment cost varies depending on the surface, with operational costs accounting for 5-15% of the total.

For more than a decade, a tiny group of forward-thinking corporations has backed this technology. MS Beluga Skysails, with a surface area of 160 square meters, was the world's first commercial container ship to be partially powered by a kite-type sail in 2008. With the use of eagles, the construction business "SKAYSAILS" can reduce fuel consumption by 50% on excellent days, with an annual reduction of 10% to 15%, while the eagle will provide 5 to 25 times more power per square ordinary cloth thanks to "dynamic moves."

MV Beluga was launched in Hamburg at the end of 2007 by the German business Beluga Fleet Management GmbH, a subsidiary of Beluga Shipping GmbH of the Beluga Group. On January 22, 2008, the expedition began from Bremen, Germany, to Guanta, Venezuela. The ship was carrying cargo for DHL, a sponsor of the effort. At the same time, the US Naval Naval Command revealed that Beluga Skysails had been contracted to bring supplies, the troops, and cargo from three European ports to the US.

Figure 19. MS Beluga Skysails

Anbros Maritime, a Greek firm, has also taken steps in this regard. One of them is

Cargill. The world's top food producers and distributors have agreed to work with Hellenic Shipping Company Anbros Maritime S.A. to install the world's largest kite on the dry cargo ship "Agia Marina." Typically, the "Agia Marina" transports agricultural and industrial raw materials. The 170 meter long transport ship, which can carry roughly 28,500 tons of dry goods and was built in 1994, is the world's largest ship to utilise SkySails GmbH's wind energy technology (SkySails).

Cargill said in February 2010 that it has established a supply agreement with SkySails, a company that intends to cut greenhouse gas emissions in the shipping industry by using wind energy technology. The arrangement stipulates that a 320O 320 sq.m. eagle will be installed on the ship "Agia Marina." Cargill's long-term charter company "Agia Marina" will use the SkySails technology for the next five years. SkySail will be in charge of training the crew of the "Agia Marina" in the use of the eagle propulsion system. The towing eagle SkySails will be attached to the ship and will soar in an octagonal pattern between 100 and 420 meters above the water. It's a system that's operated by an autonomous pod to make the most of the wind's benefits.

1.9.5 WIND TURBINES

The use of wind turbines for ship propulsion has been discussed for several years. There have been no successful prototypes of their execution so far. This is due to systemic concerns with their final stability and vibrations, as well as their fundamental inadequacies in energy conversion compared to alternative technologies. Wind turbines have the advantage of continuing to create energy even while the boat is going against the wind. Wind turbines could, in some cases, succeed as power producers for auxiliaries ship systems or offshore power generation by substituting the production of electricity from non-renewable sources. There are likely to be substantial lessons to be learned in the realm of shipping, given the huge developments in wind turbine technology for energy generation.

1.9.6 AIR LUBRICATION

A recess in the lowest half of the hull receives compressed air. By lowering the friction resistance between the water and the hull surface, the necessary propulsive force is reduced. Fuel savings of up to 15% for tankers, 7.5% for container vessels, 3.5% for ferries, and up to 8.5% for cargo ships can be achieved with this strategy. [70]

1.10 WAVE POWER

When the wind blows across the water's surface, waves form. Wave energy converters are devices that capture the energy from waves and convert it to electricity. Various methods are employed. Some of the devices are submerged, while others are moored to the ocean floor. Another method is to direct the waves into a tight channel, where they will drive a turbine.

When compared to other renewable energy sources such as wind, solar, biomass, and geothermal, waves have the highest energy density. According to academics at the University of Plymouth, waves have the greatest potential to contribute to the world's "energy mix resilience." The problem is that, in comparison to other renewable technologies, wave energy is still in its infancy.

Ocean energy systems are being developed in a number of nations. To encourage this, policies are being implemented. In Australia, for example, a national Offshore Electricity Infrastructure Bill was approved by the government in 2021. This establishes a policy framework for the development and operation of offshore energy projects.

Islands are expected to play a crucial role in the development of ocean energy technology in the European Union as part of an Offshore Renewable Energy Strategy.

Wave energy was initially created in the United Kingdom in the 1970s, and there are currently active projects in Scotland, England, and Wales. Since its inception in 2014, Wave Energy Scotland, a national technological development agency sponsored by the Scottish government, has invested more than $52 million (£40 million) in nearly 100 initiatives. CorPower Ocean, a wave energy firm based in Stockholm, claims to have created the world's largest wave energy test rig.

Wave energy has a variety of specialist applications that are paving the way for larger utility-scale projects. Wave energy can be used to power oil and gas platforms, marine farming, distant islands, naval bases, oceanography services, and luxury resorts, among other things.

Due to limited availability of fossil fuels, renewable energy sources such as wave energy are becoming more important.

A number of reasons are driving up oil, gas, and coal prices, resulting in a worldwide energy crisis. Demand for energy has risen as the world recovers from COVID-19, but supplies have dwindled. Lower coal production in China, poor oil production investment in the United States, and decreased gas production in Europe are all contributing factors. There have been worldwide transportation constraints as well. Now, fears of supply interruption are driving oil prices to new highs as a result of the fighting in Ukraine.

Against this setting, wave energy's dependability is a major selling point. While wind and solar energy are inherently unreliable, waves are consistent and store more energy than other renewables. [71]

Wave energy units are expected to become an entirely new design idea in order to meet the needs of the transportation sector, according to current plans. A small number of producers in this industry are attempting to learn from biology and duplicate the muscular energy of dolphins and pelagic fish in maritime environments. The ambitious E/S Orcelle car transport company Wallenius Wilhelmsen Logistics (WWL) has developed a series of 23 submarine flaps, inspired by the movements of Irrawaddy dolphins' tails, to harness and convert wave energy into the ocean and generate propulsion as well as electricity and hydraulic energy to power ship systems. The ship will also use solar sails, which are a combination of wind and solar energy and which we shall see later, as well as fuel cells, in addition to wave energy. [70], [72], [73]

Figure 20. E/S Orcelle

2. ENVIRONMENTAL EFFECTS

As previously indicated in this paper, climate change and strict pollution rules in many countries need fuel and engine professionals to investigate sustainable fuels and alternate sources of energy for internal combustion engines. Recently, it has been predicted that global energy demand is increasing on a daily basis. The growing use of energy produces a considerable amount of greenhouse gases (GHGs) from the consumption of petroleum products, which eventually leads to an increase in global temperature, resulting in climate change. Currently, diesel is mostly used as a petroleum derivative in the industrial and transportation sectors. Researchers and environmentalists all over the world are concerned about how to eliminate this massive amount of energy consumption while also reducing carbon dioxide (CO2) emissions, which is one of the most significant components of GHGs. [73], [74]

Other fuel sources may be a more sustainable alternative to traditional fuels in this regard. Engine tuning and the proper use of LNG, for example, can significantly increase framework production while lowering greenhouse gas (GHG) emissions, which is extremely beneficial to a reasonable course of events and leads to sustainable development. In addition, some key current studies are being undertaken in order to find the technology's drawbacks, progress, and future examination potential. Vessels use fuel oil through diesel engines, and heavy fuel oil (HFO) is commonly used as a marine fuel oil since it is less expensive than other fuel oils such as marine gas oil (MGO).

According to the IMO's 2020 standards [75], this gasoline, with an average sulfur level of 0.1 percent, is a compliant fuel. Air pollution and contamination from marine shipping, on the other hand, is a growing environmental concern, and HFO has considerable sulfur oxide (SOx) and nitrogen oxide (NOx) emissions [76]. Heavy Fuel Oil (HFO, with an average sulphur content of 2.8%), which has the lowest price but is the most detrimental to the environment and produces the most pollutants when compared to the other fuels, is the most commonly utilized by vessels. Scrubbers are now required for vessels that use HFO. As a result, their total capital and operating costs increased [77].

2.1 IMPACT ON THE GREENHOUSE EFFECT AND GREENHOUSE GASES

Industrialization expands in tandem with the human population over time. This has the cumulative impact of raising atmospheric emissions and the greenhouse gas concentrations in the atmosphere. The result of increased emissions is an imbalance between greenhouse gas releases from natural sources and their removal from so-called "sinks," which in the pre-industrial era maintained a steady atmospheric concentration. A further issue as a result of human-caused gas emissions is the increase in infrared radiation that is trapped in the atmosphere, leading to the greenhouse effect and a rise in global temperature.

The onset of the phenomenon includes the considerable destruction of rainforests, which are known to absorb carbon dioxide and create oxygen through photosynthesis, as well as regulate water vapor in the atmosphere, so impacting the equilibrium of greenhouse gases. In addition, the current way of life, which includes a rise in economic activity, energy consumption, and technological advancement, contributes to the growth in emissions.

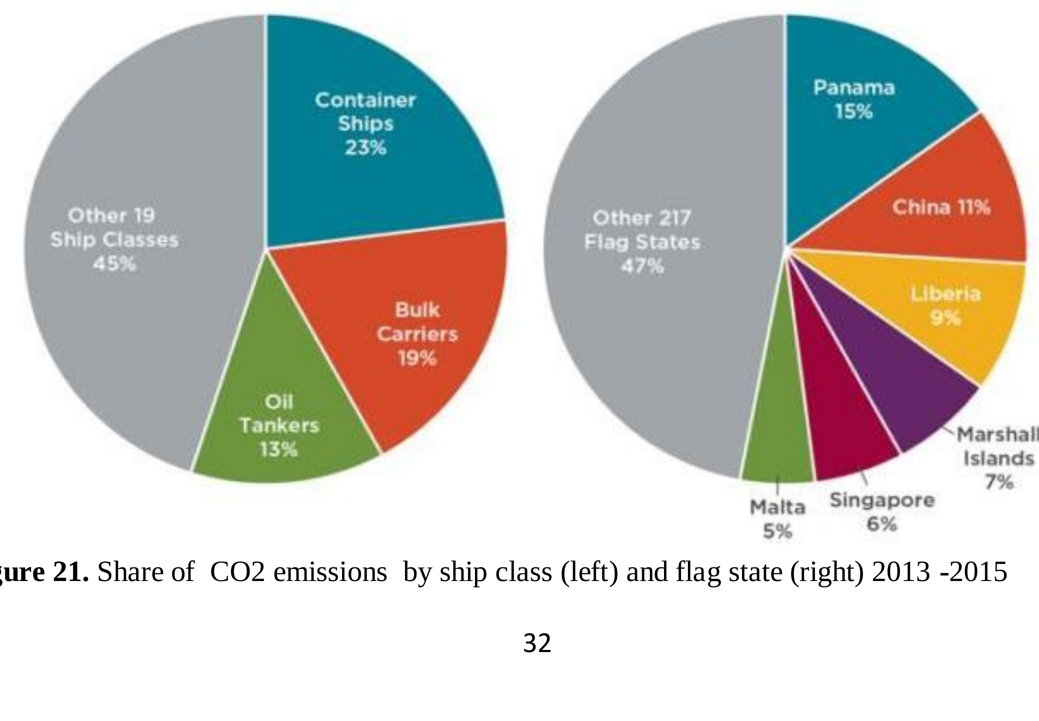

Figure 21. Share of CO2 emissions by ship class (left) and flag state (right) 2013 -2015

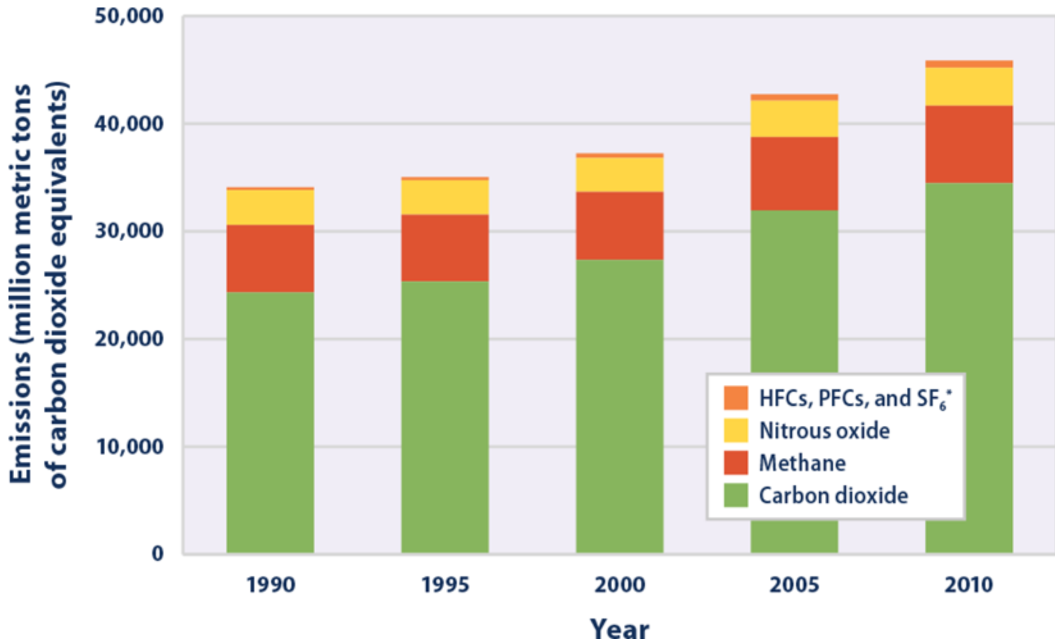

Figure 22. Increase Greenhouse gas emissions

The concentration of gases in the atmosphere is not viewed as unchanged, and they are unaffected by human activity. Therefore, the concentrations of gases affected by human activities will be analyzed. The principal greenhouse gas is water vapor (H2O), which contributes 66% to the occurrence or 85-95% if clouds containing diverse kinds of water are included. Carbon dioxide (CO2), methane (CH3), nitrous oxide (N2O), ozone (O3), and fluorinated gases are included in addition to water vapor (H2O). These gases can be produced either by humans or by natural processes. The level of impact that gases have on the temperature of the earth is dependent on their lifetime and their ability to absorb energy. Scientists calculate the potential contribution of a gas to the greenhouse effect (Global Warming Potential - GWP, which estimates how much a given mass of a greenhouse gas is anticipated to contribute to global warming over a period of time (e.g. 100 years) based on the preceding information. Compared to carbon dioxide, which has a global warming potential of 1, global warming potential values are calculated relative to other gases. [78]

2.1.1 CARBON DIOXIDE (CO2)

Carbon dioxide (CO2) is produced by natural sources such as animal respiration, the process of photosynthesis in plants, the decomposition of organic matter, volcanoes, and the dissolution of carbonate rocks, as well as by anthropogenic activities such as the burning of minerals (oil, coal, natural gas), solid waste, and forestry products, which emit CO2 directly into the atmosphere, as well as by indirect practices such as the conversion of forest land into arable land. The contribution of carbon dioxide to the greenhouse effect is projected to be 76%, with 65% coming from fossil fuels and industrial processes and 11% from forestry and other land uses, according to statistics from the Intergovernmental Panel on Climate Change (2014).

CO2 absorbers include land and ocean atmosphere exchanges, orption that is largely countered by anthropogenic emissions. If not for the foregoing natural "absorbers," CO2 levels in the atmosphere would be substantially higher. Since the gas is not lost over time, but rather flows between different parts of the land system's atmosphere, its lifetime cannot be represented just by a price. Some of the excessive amounts of carbon dioxide are immediately assimilated from the ocean surface, while others will persist in the atmosphere for thousands of years due to the extremely glacial transfer of carbon to ocean sediments. [79]

Carbon dioxide is the primary exhaust gas produced by the combustion of fossil fuels. By far the most significant greenhouse gas emitted by ships. Ships emit roughly 1 Gt of CO2 into the atmosphere each year, accounting for about 2% to 3% of worldwide CO2 emissions. It is a radiative forcing agent in all of itself, and it has the greatest overall global warming impact of all shipping emissions (see Figure 23). It is also the most crucial sort of emission for two additional reasons: its longevity and the fact that its production - by burning fossil fuels - is what powers ships and thus is at the heart of the entire system. [80]

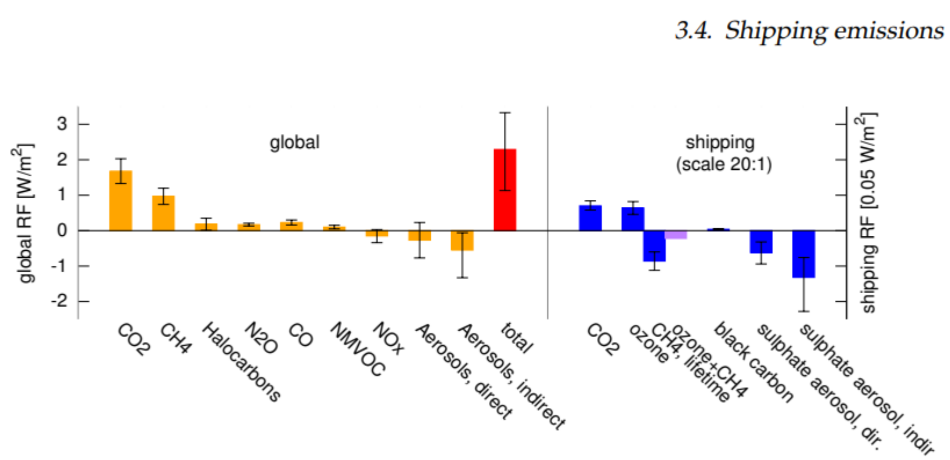

Figure 23. Radiative forcing from various emissions on a worldwide level, as well as total radiative forcing, are shown on the left hand side of the graph in 2011 since pre-industrial times. The right-hand side depicts radiative forcing from shipping emissions since pre-industrial times in 2000. Shipping emissions include CO2, black carbon, and sulphate (through SOx). The influence of ozone on the lifetime of CH4 is caused by a variety of pollutants, the most important of which is NOx. Take note of the scale difference. IPCC data on the world (2013). Fuglestvedt et al., Fuglestvedt e (2008).

2.1.2 METHANE (CH3)

With a 16% contribution to the greenhouse effect, methane is the second most important gas after carbon dioxide. It comes from both natural and anthropogenic sources, with natural sources such as wetlands (swamps, lakes) being the most abundant. Its most basic component is natural gas, which humans use as a source of energy since it is flammable and efficient. Methane absorbs 23 to 27 times more radiation than carbon dioxide, but it exists in lower concentrations in the atmosphere and has a shorter life span. [81]

CH4 is created in nature mostly by bacterial decomposition of organic matter (anaerobic decay), but also through biological processes such as those found in ruminants' digestive systems. Oceans, termites, and geological sources are examples of natural resources (hydrates, geothermal methane, volcanoes). Nonetheless, human activities contribute for 60% of worldwide methane emissions, according to the US EPA, and include fossil fuel extraction and incineration, rice growing, livestock farming and animal management fertilizers, biomass incineration, and waste disposal landfill. Methane is released into the atmosphere for about 8.4 years until it is absorbed primarily through chemical oxidation in the troposphere or even uptake from the soil, where biological oxidation occurs, and subsequently destroyed in the stratosphere. [82]

The amount of methane released by shipping is negligible. As low-sulphur regulations tighten, liquefied methane, or liquefied natural gas (LNG), may become a more appealing low-sulphur fuel choice, and methane slip may become a problem. According to Fuglestvedt, shipping emitted 30 kt of methane in 2000. [83] According to the 2nd IMO GHG assessment, shipping emits 70 kt of methane in 2000 and 100 kt in 2007. The amount is less than 0.01% of the relevant CO2 emissions in each case, and the influence of methane emitted by ships is minimal. In fact, the most significant influence of shipping on methane levels is indirect, as sulphur, black carbon, and other species diminish the amount of time methane spends in the atmosphere. [84]

2.1.3 NITROGEN OXIDE (N2O)

Because it is a greenhouse and soil gas, nitric oxide impacts up to 6% of the greenhouse effect as well as the physico-chemistry of the atmosphere. It can absorb infrared radiation roughly 270 times more than carbon dioxide and is found in lesser quantities in the atmosphere. The nitrogen cycle, which is the natural circulation of nitrogen between the atmosphere, plants, animals, and microbes living in soil and water, releases N2O into the atmosphere through natural sources. It is mostly formed when microbes in water, soil, and oceans degrade the substances contained within. The main supply of nitrogen is soil, particularly in the tropics north of the equator. [81] Nitrogen fertilizers in the soil, animal feces, their processing waste and sewage, biomass and fossil fuel combustion, and certain nitrogen-based industrial processes, such as plastic manufacturing, are all responsible for the emission of N2O. Human activities, primarily crops, account for nearly a third of all nitrogen oxide emissions into the atmosphere. Because of their disintegration in the stratosphere, where most of them are destroyed by sunlight into harmless nitrogen and oxygen molecules, nitrogen remains in the atmosphere for around 114 years before being removed. [85]

One of the biggest producers of nitrogen oxides is shipping. It is created when fossil fuels are burned. Emissions are difficult to determine from the amount of fuel consumed since their production rate is dependent on the exact conditions under which combustion occurs. The relative production rate of diesel engines, in particular, changes with the operating point. In 2007, NO2 emissions from shipping were estimated to be 25 Mt, according to the 2nd IMO GHG study. [84] According to Fuglestvedt shipping emitted 14.4 Mt of NO2 in 2000, accounting for 11% of global NOx emissions. According to Eyring et al. (2010), shipping accounts for 15% of global 2Ox emissions. NOx, like SO2, is a pollutant in its own right, with negative health consequences. Under MARPOL Annex VI, which went into effect in 2005, newbuild ships are subject to NO2 management regulations. NO2 has two significant radiative forcing effects: it shortens the lifetime of methane in the atmosphere and acts as a precursor to tropospheric ozone. Both effects cancel each other out to a great extent (see Figure 19), and both effects fade over periods far shorter than the atmospheric CO2 equilibration duration. [83]

2.1.4 SULFUR DIOXIDE

Marine bunker fuels have a high sulfur concentration, with certain types of heavy fuel oil (HFO) containing up to 4,5% sulfur. Sulphur reacts with oxygen during the combustion process and is discharged into the atmosphere via the exhaust, where it forms sulphate aerosols. Their light-reflecting properties cause a negative radiative forcing, and they also cause a negative radiative forcing indirectly by acting as condensation nuclei in clouds. [86], [87], [88] The amount of sulfur emitted by ships is determined by the sulfur content of the fuel and the amount of fuel used. To give you an idea, around 320 Mt of fuel is responsible for 1 Gt of CO2 emissions from shipping. Using a 2% sulfur content as a baseline, annual sulfur emissions from shipping would be 6.4 Mt. (or 12.8 Mt of SO2). Other studies may differ slightly in the expected amount of fuel burned or average sulfur content of the fuel, but this basic calculation is in line with them: The 2nd IMO GHG study estimates 7.5 Mt of sulfur emissions in 2007, assuming a slightly higher average sulfur content [84], [89], [90]; Corbett and Kohler estimate 6.5 Mt of sulfur in 2001, in broad agreement with various other studies cited there in; Endresen [91] estimate 3.3 Mt of sulfur from shipping in 2001 - as their assumed fuel consumption. According to Eyring [88], shipping accounts for 4 to 9% of worldwide sulfur emissions.

It's challenging to model the atmospheric sulfur cycle and the radiative forcing effect of sulfur emissions over time. The negative forcing effect is enormous, and it has the potential to disguise a significant amount of global warming caused by increased greenhouse gas concentrations in the atmosphere. However, the accompanying uncertainty is significant as well. [92] Unfortunately, NASA's Glory satellite, which was designed to explore the effects of sulphate and other aerosols in the atmosphere, failed to launch and was lost on March 4, 2011.

The climate forcing from sulfur emissions from shipping, which they estimate as 4.1 Mt in 2000, is examined by Fuglestvedt. [80] They calculate a direct radiative forcing effect from sulphate aerosol due to shipping of -31 mW/m2 (with an uncertainty range of -47 mW/m2 to -16 mW/m2), with an uncertainty range of -47 mW/m2 to -16 mW/m2. As illustrated in Figure 19, the indirect effect is -66 mW/m2 (with an uncertainty range of -114 mW/m2 to -38 mW/m2).

Lund [93] investigate how simple climate models respond to alternative representations of shipping aerosol in terms of temperature. The indirect radiative forcing effect is nearly an order of magnitude higher than Fuglestvedt results for varied initial sizes and geographical distributions of sulphate aerosol. [80] This emphasizes the ambiguity around the cooling effect of sulfur emissions from ships, making it a worthwhile research issue in and of itself. The radiative forcing effect of sulphate aerosol is short-lived compared to CO2 [83]; however, because sulfur is a pollutant that causes acid rain and harms human health, there is a regulation in place to reduce the sulfur content of shipping fuels to 0.5% from 2020 or 2025 onwards. Rather than sulfur, CO2 emissions are the most critical and pressing concern.

2.1.5 TROPOSPHERIC OZONE (O3)

Natural processes produce ozone in the stratosphere, which accounts for around 90% of the total ozone in the earth's atmosphere. When limit values are surpassed, the remaining 10% of ozone is found in the troposphere, the lowest layer of the atmosphere, and is classified as air pollution associated with periods of photochemical clouds in and around metropolitan areas, with severe effects on human health and the environment. The stratospheric ozone layer is essential for life on Earth because it works as a filter, keeping damaging UV light from reaching the surface. O3 has a direct effect on the greenhouse effect because it is a greenhouse gas, but it also has an indirect effect on other greenhouse gases. Tropospheric ozone is a hysterogenic pollutant that is produced by a series of chemical reactions involving oxygen (O2), volatile organic compounds (VOCs), and nitrogen oxides (NOx) in the presence of sun radiation. Vehicles, chemical facilities, chemical solvents, and petrol stations are all anthropogenic sources of ozone (VOCs and NOx) emissions. When compared to other greenhouse gases, tropospheric ozone is resistant to a few days to weeks of exposure, and its concentrations vary greatly depending on the availability of precursors such as water vapor and solar radiation. Another potentially detrimental aspect of O3 is its effect on plant physiology and carbon dioxide absorption. If the foregoing process occurs, we will see an increase in the release of carbon dioxide into the atmosphere, affecting the radiation balance and the indirect effect of ozone, which comes from sources other than direct emissions (Katsafados & Mavromatidis, 2015). [85]

In the presence of NOx, CH4, CO, and NMHCs operate as ozone precursors in the atmosphere, producing radicals that eventually lead to ozone formation [93] and hence have an indirect impact on climate. Since preindustrial times, transportation has contributed to 31% of total man-made O3 forcing, according to Fuglestvedt. [80]

2.1.6 FLUORINATED GASES (HFCs, PFCs, NF3, SF6)

These gases are exclusively the result of human activity and are emitted into the atmosphere through a variety of industrial operations, such as the fabrication of semiconductors and aluminum. Obviously, the scientific and technical revolution of the 20th century led to the protracted and widespread usage of halogen-containing gases manufactured from chemicals. Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3) are the four primary kinds. In addition, there are halocarbons, which include chlorofluorocarbons such as CFC-11 and CFC-12, which were widely used as refrigerants in refrigerators and air conditioning systems, in various sprays as propellants, and for other industrial applications, before it was discovered that their release into the atmosphere causes stratospheric ozone depletion and their use was banned.

The majority of the gases listed above have a high heating potential (Global Warming Potential (GWP)) relative to other greenhouse gases, and can therefore have a significant impact on global temperature in small quantities. It is remarkable that perfluorocarbons (PFCs), in particular, have a longevity in the atmosphere that can exceed thousands of years. Clearly, the life span of chlorofluorocarbons (CFCs) in the atmosphere varies from 45 to 100 years, hydrochlorofluorocarbons (HCFCs) from 1 to 18 years, and hydrofluorocarbons (HFCs) from 1 to 270 years.

The estimated 2% mixing of these gases is mostly a result of the policies adopted under the 1987 Montreal Protocol on chemicals that destroy the ozone layer. By 2030, it is anticipated that the quantities of Hydrochlorofluorocarbons (HCFCs) would have decreased progressively. The use of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) as substitutes for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) continues to increase the concentration of HFCs and PFCs in the atmosphere, which is a result of the Kyoto Protocol. [85]

<u>2.2</u> <u>CLIMATE CHANGE</u>

In 1992, the United Nations conducted the World Conference on Environment and Development in Rio de Janeiro, Brazil, with the participation of political power officials, non-governmental organizations, and scientific bodies to discuss the environment in combination with development. Prior to 1990, the Intergovernmental Panel on Climate Change (IPCC) issued its first formal evaluation report, concluding that 400 scientists agreed that global warming was serious and needed to be addressed. This meeting resulted in the creation of two legally binding conventions: the Convention on Biological

Diversity and the Framework Convention on Climate Change. These two agreements established the legal framework for two of the most critical environmental issues of our day, biodiversity loss and the greenhouse effect, on a global basis.

The United Nations Framework Convention on Climate Change (UNFCCC) has 197 parties, making it the most widespread environmental pact. It entered into force in 1994. The Convention attempts to "establish" a limit so as not to surpass the atmospheric concentration of greenhouse gases and to prevent harmful human interference with the climate system. In addition, this limit should be reached within a sufficient amount of time so that ecosystems may adapt naturally to climate change, food production is not jeopardized, and economic growth can proceed in a sustainable manner (UNFCCC). The Convention established a general framework recognizing the principles on which States were to base future decisions to address climate change, such as the principle of sustainable development, the principle of prevention, the "polluter pays" principle, and the principle of joint but differentiated responsibility. After the Contract, for purposes of oversight, the Conference of the Parties (the COP) was established, bringing together representatives of all states that have ratified the pact. Nonetheless, this Convention was a general agreement that led to the December 1997 signing of the Protocol with the same name in Kyoto, Japan, which was now legally obligatory.

Following the UNFCCC framework, the Kyoto Protocol aimed to reduce or stabilize emissions targets for developed countries and some former Eastern bloc countries on the basis of shared but differentiated responsibility, as these countries are historically responsible for rising levels of greenhouse gases in the atmosphere, but still have the ability to reduce them. These goals attempt to reduce the overall emissions of six greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) by 5.2% relative to 1990 levels, with the reduction occurring between 2008 and 2012. In addition to the foregoing, compliance with these pledges is now a legal requirement, and countries must create policies and actions to reduce emissions and report on them.

In February 2005, the Kyoto Protocol was fully implemented after extensive negotiations and a number of technical and regulatory conferences on compliance concerns, financial measures, and flexible procedures. Notably, in addition to the greenhouse gases listed in Annex A' of the Protocol, the regulated sources and sectors are also listed.
Sources include energy, industry, agriculture, garbage, and solvents.

Due to the transnational nature of shipping and aviation, the Kyoto Protocol includes procedures that exclude them from the aggregate national inventory statistics. Finally, it is suggested that industrialized nations should strive to minimize their greenhouse gas emissions by shipping and air transport in collaboration with the IMO (International Maritime Organization) and ICAO (International Civil Aviation Organization), the relevant UN bodies for shipping and air transport. [95]

In terms of shipping's impact to climate change, the Third IMO GHG Study (2014) projected that between 2007 and 2012, shipping emitted roughly 1,000 Mt CO2, or about 3.1 percent of annual world CO2 emissions. According to the most recent update to the CE Delft study, assuming other sectors successfully decarbonize, shipping emissions could grow by up to 120 percent by 2050. In a business-as-usual scenario, shipping might account for 10% of global GHG emissions by 2050, assuming other sectors of the economy reduce emissions to keep global warming below 2 degrees Celsius.

Shipping also contributes to climate change by emitting Black Carbon, which is made up of small black particles created by the combustion of marine fuel. Ships burning heavy fuel oil produce the highest amounts of black carbon particles. After carbon dioxide, black carbon accounts for 21% of CO2-equivalent emissions from ships, making it the second most important driver of shipping's climate consequences. There are currently no laws in place to regulate black carbon emissions from shipping. [96]

The negotiations for a legally enforceable worldwide agreement on climate change continued throughout the 20th century, and the first phase of the Kyoto Protocol would conclude with no other plan for its continuation. The catalyst was the concentration of nations responsible for eighty% of global greenhouse gas emissions. At the 2009 Copenhagen Summit, it was agreed that carbon dioxide emissions must be decreased to prevent a 2 degree Celsius global temperature rise by 2050. However, neither reduction targets nor a monitoring system were agreed upon, and negotiations persisted.

The "Paris Agreement" refers to marine pollution from land-based sources; it is one of the oldest conventions aimed at safeguarding the oceans from land-based pollution; and it serves as the foundation for future agreements. Even though this source of pollution is the most prevalent statistically, there is no international convention that specifically targets it. The "Geneva Convention on the Law of the Sea (1958)" is global but only applies to underwater facilities and lacks precise restrictions, whereas "The Paris Convention" is limited to the North Sea and Northeast Atlantic. This could be explained by the unwillingness of developing nations to limit their economic expansion. There is also the Helsinki Convention for the Baltic Sea and the Barcelona Convention (Third Protocol) for the Mediterranean Sea. [97]

The question of who is responsible for the resulting emissions emerges as delegates fly and equipment is shipped to another climate summit in Bonn. The prevailing opinion is that they are covered by the two UN bodies that were established to regulate these sectors, the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO). This might have made sense three years ago. The Kyoto Protocol, which tasked developed countries to work through ICAO and IMO to limit emissions until the Paris agreement was finalized at the end of 2015, was the principal climate agreement in force.

It is known, however, that the Paris Agreement changed everything. Unlike the Kyoto Protocol, which set specified emission objectives for wealthy countries alone, the Paris

Agreement expects all parties to address all emissions. Parties must set 'economy-wide' carbon reduction targets, as stated in the agreement. Few would deny that shipping and aviation play an important role in our economies.

The final agreement states unequivocally that all emissions would be regulated, although it is unclear what action this will entail for shipping and aviation. The Paris Agreement has clearly put ICAO and IMO in the spotlight like never before, and efforts are being increased. In May 2018, the ICAO agreed to develop an offsetting mechanism for some emissions beginning in the 2020s, while the IMO committed to a long-term target of cutting emissions by at least 50% by 2050 while pursuing full decarbonization initiatives. The judgment is yet out on whether the ICAO agreement will benefit the environment and the IMO's commitment will only be tested once it agrees on immediate steps. [98]

The International Maritime Organization (IMO) approved a draft greenhouse gas strategy for shipping in April 2018, urging the shipping industry to reduce emissions by at least 50% by 2050 compared to 2008, while pursuing measures to phase them out as soon as practicable. It was agreed that the carbon intensity of international shipping should decrease with reductions in CO_2 emissions per transport work of at least 40% by 2030, with a goal of 70% by 2050, compared to 2008.

This will be accomplished by a set of agreed-upon short, medium, and long-term policies that are now being negotiated. Strengthening the energy efficiency criteria for existing ships (EEDI), speed, and other technical and operational initiatives are among the proposed short-term measures. CE Delft examined the impact of proposed short-term solutions on emissions and concluded that the 2030 objective can only be attained if operating habits (for example, vessel speed) are changed. Technical solutions or efforts to remove market obstacles alone will not be enough to reach the worldwide objective of reducing shipping's energy intensity by 40% by 2030.

Despite these plans and numerous rounds of negotiations, the IMO has yet to approve reduction measures that would put the maritime sector on a path that is compatible with the Paris Agreement's temperature goals. [96]

2.3 ENERGY EFFICIENCY MANAGEMENT

In recent years, shipping companies have had to contend with escalating costs and the prevailing energy crisis. As a result, they have turned to the formulation of various energy management regulations and the optimization of their energy efficiency in an effort to reduce the emission of harmful gases that contribute to the greenhouse effect. With energy management systems, shipping businesses can minimize their energy usage (where feasible) and increase their energy efficiency. Study of the International Maritime Agency (IMO) has revealed that a reduction in harmful gas emissions can be achieved by 20-50%. According to the European Union, Member States should reduce energy consumption by 40-50% between 2005 and 2050, with shipping companies in particular minimizing carbon dioxide (CO2) emissions.

The International Organization for Standardization (ISO) established the energy management standard ISO 50001 in 2011, based on which corporations can clarify their energy impact and implement conservation programs according to their needs, with the goal of lowering their energy footprint. The goal of the above standard is to enhance, define, execute, and sustain energy management by using a systematic method to optimize energy efficiency and use, as well as consumption.

According to surveys undertaken by maritime industries, energy efficiency can be managed to lower construction costs. Still, in the shipping sector, approaches for optimal energy efficiency, as well as financial efficiency, can be utilized throughout their lives, as well as at various organizational levels. However, due to the costly installation of special equipment, the particular technical characteristics of alternative fuels or energy sources, meant for newly built ships.

For a long time, shipping corporations have used it to reduce slow steaming in order to reduce their fuel expenses. Typically, the ship's speed corresponds to the current fuel price. However, in the case of ships built with the goal of being efficient at specified speeds, some technical limits are imposed. Fuel consumption is lowered up to the "energy efficient speed" limit, and fuel is spent per transport unit below this limit.

An effective tool in energy management, could be ship route planning, which involves determining short sea routes with the participation of weather conditions throughout the above procedure, which can save between 0.1-4%. Apply more correctly to longer trips for the best benefits.

Reducing the vessel's speed during the duration of its journey, can be considered as another strategy for regulating energy efficiency. The reduction in port stay time can result in fuel savings of 2-8%.

2.3.1 EEDI & EEOI

The International Maritime Organization (IMO) imposed energy efficiency rules on international shipping in July 2011, with the decision MEPC.203, which is the first global energy efficiency model applied to industry. Furthermore, it is the first legally binding resolution taken by the Kyoto Protocol, and it refers to GHG (Greenhouse Gas) emissions management and the first worldwide regulation of their reduction, for global industry.

The revised changes to MARPOL Annex VI, which became effective on January 1, 2013, added a new chapter called "Regulations on energy efficiency for ships" to the decision MEPC.203. It's called EEDI (Energy Efficiency Design Index), and it's used on new ships of 400 GT and more. It determines the lower energy efficiency limit for each kind and size of ship in terms of work consumed, such as CO_2 emissions per tonne-mile. The EEOI (Energy Efficiency Operational Indicator), on the other hand, is an optional indicator that is used to control operational energy efficiency. [99], [100], [101], [102], [103]

The numerator of EEDI is a component of all power generated by the vessel (main engine and auxiliaries), while the denominator is a result of the vessel's deadweight (or payload) and the vessel's "reference speed", which is defined as the speed compared to 75% of MCR, the main engine's maximum force. EEDI is measured in grams of CO_2 per ton mile. The EEDI of a new-building vessel should be compared to the "EEDI (reference line)," which is defined as EEDI (reference line) = aDWT-c, where DWT is the extra weight of the vessel and a and c are positive coefficients determined by relapse from the world fleet database, per major vessel category [104].

The obtained EEDI value for a specific vessel should be equal to or less than the required EEDI value, as determined by the equation below.

$$\text{Achieved EEDI} \leq \text{Required EEDI} = (1-X/100)\ aDWT^{-c} \quad (1)$$

where X is a "decrease factor" determined for the required EEDI in comparison to the EEDI Reference line (The values of X specified by the IMO are 0% for ships built between 2013 and 2015, 10% for ships built between 2016 and 2020, 20% for ships built between 2020 and 2025, and 30% for ships built between 2025 and 2030). This means that in the next years, being EEDI compliant will be more difficult). After a lengthy discussion inside the IMO, regression analysis was used to finalize the reference line bounds a and c in (1). It's worth noting that Ro/Ro vessels are currently omitted from EEDI due to a lack of suitable regression coefficients for this kind of vessel.

Because the left-hand side of inequality (1) is a polynomial function of the designed speed and the right-hand side is speed-independent, EEDI compliance effectively imposes a restriction on a vessel's design speed. While the true goal of EEDI is to build boats with better hulls, machinery, and propellers in order to be more energy efficient, a simple approach could be to reduce design speed and, as a result, installed power. This could have a significant impact on the health and safety of ships. It could also have an impact on total CO_2 emissions, as an underpowered vessel would consume more fuel and, as a result, generate more CO_2 at the same exact speed, especially if it tries to keep up with speed in adverse weather [106].

Regardless of the effect on ship speeds, EEDI, as a design index, will only influence speeds at the strategic level and will miss the impact of slow steaming. EEDI basically ignores freight rate and bunker price variations across a vessel's life cycle in this way.

Indeed, if the market is down, an EEDI-compliant vessel has little incentive to slow down, and an underpowered vessel will spend more fuel when urged to speed up during boom market conditions.

EEOI, or "Energy Efficiency Operational Indicator," is comparable to EEDI. EEOI employs a similar equation to EEDI, with the exception that all factors are assigned to their functional rather than configuration values. This would entail using the actual cargo of the vessel rather than the deadweight, as well as the actual operational speed rather than the design speed. The IMO's Ship Energy Efficiency Management Plan (SEEMP), which was also established in July 2011, anticipates the use of EEOI. Despite the fact that the logic of using a particularly valuable file can be demonstrated, reservations about EEOI's use have been expressed. These have been widely voiced on the basis of pragmatic execution; however, if EEOI inadvertently imposes a functional speed limit during boom periods, this is also a big concern. Significant distortions and expenses may result if this is the case. A market-based policy, such as a fee, would appear to be a more efficient way to encourage slow steaming and reduce emissions, and the models established here may be used to evaluate the impact of such a measure.

After a period of time, all newly constructed vessels joining the fleet will meet the relevant design efficiency standards (EEDI) for the given vessel type and size. These are currently known and will become more burdensome within a defined timeframe (in all situations 10%, 20% and 30% improvement by 2015, 2020 and 2025 separately).

The standards only specify a minimal compliance prerequisite. Regardless, fuel change (to reduce carbon factor), plan speed reduction, or innovations may result in an EEDI that is lower than required, which is also advantageous at the specified time-step. In this instance, this is selected as the vessel's specifications.

Consequently, the EEDI pattern of new-build ships may increase over time, for example if a specific cost, market, and regulation environment in a later time-step identifies a profit-maximizing solution that complies with the minimal EEDI guideline but results in a higher emission level that will not indicate lack of compliance (EEDI will still be equivalent to the regulatory level).

It must be noted that the EEDI boundary is merely a means to stress the development of the fleet's technical specifications. The real energy demand and emissions of the fleet are a consequence of functional parameters, and as the functional speed departs entirely from the design speed, EEDI will become progressively inaccurate (this is regularly seen in the scenario results, with older and less technology advanced vessels operating at lower speeds to remain competitive in an environment of higher fuel prices).

It would be excellent if we attempted to foresee the unpredictable and intricate relationships between transport demand, speed, EEDI and fuel, innovative technologies, and machinery combinations. [107]

3. FINANCIAL EFFECTS

The commercial viability of alternative fuels will be a key factor in deciding their level of deployment, in addition to the life-cycle environmental implications examined in this paper. Despite the fact that the role and degree of renewable energy adoption by shipping vary depending on the size, purpose, and operating area of each ship, the technology providers contend that efforts in research and innovation in the use of renewable energy sources, combined with efficient designs/studies, have already achieved remarkable results for immediate or short-term energy savings in a number of selected applications. This section performs a cost analysis of the chosen alternative fuels across various fuel production methods. The total capital investment costs for the alternative fuel-based systems are also calculated by adding the costs of onboard fuel storage systems and construction/purchase propulsion systems.

The cost of transport LNG has always been a crucial factor when determining the breakeven economics of a new LNG project or determining the optimal destination for a single shipment of LNG. Such shipping cost estimations are frequently relied on current short-term charter rate information released by the analytic teams of specialized price reporting agencies or other such entities. [108]

Costs associated with LNG production, liquefaction, logistics, and bunkering mean that prices will vary depending on location. There will be a comparison for supporting factors. The price of LNG is less expensive than HFO when the lower heating value (LHV) of fuels is taken into account. The fundamental premise underlying the fuel price forecast is that prices will continue to rise as a result of anticipated increases in the cost of producing oil and gas. In 2013, the cost of fuel is approximately 15–16 USD/mmBTU for HFO and 11–12 USD/mmBTU for LNG. [109] In the years to come, HFO and LNG prices are anticipated to increase in a similar manner, and by 2020, HFO and LNG prices are anticipated to reach roughly 17 and 14.7 USD/mmBTU, respectively. [110] The fuel saving cost is estimated for three different engine ratings, namely, 5000, 10,000, and 15,000 kW, based on the typical load for all diesel engines at 85% maximum continuous rating (MCR) and 8000 working hours per year. The estimates revealed average fuel saving costs of 1.32, 2.63, and 3.95 million USD/year, respectively, as shown in Figure 24. At each engine grade, this equates to a cost savings of around 31% per year.

Other expenditures, such as investment, installation, and maintenance costs, should be taken into account when analyzing the advantages of switching from HFO to LNG-fueled ships. A prior research by Wartsila Company, which evaluated the advantages of switching from HFO-fueled engines (equipped with scrubber systems) to LNG-fueled engines, estimated the initial machinery investment cost to be around 14 $/kW for both HFO-fueled engines and LNG-fueled engines. Additionally, the yearly machinery expenses for HFO- and LNG-fueled engines were 2600 and 2100 $/kW, respectively, and included annual capital, lubricating oil, maintenance, scrubber, and SCR running costs. This indicates that switching from HFO to LNG will result in further machinery cost savings of around $500/kW annually. Additionally, the longer sailing times required for ECAs, where high-quality fuel is required, would result in more financial advantages for LNG-fueled engines than HFO-fueled ones, where stricter pollution standards are in place. [111]

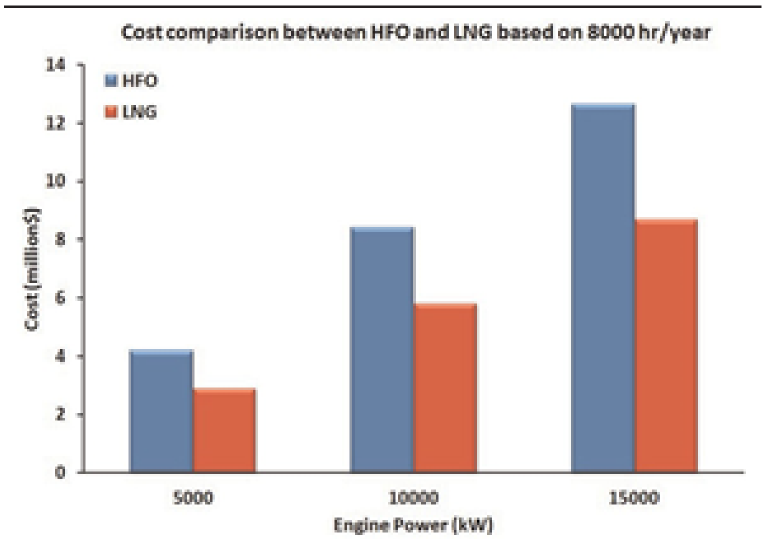

Figure 24. HFO and LNG price comparison for various engine ratings.

Another alternative fuel to be considered in CNG. The midstream transportation component, which accounts for up to 85%–90% of the required capital expenditure, is the greatest investment cost in the CNG supply chain. CNG projects are less hazardous because the majority of the investment is in ship assets that can be provided by a shipping contractor, as opposed to about 25–35% of the entire investment for LNG shipping. As opposed to an LNG project, which requires costly liquefaction and regasification facilities, less investment is needed for a project's upstream and downstream fixed end assets.

The CNG supply system is customized, modeled, and created for each unique project situation because each project has a particular set of requirements. [53]

LPG is typically less expensive than marine gas oil as a fuel (MGO). Future fuel price fluctuations can be benefited from by using our dual-fuel engine technology. Importantly, the option to employ LPG cargo as an additional fuel source allows VLGC owners or charterers to significantly cut costs, including time and fees for fuel bunkering.

Since 2011, LPG has been marketed in the USA at a lower price per unit of energy than crude oil but at a higher price than natural gas. The decreased price of LPG and the decoupling of LPG from oil prices may be ascribed to the higher yield of propane from shale gas extraction. Following 2011, the US began to export LPG instead of importing it as a result of this trend.

Normal butane is generally more expensive than propane but has a volumetric energy density that is around 10% higher. Additionally, because of the high boiling point of regular butane in outboard engines, pure butane cannot be used in colder locations. Therefore, it is projected that small boats will use propane or an LPG combination that contains a lot of propane, and that ships will utilize butane instead of LPG. [112]

Locally generated hydrogen is priced according to daily production capacity and consumption. The cost of hydrogen was calculated using a model created at IFE [113] and is shown in Fig. 25. The following assumptions were made: a local hydrogen supply sufficient for 1.5 days of usage, electricity priced at 0.3 NOK/kWh, a single dispenser for bunkering, complete electrolyser utilization, two compressors (full redundancy), a return rate of 5%, and a depreciation period of 10 years. Although investment support was not considered, it is likely that government support programs will cover a sizeable portion (i.e., 40%) of the CAPEX, lowering the cost of hydrogen. Florø is also served by a number of other long-distance, high-speed, perhaps hydrogen-powered passenger ship routes. For this analysis, a hydrogen cost of 45 NOK/kg and a consumption rate of roughly 1000 kg/day (including other consumers) were deemed reasonable for this type of "early day" operation.

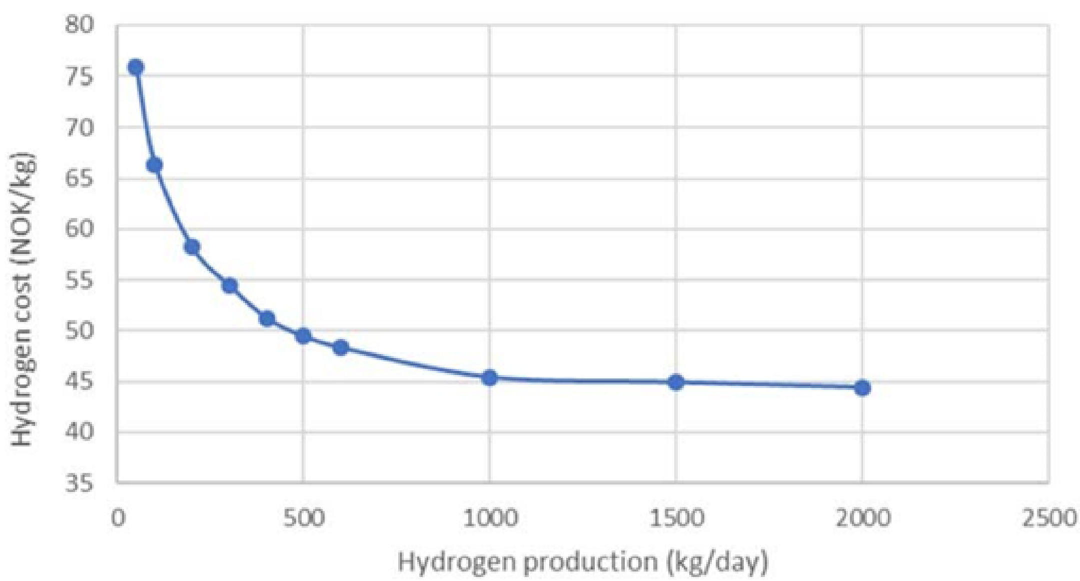

Figure 25. Hydrogen production capacity installed versus estimated cost [113].

There are a number of effective approaches to lower the price of hydrogen. Typically, a steady and significant consumption (more than 1000–2000 kg/day) is required. Government incentives may be available to reduce infrastructure CAPEX and to sell waste heat and oxygen to nearby fish farms, among other uses. Future hydrogen sales prices around 30 NOK/kg may be feasible if oxygen costs 1-2 NOK/kg. [114]

In regards to fuel cells cost, the biggest difficulty that fuel cell developers are facing is coming up with technically sound but affordable solutions. Current fuel cell systems cost 5 to 20 times as much as comparable combustion engines.

PEM (proton exchange membrane), DM (direct methanol), PA (phosphoric acid), SO (solid oxide), and MC (molten carbonate) fuel cells are the five main possibilities for fuel cells that are currently being developed. The operating temperature, which ranges from below 100°C (PEM/DM) to above 600°C (MC/SO), is one significant variation. Low temperature fuel cells have a quick startup time as its main benefit. The main drawback is the requirement for costly catalysts and clean fuel. The latter is produced either by reforming existing hydrogen carriers or by utilizing hydrogen. Although high temperature fuel cells may take a long time to start up, there are more fuel choices available because they are less susceptible to pollutants. The aforementioned traits suggest that distinct fuel cell systems appeal to varied markets in different ways. There are differences in maturity as well. High temperature fuel cells are still more in the experimental stage, which may make them more relevant for maritime transportation. [115]

The majority of fuel cell studies for marine applications take some direct economic considerations into account but focus more on technical difficulties. [116], [117], [118] Karni [119] compare two different types of (5.5 Mw) fuel cells with conventional diesel engines of a comparable size in a very in-depth cost analysis of propulsion systems for a representative ship. The research shows that a trade-off between investment expenses and operating costs will result in the best technology choice. It is concluded that fuel cells can become competitive at tolerable levels of fuel costs without discounting the fact that many parameters are unclear. Focusing on fuel cell propulsion in Norwegian ferry operations, Bingen [120] reach a similar conclusion.

More dubious than the aforementioned references, Würzig [115] emphasize that all cost estimates are merely target values. Any cost projection for the foreseeable future is highly speculative because existing fuel cells are significantly more expensive. In terms of ship propulsion, the technology has barely been tested on a scale of interest.

There is a general consensus that fuel cells will not replace traditional propulsion systems for long-distance shipping any time soon, primarily for two reasons. First, crude oil is a major source of energy for this activity. Crude oil is inexpensive and cannot be transformed with current technology. Cleaner fuels like hydrogen or methane are also unsatisfactory replacements because of their price and safety issues. Diesel is more promising, but because it contains sulfur, it could also cause technical issues and drive up expenses. Second, combustion engines perform best at loads between 70-90%, but high temperature fuel cells—the most desirable kind in this situation—perform best when operated at 20-40% of total capacity. Therefore, relying on high temperature fuel cells for efficient long-distance shipping necessitates a lot of capacity that is rarely required. Short-sea shipping is in a different scenario since there is a greater need for extra electricity to ensure harbor operations run well and owing to safety concerns.

It is obvious from the comments above that fuel cells are more practical for short-sea ships. The fact that short-sea shipping benefits more from reduced pollution levels supports this claim. Although a lot of the discussion below is general in nature, ships travelling on internal rivers, shuttle tankers, or other types of short-sea transport are likely the most applicable. Long-haul shipping may benefit from new environmental regulations, but it will be some time before a new VLCC is powered by a fuel cell system. On the other side, fuel cells might be advantageous for producing supplemental power even if they are ineffective for propulsion. For example, to lessen noise and other pollution, they might take the role of diesel generators in cruise traffic.

Modern fuel cell propulsion systems typically have investment costs between $400 to 7000 per kW, with expected prices between $100 and 1500 per kW. [121], [118], [119] In a comparison of other ship propulsion technologies, Karni [119] estimated the cost of a sample fuel cell system (5.5 Mw) to be $6500-6800 per kW. This was about three times the estimate for a CODAD (conventional diesel) system and around 50% more than the estimate for a comparable IDE (integrated diesel) system. With regard to big fuel cell installations suitable for ships, Bolind [118] is more upbeat, anticipating prices as low as $1000–1500 per kW at the end of the present decade. The variation in cost estimates, while somewhat reflecting pricing variations among different applications, primarily shows that accurate estimates are not possible at the current stage of development.

For investment cost comparisons to be meaningful, it is necessary to account for variations in predicted lifetime and deterioration over the course of the product's life. Due to contaminants in the air and fuel, fuel cells contain various parts that are prone to deterioration over time. Each time the temperature inside the cell is altered, high-temperature fuel cells deteriorate. Additionally, it could take the cells hours or even days to cool or warm up, therefore the temperature should be maintained even when the cell is dormant. This is relevant to maintenance because there may be intricate trade-offs between operating effectiveness, overhaul, and degeneration.

In terms of lifespan, the technical potential is undetermined. After about 40000 hours, the original marine MC(molten-carbonate) fuel cells may need to be changed. Typically, only the first five years of service are covered. The fuel that makes achieving such a lifetime goal the easiest is natural gas. The majority of fuel cell power systems can likely last as long as conventional engines, often 20 to 30 years [115], [117], although stack replacement expenses must be taken into account in addition to other maintenance requirements.

The potential for reducing running costs is the primary financial benefit of fuel cell power generation. Because the predicted price of various fuels typically varies in terms of efficiency, the advantages clearly depend on the fuel choice. Due to options switching, differences in price uncertainty may also be at play, such as when slow steaming is lucrative at high fuel prices.

Karni [119] found that the MC (molten-carbonate) fuel cell system used 25% less fuel than the IDE (integrated diesel) system in their comparison research. Allen [117] assert that fuel cells might, on average, cut fuel expenditures by 50% based on comparisons of various fuel cell and combustion systems.

Regarding absolute cost levels, Karni [119] calculated that the MC fuel cells' total yearly fuel expenditures would be $80 per kW compared to the IDE system's $110 cost. Based on statistics from the United States and a diesel price of $270 per ton. A life-cycle perspective indicates that the decrease in fuel prices is insufficient to make up for higher initial investment expenditures. The diesel price would need to be closer to $600 for the fuel cell to be competitive during a 25-year life cycle. The analysis by Karni shows that fuel cells may be competitive for some fair combinations of factor prices because the latter is still below the price level in several European marketplaces. [119]

According to the Methanol Institute, methanol is a fuel that doesn't require an expensive and complex cryogenic shipboard and supply infrastructure because it emits almost no sulphur oxide (SOx), very little nitrogen oxide (NOx), and very little particulate matter (PM), credentials it shares with LNG (MI).

Methanol can be stored in existing fuel storage tanks or, because of its miscibility with water, even in ballast water tanks. This lowers the investment costs associated with building or converting ships to run on methanol, according to Chris Chatterton, COO of MI.

The 51,837-gt cruise ferry Stena Germanica from Stena Line Group is an illustration of a renovated ship that transports methanol in its ballast water tanks. After converting its four main engines to a hybrid configuration that burns methanol and diesel, Stena Germanica began utilizing methanol as fuel in 2015.

Draft regulations for the safe operation of ships utilizing methanol were confirmed by the IMO's CCC5 subcommittee in September, putting them on track for formal approval by the Maritime Safety Committee of the organization.

According to MI, methanol has the potential to be a marine fuel that is future-proof and can assist the IMO meet its goal of cutting carbon dioxide (CO_2) emissions from ships in half by 2050.

According to MI, numerous mega-scale plants already manufacture methanol in a reduced carbon form using CO_2 capture technology. Several companies currently use electrolysis, gasification, or fermentation-based technologies to produce renewable, low-carbon, or low-emission methanol.

For instance, MI and Singapore's Nanyang Technological University (NTU) are collaborating to fund the first Asian pilot project to assess methanol's potential as a maritime fuel.

In the first of the two phases of the pilot study, the methanol-powered engine used in the GreenPilot assessment program in Gothenburg, Sweden, was bench- and desktop tested. The GreenPilot engine will be transported to Singapore for the second phase, where it will be installed on a harbour craft vessel and put to use within a fleet for a six-month sea trial.

The pilot project is expected to cost less than $200,000 and will include bunkering, training, and any ensuing sea trials as well as the retrofitting of a ship to be equipped with the methanol-fueled engine.

Compared to marine gas oil, methanol also offers advantages in terms of cost and efficiency (MGO). Methanol is now more expensive than Singapore MGO as a maritime fuel, costing about $350 per metric tonne (pmt). In fact, Chatterton said that because methanol does not need to be in its purest form for ship propulsion, it may be made even more affordable when diluted with a 25% water injection. Additionally, the combustion efficiency of the blended down methanol can still be 2-4 percent higher than that of MGO. Based on Waterfront Shipping's newbuild offers, building a ship powered by methanol is just slightly more expensive than building a ship powered by heavy fuel oil. [122], [123], [124], [125]

Ammonia is currently more expensive than heavy fuel oil (less than $100 USD/MT in June), and few governments impose carbon fees or offer incentives to encourage ship owners to adopt ammonia. Cost is highly dependent on the type of ammonia a ship uses. Black or conventional ammonia, which is produced using natural gas, costs approximately $250 USD/MT at present.

Blue ammonia, which combines natural gas with carbon capture and storage technology to reduce carbon emissions by two-thirds, might cost between $350 and $400 USD per metric ton. And it is anticipated that hybrid green ammonia, which is produced by adding front-end electrolysis to existing ammonia plants, will initially cost between $350-$400 USD per metric ton before reducing to $250 USD per metric ton.

Ammonia is one of the zero-emission fuel candidates that will facilitate the decarbonization of ships. Ammonia bunkering does not necessitate significant adjustments, as supplies are already accessible at certain locations. Demonstrations and pilot projects are essential, as scalability will result from cost reductions and lessons learned. Ship design and layout are affected by the need to address safety and technical concerns.

According to the Getting to Zero Coalition, regulatory instruments and market-based measures are necessary to bridge the competitiveness gap between conventional and zero-emission fuels in order to promote widespread adoption. To reach zero emissions by 2050, the current average carbon price of US$173/tonne CO2 must increase to US$100/tonne CO2 by early 2030. To grow ammonia production, investments are required, with the great majority required upstream in hydrogen generation, fuel synthesis, and port infrastructure. [126], [127]

Depending on the cell chemistry, electric battery costs, including the battery management system (BMS), have historically ranged between 550 and 1400 USD/kWh. In addition, about 160 USD/kW of power conversion hardware is included. There may be additional expenditures associated with the propulsion system and ship design compared to traditional alternatives, however this is highly case-specific and difficult to evaluate in general. Gravimetric and volumetric battery densities are extremely low. This results in batteries becoming frequently huge and heavy, necessitating a careful evaluation of each maritime application.

It is anticipated that energy density will continue to increase, a crucial component in the anticipated price reduction. In addition, short-sea applications must be carefully considered, taking the cost of batteries for a given vessel into account. Consideration must also be given to whether the battery cells would need to be replaced during the lifetime of the ship. Degradation of a battery is a function of both number of cycles and age, and it must be evaluated on an individual basis. The number of charging cycles for deep sea vessels will be relatively modest, but battery deterioration after 30 years may pose a problem. [128]

To determine the cost-effectiveness of cold-ironing, it is necessary to consider the primary parameters that influence the cost of operations with and without this operational adjustment. The primary inputs here are petroleum fuel costs. Without cold-ironing, ships in port use heavy fuel oil or diesel fuel. Using cold-ironing technology moves the expense to the purchase of power. Existing ships will be required to pay for the necessary retrofits to enable them to utilise shore-based electric power.

The initial capital cost estimates for retrofitting a container ship for cold-ironing varied between $500,000 and $700,000. Using the technique from Environ's analysis of the Port of Long Beach, this cost will be amortized over a 10-year project life using a discount rate that reflects the real interest rate of 2.4%. With ships having a lifespan of 20 to 25 years, a 10-year project duration seems reasonable. On the power side, the price of electricity in dollars per kilowatt-hour, the load factor for the auxiliary engines, the number of calls per year, and ship capacity are additional cost factors. Cost per gallon of heavy fuel oil, the fuel efficiency of auxiliary engines, and the number of operating engines are the key factors of fuel expenses. [129]

For soft sails, increased manufacture and maintenance costs of 10-15% of the total cost are anticipated in exchange for expected fuel savings of 60%, considerable reductions in engine and propeller wear, cleaner costs compliance, and a potential future emissions trading fee. Folding Delta Wing Sails are expected to save 9-19% and have a 3 to 4 year payback period, according to Seagate.

OCIUS Technology Ltd. reported 5-100% fuel savings for solid sail technology, depending on the application. The company claims that by attaching opening wing sails to a motor sail without altering the primary propulsion system of a modern tanker or truck, ship operators can expect fuel savings of 20-25% on voyages across the equator and 30-40% on trips within the same hemisphere, representing an estimated return on investment of between one and two years based on 2013 fuel prices. Oceanfoil has projected a 20% reduction in fuel consumption and a 15-18 month payback period for the new wingsail design. The University of Tokyo estimates that fuel expenses for the 60,000gt UT Wind Challenger can be reduced by one-third. 103 The EffSail, developed by the EffShip project, has been modeled to show that under certain situations, fuel savings can exceed 40%, delivering a quicker payback period than kite-type sails and the usage of Flettner rotors, based on simplified economic assumptions.

Utilizing kite sails has also resulted in fuel savings. On specific itineraries, the MS Beluga system Skysails has saved 10-15% of fuel. According to the EU-funded WINTEC project, however, the annual savings in fuel usage for the majority of routes is on the order of 5.5%. Only when the wind is blowing from the rear of the boat can propulsion-related savings be realized. [130] Recent studies within the EffShip program have predicted savings utilizing utility constant sails, rotors, and kite-type sails on a Panamax97 and compared boats with rotors and kite-type sails on transatlantic travels.
With rotor technology, the amount of fuel savings diminishes as the ship's size increases. Small ships have achieved savings of up to 60%, while VLCC (Very Large Crude Carriers) ships are reaching 19%. For instance, Enercon stated in 2013 that its prototype rotor sail ship, E-Ship 1, saved 25% after 170,000 nautical miles.

The Ulysses project focuses on ultra-slow steaming scenarios to demonstrate that the world fleet's emissions can be reduced by 80% by 2050 in comparison to 1990 baseline values if ships of the future move at 5 knots. In such a scenario, renewable energy technology may play a predominating role. [131]

Even though, wind turbine transportation needs a considerable amount of resources, for its realization, after all the labor involved, completing a wind project is its own reward. As for compensation, ATS charges between $30,000 and $40,000 per wind turbine for short-haul shipments and more than $100,000 for long-haul shipments.

In addition, a typical wind turbine will recoup its carbon footprint in less than six months and produce emission-free power for the balance of its 20 to 30-year lifespan, making it an attractive alternative fuel source for vessels. [132]

MSC Mediterranean Shipping Company has chosen to install more than 30 air lubricating systems from Silverstream Technologies on new container ships. The installations are anticipated to cut carbon emissions by 1,6,000,000 tonnes and save about €257,500,000 throughout the vessels' 25-year lifecycles. The order represents a significant percentage of MSC's newbuild pipeline, with a number of the vessels slated for deployment on the world's busiest commerce lanes between Asia and Europe.

It has been independently demonstrated that Silverstream's technique saves 5 -10% of fuel and emissions by generating a stiff carpet of air bubbles that reduces hull-to-water friction. The system is efficient in all weather conditions and supposedly has the highest utilisation rate of any air lubrication technology on the market, or the proportion of a journey for which it may be active. Additionally, it is ideal for both new construction and retrofit installations. [133]

Finally, due to the stage of development, it is difficult to determine the levelized cost of energy (LCOE) for wave energy. Recent prototype devices reveal an LCOE greater than £300 per MWh. It is difficult to precisely estimate expenses due to a lack of data, especially regarding energy production. [134]

3.1 WAR AND THE IMPACT ON THE SHIPPING INDUSTRY

The conflict in the Ukraine impedes trade and logistics in the Black Sea region and Ukraine. The rising demand for land and marine transport infrastructure and services is a direct result of the Ukrainian economy's hunt for alternative trade routes.

Numerous commodities must now be procured from farther afield by Ukraine's trading partners. This has boosted worldwide vessel demand and the price of international shipping.

The Russian Federation is a prominent exporter of oil and gas. Faced with trade restrictions and logistical obstacles, the price of oil and gas has risen as other sources of supply, frequently in more distant regions, are explored.

Increasing energy costs have contributed to a rise in marine bunker rates, which has increased transportation costs across all industries. By the end of the month of May in 2022, the global average price for very low sulphur fuel oil (VLSFO) had risen by 64% compared to the beginning of the year. Cumulatively, these cost increases imply higher prices for consumers and threaten to expand the income divide.

A sophisticated web of ports and ships that connect the world facilitates global trade. If global trade is to move more freely, it is essential that Ukrainian ports remain accessible to international ships and that transport stakeholders continue to work together to deliver services. Additionally, other modes of conveyance must be pursued. And investment in transport and trade facilitation should be encouraged alongside assistance for the most fragile economies. [135]

Disrupted regional logistics, the cessation of port operations in Ukraine, the damage of vital infrastructure, trade restrictions, increased insurance premiums, and higher fuel costs have all contributed to the logistical difficulties in the Black Sea region. In addition, they have contributed to a more expensive and uncertain global business and shipping environment. Many nations have forced to go further afield for oil and gas providers. Consequently, shipping distances, transit times, and expenses increased.

It is impossible to attribute all global shipping trends to a single reason. In addition to the COVID-19 pandemic, port congestion, and the necessity to adapt to low-carbon fuels, the conflict in Ukraine is one of the most significant crises currently impacting worldwide maritime trade. Nonetheless, it is evident that the disruptions and increased demand for ton-miles induced by the conflict in Ukraine significantly contribute to higher transportation costs (figure 26).

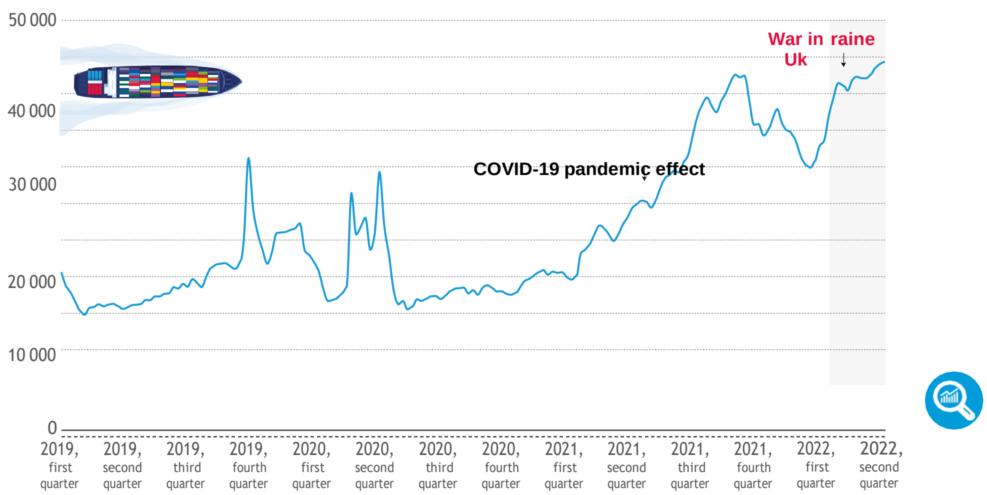

Figure 26. The cost of shipping has increased once more. Clarksea index in dollars per day for every shipping market

Clarksons Research Shipping Intelligence Network provided the data used by UNCTAD as the source.

This series measures the average vessel earnings throughout the various shipping sectors, such as tankers, bulkers, containerships, and gas carriers, weighted by the number of ships in each segment.

Increasing energy costs intensify the difficulties encountered by shippers. The Russian Federation is a prominent exporter of oil and gas. However, trade restrictions and changes in trading patterns caused by the war have led to an increase in demand for ton-miles. The daily prices for smaller-sized tankers, which are essential for regional oil trade in the Black Sea, Baltic Sea, and Mediterranean Sea, have risen considerably.

The greater energy costs have also resulted in higher marine bunker prices, which has increased the shipping costs for all maritime transport sectors. By the end of May 2022, the global average price for very low sulfur fuel oil (VLSFO) surpassed $1,000 per ton, a 64% increase from the beginning of the year, and the average fuel surcharges levied by container shipping lines have increased by close to 50% since the start of the conflict.

Even though the Russian Federation and Ukraine are not substantially connected into global container shipping and value chain networks, the conflict and trade restrictions have damaged this part of the shipping industry. The capacity of container ships designated to the Russian Federation was reduced, and operations at Ukrainian seaports were suspended (figure 27). In the ports of several neighboring nations, ship capacity increased slightly.

Due to the closure of ports and the cessation of shipping services to the Russian Federation and Ukraine, ships and containers were had to reroute. The ports of Hamburg, Germany, Rotterdam, Netherlands, Constanța, Romania, and Istanbul, Turkey are currently clogged with cargo bound for the Russian Federation and Ukraine. Delays are occurring, and shippers can anticipate an increase in detention and demurrage fees at ports. Cargo from the Russian Federation is also stranded in ports, such as in Europe. This increases strain on warehouse and storage space as well as costs. Since the epidemic, freight charges have increased, and the need to shift ships and cargo during the battle adds to the rising pressure.

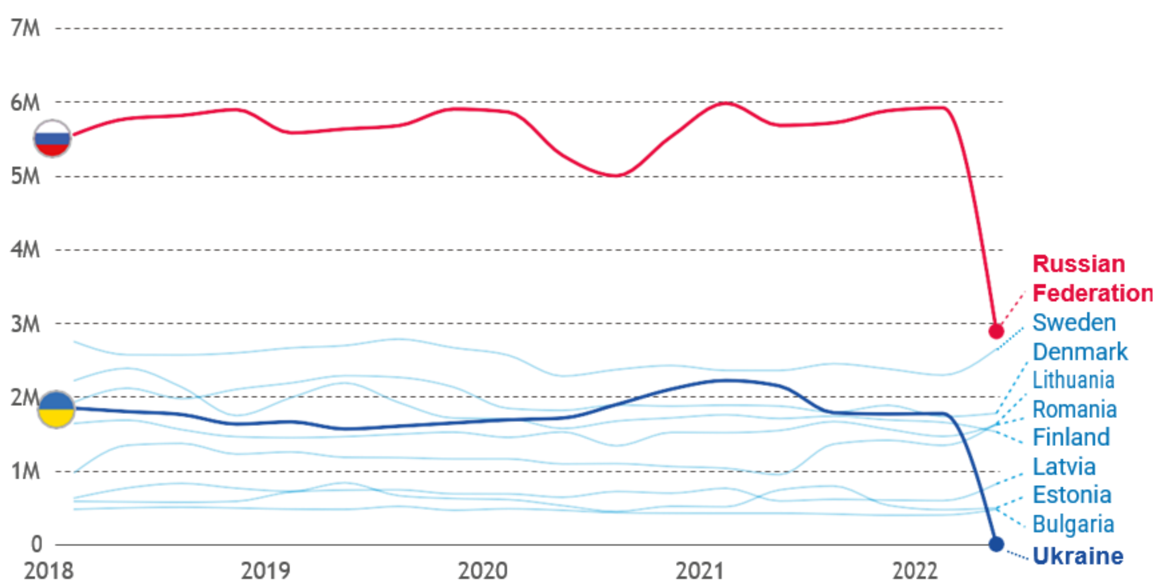

Figure 27. The container shipping deployment for the Russian Federation and Ukraine is decreasing. Deployment of container transport fleets in specific nations, in TEU capacity

UNCTAD data based on information supplied by MDST Transmodal.

TEU capacity is the annualized twenty-foot equivalent unit carrying capacity of a vessel.

The UNCTAD simulation predicts that the high container freight costs seen in 2021–2022 will be passed along to consumers and result in an additional global increase in consumer prices of 1.6%. In addition, it predicts that prolonged rises in freight rates will cause an average increase in import price levels of 11.9% worldwide. [135], [136]

The increase of 8.1% will be most severe for small island developing States (SIDS). SIDS import costs may see an overall increase of 26.7%. Small island developing states (SIDS) are heavily reliant on imports of energy and consumer goods, have acute trade imbalances (i.e., ships frequently return empty), are serviced by a modest number of shipping companies, and generate small volumes of commerce. They spend two to three times as much on transportation for imports as the rest of the globe. SIDS already pay more for transportation, and rising transportation costs have a greater negative effect on their economies. [135], [137]

In response to the COVID-19 pandemic, global seaborne trade abruptly decreased. However, there has been a quick recovery by the end of 2020, primarily in container and dry bulk transportation. Pressure on supply chains, ports, ships, and commerce intensified as a result of the asymmetric maritime trade recovery, which focused mostly on East-West containerized trade lanes. Supply chains will be under pressure in 2021 due to the rise in e-commerce, capacity limitations, a lack of equipment, and resurgent viral epidemics in some regions of the world. 2022 is still showing severe port congestion and congested logistics and transportation networks due to pressure. Between epidemic times and the end of 2021, the median wait time in ports for container ships climbed by almost 20%.

Delays and dwell times increased as freight rates increased, surcharges multiplied, and service reliability fell. By the end of 2020, container rates were more than five times higher than they had been in 2019. Despite a decline, they are still very expensive. The system has been further destabilized by fresh interruptions, such as the shutdown of factories and ports in China in the first half of 2022 as a result of additional COVID-19 infections. All merchants and supply chains have difficulties as a result of rising expenses, but smaller shippers are particularly affected because they are less able to absorb the cost and have less negotiating power when it comes to setting ship rates and reservations. [135]

Finally, given that the shipping sector's greenhouse gas emissions have increased by about 10% between 2012 and 2018, there is growing demand on it to step up its sustainability efforts as momentum for global efforts to combat climate change gathers.

Large-scale investments in green technologies and alternative fuels are necessary for decarbonization. While various alternative fuels including ammonia, hydrogen, and methanol as well as electric-powered ships are being developed, an increasing number of ships are already transitioning to liquefied natural gas (LNG). As new technology develops and workers become accustomed to new practices, switching to alternate fuels will probably increase the chance of machinery breakdown claims, among other dangers. [138]

4. FUNCTIONAL IMPLEMENTATION AND SUSTAINABILITY

Sustainability has grown in significance as a strategic factor across industries and regions. The maritime sector is crucial for global trade and significantly contributes to sustainable development worldwide. [139] Decarbonization is a top priority for national and international policy, and it depends on changing how development proceeds in various industries, including shipping. Although maritime shipping now contributes just a modest amount to global CO_2 emissions (about 3%), the industry's emissions are anticipated to rise as other sectors cut their carbon emissions through rapid decarbonization efforts. [140] Additionally, despite a modest reduction in carbon intensity, maritime transportation continues to outpace any advancement; it is predicted that CO_2 emissions from shipping would rise by 50% compared to 2018 by 2050.

The United Nations Framework Convention on Climate Change (UNFCCC historic)'s Paris Agreement of 2015 commits all nations to limiting global temperature increases to well below 2 °C while aiming for 1.5 °C. To achieve this, the transition to low-emission economies must happen across all sectors. International shipping isn't specifically included in the Convention, but the international marine organization (IMO), a specialized UN agency in charge of overseeing international shipping, acts as a bolstering anchor for pathways toward maritime decarbonization. To comply with the Paris Agreement's objective, the IMO adopted the Initial Strategy on the Reduction of GHG Emissions from Ships in 2018. The roadmap includes a promise to minimize CO_2 emissions per transport work by at least 40% by 2030 and to reduce overall GHG emissions from international shipping by at least 50% by 2050, with the goal of reaching 70% by 2050. [141], [142]

Decarbonization, the labor and human rights of seafarers, and ethical shipping recycling are only a few examples of sustainable shipping activities. The provision of bunkering of alternative fuels, as examined in this study, new vessel design and propulsion technology, and more effective operation techniques are just a few of the creative solutions that are required for the shipping sector to become decarbonized. To reach the IMO targets to reduce GHG emissions from shipping, a switch to alternative low- and zero-carbon fuels is necessary because these measures alone won't be able to achieve the desired emissions reduction. According to previous findings in this study, there are a number of potential low- and zero-carbon marine fuel options for the shipping industry, including liquefied natural gas (LNG), hydrogen, ammonia, methanol, liquefied petroleum gas (LPG), compressed natural gas (CNG), wind, electric, and wave power. Depending on the basic energy source, the fuel processing methods, and the propulsion technology, each fuel type has varying degrees of potential for reducing emissions as well as other economic, environmental, and societal effects. Each maritime fuel choice has distinct qualities and presents particular difficulties in terms of adoption and scalability. Due to the numerous uncertainties and competing, multi-attribute criteria, the maritime industry now faces the challenging task of choosing the most viable and promising marine fuel(s). [143]

Collaboration, openness, and knowledge sharing are more likely to be successful in addressing the worldwide challenge of maritime decarbonization. The IMO's guidelines for marine decarbonization have pushed nations to adopt decarbonization measures3, and the sector to keep enhancing its energy efficiency and emission controls. International and local governments must create resolute and trustworthy policy measures to forbid the use of high-carbon marine fuels. [144] The IMO has explored the creation of market-based policies, such as a tax on marine fuels and a global CO2 emissions trading system, whose implementation would lead to a reduction in shipping's GHG emissions. [146] The potential regulatory fine, which is an application of the "polluter pays" principle, aids in internalizing the external costs of emissions brought on by the use of alternative marine fuels. [146] Additionally, it's critical to avoid policies that take a "one-size-fits-all" approach and fail to take into account the diversity of the shipping industry (e.g., different ship types have varying fuel needs and operational patterns). [147]

The introduction of a carbon tax and carbon trading program that can support a number of other policy goals may help to encourage and speed up the use of alternative marine fuels. The fast global energy transition as well as the nation's long-term sustainability objectives should be well reflected in national and regional roadmaps for reducing emissions from shipping. The current major obstacles to the adoption of alternative marine fuels can be categorized into four categories: cost, global availability, infrastructure, and technology readiness. These obstacles are in addition to the uncertainties associated with a timely international agreement on a reasonable timeline for the introduction and implementation of new policies.

The price of fuel is a major barrier to the use of alternative marine fuels. The overall cost of a fuel is comprised of the cost of production, transportation, storage, and any future regulatory expenses (such as a carbon tax), which were examined in the preceding chapter of this study.

Concern over the supply of fuels globally is a second barrier to the use of alternative marine fuels. Fuel availability in the necessary quantities is a complicated and multi-faceted difficulty due to the uncertain supply-demand dynamics, which range from physical access to local resources to political and social restraints. Energy from a primary source, like natural gas or renewable solar and wind energy, must be transformed into a dependable final energy vector, like hydrogen, in order to produce a fuel. To power ships using a propulsion technology, the final energy vector is subsequently transformed into a marine propulsion fuel (e.g., internal combustion engine, fuel cell, electric motor paired with battery).

The third obstacle to the use of alternative marine fuels is a lack of infrastructure.

Accelerated production, supply, and distribution infrastructure development is necessary to meet the rising demand for alternate marine fuels. Although it appears that existing equipment might be reused, the current infrastructure is insufficient to produce low- and zero-carbon marine fuels. [148] The major bunkering ports will need to make infrastructure changes in order to facilitate the bunkering of alternative marine fuels. [149] Investing in new infrastructure may open up huge commercial opportunities, but there is also some risk involved. Given the size of the investment required for infrastructure development to fulfill the anticipated needs, many ports are seeking greater clarification from governments or specialized organizations on laws and regulations. [150]

Technology competence is the fourth obstacle to the adoption of alternative marine fuels. Uncertainty exists over the role of emerging technologies and how they will be used in the shipping sector, as well as the efficiency and expense of scaling up existing technology for broad industry adoption. Performance, cost, and timely availability uncertainties often cause the sector to freeze up when it comes to strategic investment and decision-making. Innovative technologies that are used in both fuel production and on board ships must be practical.

Over the past ten years, a large number of scholarly papers and industry publications on the performance assessment of marine fuels have been published. What alternative marine fuels provide the best performance to meet decarbonization goals is still a topic of discussion. [151] The difficulty is that each maritime fuel alternative has unique qualities and presents various economic, environmental, and societal difficulties.

As some alternative fuels may lower emissions of a number of air pollutants but produce GHG and other air emissions, it is crucial to evaluate marine fuels based on not only their use-phase implications but also those of production and logistics.

Alternative marine fuels have been evaluated in the literature based on various environmental, social, and technological-economic criteria. Numerous studies evaluate alternate marine fuels based on their cost, safety, and GHG emissions. In numerous studies evaluating marine fuels, additional factors like air pollution, ocean acidification, capital expenditure, and operational cost have also been included. The difficulty is that comparing results that are obtained using multiple evaluation criteria will be difficult and inconsistent, which may reduce the usefulness of the suggestions. Additionally, evaluating marine fuels using a small set of criteria runs the danger of underestimating the impact of specific marine fuels or prematurely introducing marine fuel options for future consideration in the effort to decarbonize the shipping industry. Therefore, it is difficult to make an informed decision regarding the choice of fuels without a complete and integrated set of criteria that can be used to systematically evaluate various alternative maritime fuels.

The choice with the highest integrated performances on economic, environmental, and social factors is expected to be the best maritime fuel to satisfy decarbonization aims and capture sustainability goals. This is due to the fact that decarbonization, which may figuratively refer to lowering carbon emissions, is a driving factor behind the maritime industry's overall sustainability. Additionally, despite the fact that the IMO's commitment to decarbonization aims to address climate change in particular, the sector's sustainability components need to be balanced in an integrated way in order to achieve harmony and complementarities. In order to ensure that both crucial GHG targets and the long-term sustainability goals of shipping are met, supported, and sustained, the choice of alternative marine fuels should be based on a holistic evaluation of the fuel options using a comprehensive and integrated set of economic, environmental, and social criteria.

In particular, hydrogen is the cleanest fuel of all the alternatives when it is created using renewable energy. One of the greenest alternative fuels for shipping is hydrogen since, when created with renewable energy, it doesn't produce any carbon dioxide emissions. However, there are certain limitations to hydrogen, such as its storage needs, which are about six to ten times greater than those of traditional fossil fuels. Other issues include the high cost of hydrogen storage and a lack of infrastructure to feed hydrogen to ships. As a result, in the near future, hydrogen will primarily only be an option for short-distance shipping and ferries that have a reliable source of local fuel.

Additionally, renewable energy should be used to make hydrogen. If fossil fuels are used to make it, carbon dioxide emissions will continue. Nowadays, fossil fuels are often used to produce hydrogen, which results in large carbon dioxide emissions. Methane leakage is another issue with this production technique.

A promising source for deep-sea shipping is ammonia made from renewable energy. It is less expensive than batteries and easier to store than LNG or hydrogen. However, it has a number of drawbacks, including the requirement for major investment in bunkering infrastructure and renewable energy production capacity to replace fossil fuels. Using ammonia as fuel on contemporary ships will require engine changes, new fuel tanks, and safety measures, as the technology for cleaning ammonia's emissions is still being developed. Such engines are anticipated to be available for purchase commercially in 2024. Ammonia is hazardous, and as it burns, it releases large volumes of nitrous oxide, popularly known as laughing gas, which is a 300-fold more potent greenhouse gas and destroys the ozone layer. The residents of the port area are adversely affected by nitrous oxide, another air pollutant.

Methanol provides a number of benefits. Methanol is less expensive to install than LNG tanks, and it is simpler to store than hydrogen. It can also be converted from conventional fuel oil to use in ship tanks. Methanol may also be stored on ships more easily and cheaply. Since methanol dissolves readily in water and only extremely high quantities can result in dangerous situations or any alteration to the surrounding marine life, it has a lower environmental impact than other shipping fuels. The abundance of methanol in the water allows it to enter and sustain the food chain because it is naturally produced by phytoplankton and quickly absorbed by bacteria and other microbes.

The low energy content of methanol, which requires 2.54 times the amount of storage space as conventional fuels to provide the same amount of energy, makes it less desirable for smaller ships. A further issue is the need to redesign ships in order to use methanol as ship fuel, such as adding larger fuel tanks to enable deep-sea journeys. [152]

With the IMO's implementation of stricter SOx (sulfur oxides) limits in January 2020*1, the majority of ocean-going vessels now utilize low-sulfur heavy oil. However, because the usage of low sulfur heavy oil has no effect on CO_2 emissions, it is evident that the fuel is insufficient to meet the IMO's aim of lowering CO_2 emissions by more than 40 percent by 2030 compared to 2008 levels.

Long-term interest is being drawn to the advent of LNG-powered vessels that do not consume heavy oil. LNG is said to have a low environmental impact since sulfur is removed during the pre-liquefaction process. As a result, it releases nearly no Sulfur Oxides (SOx) or Particulate Matter (PM) when burned and less NOx and CO_2 than other fossil fuels. It is also relatively safe due to the fact that its specific gravity is less than that of air and it is simple to distribute, hence reducing the risk of explosion. In addition, its proven reserves outweigh those of oil, and its potential to guarantee a constant supply for more than 50 years is a significant advantage.

Globally, the number of LNG-powered tankers has expanded from 18 completed vessels in 2010 to 175 vessels now in operation, with more than 200 vessels on order for 2020. (Reference: DNV GL). As a result of the stiffening of SOx rules in January 2020, it is anticipated that the transfer from heavy oil to LNG or other alternative fuels would be pushed further in Europe, where the majority of ships are now in operation. Mitsui O.S.K. Lines, Ltd. (MOL) and Nippon Yusen Kaisha (NYK) have launched the first LNG-powered tugboats in Japan, and the construction of LNG-powered vessels is ongoing.

Although using LNG as a ship fuel has a little impact on the environment, there are three main drawbacks. The installation of engines capable of running on LNG fuel will be necessary first. Additionally, capital investment is needed for equipment other than engines, including as re-liquefaction machinery and fuel tanks that are two to three times bigger than standard ones. Last but not least, the price at the time of new construction is 15–30% greater than for conventionally powered boats.

The advantages of LNG-fueled vessels, such as their "zero sulfur content, approximately 25% reduction in CO_2 emissions, and overwhelmingly low nitrogen compound emissions," and "LNG is more competitively priced than expensive low-sulfur heavy oil," are expected to help them gain market share as environmental regulations become more stringent. [153], [154] The following major benefits should be recognized while choosing LPG as a fuel. The IMO's 2050 GHG policy is substantially supported by LPG, and its use for bunkering is widespread. More specifically, there are currently more than 1000 terminals and storage facilities, as well as more than 700 small carriers operating ship to ship bunkering. Furthermore, LPG is making waves in the green route as it delivers 90% less lees specific matter, 90% less SOx, 15% less CO2, and 10% less NOx. STS operations are feasible anywhere in the world and can give LPG momentum. There are already 4 LPG-powered ships, and more than 71 ships will be converted or built specifically to use LPG.

Despite this, there are a number of disadvantages to this alternative marine fuel that must be taken into account, including LPG fuel system leaks and spills, risks related to LPG fuel storage tanks, and the location of leak detection in LPG fuel systems must be evaluated using a gas dispersion analysis. Moreover, all remotely operated valves in the LPG fuel system should be placed in failsafe settings to account for instrumentation and control system failure scenarios. Flammability standards for this extremely flammable gas range from 1.0-12% in air. [155]

Both onshore and offshore reserves that cannot be produced because a pipeline solution is unprofitable or because an LNG option is too expensive are suitable for CNG marine technology.

Between pipelines and LNG, there is a market niche for CNG. Compared to LNG, CNG projects are easier to implement. Additionally, CNG shipping can swiftly generate revenue from stranded gas reserves and offer a workaround, building a market history that can subsequently be used to support a pipeline or LNG transportation. The best applications of CNG technology are for short- to medium-distance projects.

The need for land-based CNG storage could be a drawback of a CNG solution; exhausted gas sources are one option. TransCanada, a Canadian business, has created a pipeline-based land storage system. The ideal way to deliver CNG is continuously and without interruption. Small-scale LNG may be an alternate approach to take into consideration if storage is a problem in a natural gas delivery project. [53]

Although hydrogen fuel cells have a lot of potential as a renewable energy source for shipping, there are still some major issues that need to be solved, including the sustainability of the energy source that will be used to produce hydrogen and the dearth of reliable, affordable low-pressure storage options.

The combination of renewable energy technologies that enhance energy source availability and complementarity in hybrid models has the most potential overall. In this way, realizing renewable energy's potential in shipping necessitates an integrated systems engineering strategy that takes on the aforementioned development-related challenges. All aspects of ship design, engineering control, and shipping, as well as business procedures, trade patterns, and levels of trade, must be considered in such a systematic approach. [156], [157], [158]

The resources for wave energy are plentiful worldwide. Both wave and tidal energy are being developed by many of the same businesses, but the technology is still in its infancy. Through their competitive stage gate approach, which has, on average, utilised 71% UK material to far, WES is significantly expediting development. It has very little operational CO_2 emissions and is a plentiful resource. In 2040, it might lower emissions by more than 1MtCO2 annually.

Despite the fact that wave energy technology is still in its infancy and that design and energy yield potential are highly unpredictable, we are aware of the enormous potential for read-through from both the offshore wind and tidal supply chains. [134]

By lowering fuel costs, renewable energy sources like wind energy applied to ships have a substantial impact on lowering the entire cost of operating the ship. In particular, the fuel savings from using sails can increase, in good weather, to 15% at a speed of 15 Knots and to 44% at a speed of 10 Knots. Nevertheless, depending on the wind's strength, the reduction in overall running costs ranges from 3.5 to 12%. [159],

New ship propulsion technology do, however, also have considerable drawbacks in a number of areas. Eagle systems, for instance, have the drawback of requiring sophisticated recovery and control systems. Therefore, training shipboard crew members in their proper use and management will be challenging. In order to be able to serve ships with modern power supply and propulsion systems, societies, and particularly ports, should construct the proper receiving systems for the individual ships. [160]

5. DISCUSSION

This study set out to find, evaluate, and analyze various alternative marine fuels that might actively contribute to the maritime and port industries' transition to a more sustainable future while also fitting into the economic and operational context of ports around the globe. The potential to minimize emissions from international shipping is also explored in this study, along with the properties of fuels, production methods, usage technologies, energy efficiency, lifecycle environmental performance, economic viability, and legislation.

In the beginning, a thorough analysis of a few selected alternative energy sources was carried out, looking at their traits, consistency, their potential to be used as maritime fuels, their subclasses and availability. It was discovered that each fuel has pros and cons when it comes to being utilized on vessels.

In addition, we reviewed the most current research on climate change, greenhouse gas

(GHG) emissions, energy efficiency management, and particularly the global reduction of CO_2 emissions. We observe that in order to guarantee that the global warming stays below 20C by the end of this century, a reduction in CO_2 emissions of between 41-72% from 2010 levels is necessary by 2050. Then, we looked at the research on carbon emissions from shipping and found that it accounts for 2.2% of world carbon emissions. It should be highlighted that even after implementing significant efficiency improvements required by the mandatory EEDI criteria, it is anticipated that shipping-related emissions would continue to increase over the next few years. This deficiency necessitates quick action and a team effort from all parties involved in the maritime sector.

In order to compare and clarify which of these energy sources would be a realistic choice and have an actual practical application in the shipping industry, an economic evaluation of the budget needed, fuel, and capital cost of each marine fuel was undertaken.

Economic considerations are given top priority when choosing alternative marine fuels, which is not a big surprise given how competitive the shipping sector is. It should not come as a shock that the cost of fuel is the most crucial economic sub-criteria because it accounts for a sizable portion of operating expenses, which have a direct impact on earnings. Social criteria, which include safety and forthcoming regulation, are the second most important criteria, closely followed by environmental criteria, for which climate change is given top priority.

For each criterion, there are some stakeholders who have different opinions from the majority. Other than the fact that it is a common phenomenon in group decisions, it is difficult to explain why some people have opinions that differ from the majority. Multi-criteria decision analysis is likewise based on the principle that people can have diverse viewpoints. However, there are a few different viewpoints that could clarify how individuals see the significance of criteria while choosing alternative marine fuels.

One might reconsider the rationale of switching marine fuel, for instance. Environmental considerations might become more crucial if the goal of changing marine fuel is to reduce emissions. But social characteristics become more significant if the goal is to adhere to laws. One might make the case that while SECA laws currently address acidification and health effects, climate change is still an unresolved issue that must be taken into consideration when altering marine fuel. However, it can be argued that while shipping contributes significantly to the global share of emissions that cause acidification and adverse health effects, its contribution to greenhouse gas emissions is much smaller. As a result, it is more crucial to take these effects into account when changing marine fuel.

Although multi-criteria decision analysis (MCDA) is a technique for assisting decision making by including and arranging more parts of the real problem than one person can do, it is vital to keep in mind that an MCDA cannot cover all aspects of the real problem.

You can't just assume that the entire issue has been solved. This implies that if other criteria were to be added, the order in which marine fuel would be the right alternative might vary.

The results of the MCDA decision about which alternative maritime fuel is the most financially viable option are only applicable to the alternative marine fuels evaluated in this study; otherwise, the outcomes might have been different. Therefore, it would be fascinating to include more alternative maritime fuels in further research, such as liquefied biogas, which is a renewable LNG substitute, and electro-fuels.

To better understand the rationale behind the priorities, it would be fascinating to incorporate more alternative marine fuels in future studies and follow up on the stakeholders' weights with individual interviews. Additionally, it would be intriguing to include a cargo owner in the role-play to determine whether customers would be prepared to pay more for a transportation business that is more environmentally friendly.

In addition, the current state of affairs with the ongoing war was also discussed and examined in this study, as it has an impact on the cost element and influences how the final price of the fuels considered in this study is determined.

During the course of this investigation, it was discovered that there are no hard and fast guidelines for selecting any of the aforementioned fuels in a sensible way, especially when it comes to price. According to what has been said, LNG appears to be the most practical answer, although it is not without challenges and drawbacks. Despite this, it is a fuel that is currently available and in use on the market, so shipowners are familiar with it, which aids in their easy incorporation into a more environmentally friendly shipping industry. There are additional fuels that meet some of the requirements for replacement in a cleaner maritime environment, but due to their drawbacks, difficulties, or stage of development, they cannot be used in this sector right away and do not pique shipowners' interest in investing in them.

It is crucial to note that although there are undoubtedly still many more measures that must be taken before the shipping industry becomes more environmentally friendly, action has already started in this direction.

Several factors that are important to the use of alternative fuels in shipping have been covered in this thesis. However, due to its complexity and diversity, the shipping sector requires a more comprehensive strategy that takes into consideration a variety of constraints.

The need for sustainable strategies to reduce emissions is urgent, and additional delays could result in irreparable changes to our ecosystem. While major companies in the shipping sector are working to increase the acceptability of alternative fuels, the industry's disorganized structure is a barrier that allows conventional marine fuels to remain widely used and uncontested. To combat climate change, which has the potential to be more deadly than war, policymakers urgently need to encourage the coexistence of various marine fuels and increase the availability of alternative fuels.

6. CONCLUSION

In order to reduce gaseous pollutants and prevent significant environmental occurrences like the greenhouse effect and climate change, this research focused on the necessity to implement new technology and creative systems on vessels and employ renewable energy sources as ship fuels. It also concentrated on the impact of war in achieving these objectives, as well as the economic ramifications of these potential changes, and the idea of maritime sustainability and its realization.

Due to the economic downturn, rising fuel prices, the war between Ukraine and Russia and the greenhouse effect, everyone has understood that ships must become more environmentally friendly, regardless of the expense. Increasing numbers of shipyards have proposed designs or have already constructed experimental ships that will employ the new technology engines as means of propulsion and fuels, which are significantly more environmentally friendly, or will use all or some renewable types of energy. In the medium term, a new trend is forming in shipbuilding, which desires to be both environmentally and economically sound. Combining the "ecofriendly" designation with cost savings, the "green" ships of the future represent the future of shipbuilding.

Despite research into the use of renewable energy solutions, the shipping industry is still in its infancy. It is also expanding at a rapid rate as demand for transportation services continues to increase. From 2007 to 2012, the global shipping fleet consumed 250-325 million tons of fuel annually, equating to 2.8% of global greenhouse gas emissions annually (3.1% of CO_2 emissions), amidst a volatile fossil fuel market in which ship fuel prices are on the rise, and rising demands for a substantial reduction in the sector's pollutant emissions. The MARPOL International Convention stipulates, among other measures, low sulfur emission control zones in the marine environment and mandatory technological and operational measures, forcing ships to use energy more efficiently and minimize emissions. MARPOL regulations mandate EEDI (Energy Efficiency Design Index) and SEEMP (Ship Energy Efficiency Management Plan) apply for all ships. These economic and environmental constraints are crucial for the maritime industry to adopt the usage of renewable energy sources.

The majority of shipping companies assert that the incentives for placing environmentally friendly applications on their ships are the largest possible economy regarding energy requirements, international and national tax exemptions in various ports, compliance with national and international requirements, the protection of the marine environment, the improvement of maritime expertise transporting passengers and cargo, and the provision of high-quality maritime transport services. The initial cost of construction, the annual operating maintenance costs, compliance with national and international requirements, the lack of ship reception and the existence of supporting businesses of the ports, i.e. the lack of compatibility with the existing one port infrastructure, and the global financial crisis are cited as the most significant obstacles to the adoption of ecological "green" ships by shipping companies.

Although none of the alternative energy sources evaluated in this study are novel concepts, they cannot be adopted on a wide scale unless fundamental technological issues are resolved. As stated previously, it is almost probable that conventional systems will be the primary source of power generation and propulsion for marine applications. The transition to clean energy shipping necessitates a substantial change away from the use of fossil fuels as transport fuels and toward the use of energy-efficient design solutions and technology that utilize renewable energy sources. Even under the most optimistic circumstances, the contribution of renewable energy sources to the "energy mix" of shipping is currently limited on both the short and medium term.

Despite this, shipbuilders are always enhancing the architecture of their vessels, and pilot application results indicate significant cost reductions in certain applications. The development of renewable energy solutions for shipping has been delayed by the abundance of fossil fuels and the large number of ships that still use this form of energy, and the relative decline in market investments. However, these technologies (in the short and medium term) have limited capacity to further contribute to the energetic demands in various fields of operation. For specific applications, renewable energy sources can play a major, even dominant, role.

In the near future, sustainable ships, sometimes known as "eco-friendly" or "green ships," will be profitable. And this is because their lower fuel consumption makes them more appealing to charterers, their operational expenses are always decreasing, and they offer greater commercial flexibility in terms of the countries to which they can travel. International rules are getting more complex and stringent, which, when combined with a poor charter market, makes new ships, eco-friendly vessels, and modern vessels more competitive.

To promote and expand the role of renewable energy sources in the shipping industry, special effort and supplementary measures should be implemented. To attain commercial viability for renewable energy solutions in shipping, it is essential to develop supporting legislation and give incentives for the promotion of research, innovation, and the development of tangible examples. For immediate success, solutions should focus on small ships (10000 tons dead weight), which are more prevalent, carry less overall cargo, but release more greenhouse gases per unit of cargo and distance traveled than the largest ships.

Energy management will undoubtedly become an even greater differentiator and source of competitive advantage for transportation firms. The market in all its aspects, from the design, construction, operation, and decommissioning of ships, will be governed by new legislation and regulations that will make the ships' exploitation economically viable by establishing suitable working conditions for individuals, providing benefits to society, and safeguarding the environment.

Wind energy (e.g., soft sails, solid sails, rotors, kite sails, wind turbines, etc.), electrical energy, and wave energy are among the sustainable kinds of energy utilized in the maritime industry. These sustainable energy solutions can be included into the existing fleet through conversions or incorporated into the design and building of new ships. These kinds of energy, such as kite sails technology, lower the quantity of CO_2 released by ships.

By minimizing the cost of fuel, renewable forms applied to ships have a substantial impact on reducing the entire cost of operating the ship. Specifically, the fuel savings associated with sails can increase to 15% at 15 Knots and 44% at 10 Knots in optimum weather conditions. Depending on the strength of the wind, the reduction in total operating costs increases to between 3.5% and 12%.

However, the new ship propulsion technology has disadvantages in a variety of industries. For instance, eagle systems have the disadvantage of requiring complicated recovery and control mechanisms. Therefore, it will be challenging to adapt the ship's crew to their effective usage and proper handling. In addition, the societies and, more especially, the ports will need to develop the required receiving systems for the individual vessels in order to serve vessels with new power and propulsion systems.

A further downside of new technology is their expensive acquisition and installation. Due to the high cost of the necessary equipment and machines, the cash conversion cycle for the funds spent on their purchase is lengthy.

In addition to the renewable sources of energy used for ship propulsion, there are also sources based on the usage of electric batteries, fuel cells, and natural gas. The Zerocat is a typical example of a ship powered by an electric battery, as its lithium ion batteries only require 10 minutes to recharge. With this energy source, similarly to the other ones, there is no emission at all, as the ship is propelled solely by batteries that will be charged in specific ports. Since fuel is unlimited, the usage of batteries considerably cuts the ship's running expenses.

The "Viking Lady" is one of the usual instances of hybrid ships powered by fuel cells. The "Viking Lady" is the first commercial vessel with a fuel cell propulsion system, powered by liquefied natural gas. Specifically, it is powered by 330 kilowatts and has successfully run for a total of 18,500 hours to date. In the first year of operation with the hybrid system, the ship has achieved a 15% decrease in fuel consumption and a 25% reduction in harmful emissions.

Regarding renewable forms of energy such as liquefied natural gas (LNG), liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, methane, and ammonia as shipping fuel, this has the effect of making ships independent of other costly fuels (e.g. oil) and promoting the adoption of environmentally friendly technology. Among the aforementioned energy sources, liquefied natural gas (LNG) is regarded as the most sustainable option due to its capacity to reduce carbon dioxide (CO_2) emissions by 25-30%.

LNG has significant potential as a marine fuel due to its consumption of clean energy, which meets current and future criteria. In addition, existing technology can be applied to LNG carriers, coastal vessels, and ferries, as dual-fuel engines are already in use in Europe and the price of LNG is competitive with that of fuel oil. The majority of conventional ships will continue to use conventional oil-based fuel since adding LNG as a fuel would necessitate the installation of new systems and the implementation of tailored risk management. However, LNG is a feasible option. Conventional fuels are depleting, and LNG is ideally positioned to fulfill ever-stricter emission regulations. In addition, the lack of sulphur and restricted amount of nitrogen in LNG's composition means that its combustion produces measurably lower emissions and necessitates significantly less fuel system maintenance.

LNG, on the other hand, must be stored at temperatures as low as -162 degrees Celsius, which necessitates the use of materials that are fragile and lose strength, as well as storage area that is up to 150% more than fuel oil storage capacity. Because LNG is odorless and colorless, it is very hard for workers to detect it, hence raising the dangers of leaks to staff and hurting their health. Last but not least, the costs of new construction for LNG-powered boats are significantly higher, and there is a possibility of, a boiling liquid/expanding vapor (BLEEVE) explosion. This type of explosion is triggered by a rupture in a storage facility, as the lowered internal pressure causes the liquid to rapidly evaporate and the valve capacity is insufficient to contain the volume of gas. However this risk can be managed most effectively by design, maintenance, and safety procedures.

Needless to add, LNG bunkering is not risk-free either. Specialized bunkering techniques, including vapor management, are necessitated by stringent planning and monitoring, specialized equipment and requirements, and approaches tailored to the installations of the receiving vessel and the terminal tank, barge, or truck.

Currently, the LNG bunkering infrastructure is a concern because it is primarily concentrated in North-West Europe, the Gulf of Mexico, and the East coast of the United States. To be successful, the LNG-powered maritime industry and bunker infrastructure must grow and improve. Although bunkering programs are expanding, LNG bunkering remains too costly for the majority of ports.

The shipping industry is under increasing pressure to adhere to pledges set in accordance with the Paris Agreement. Despite the hazards, LNG offers substantial advantages over fuel oil. However, LNG is considered the most comparable alternative fuel for ships. LNG is a feasible fuel choice because the technology for ship engines and bunkering is available and the environmental benefits are evident.

Combining renewable energy sources has the greatest potential to maximize the availability and complementarity of energy sources in hybrid systems. In this regard, realizing the full potential of renewable energy sources in the maritime sector necessitates an integrated systems approach that addresses the obstacles to their development.

Nevertheless, despite the need to reduce CO_2 and to increase clean energy, the shipping world appears divided and favours safe investments in semi-green ships during economic downturns. Complex or limited research and development funding, especially for technologies with initial proof of feasibility, is a significant barrier to the adoption of renewable energy sources in shipping, as are shipowners' concerns about the risk of hidden or additional costs and the opportunity cost of renewable energy solutions. This is especially true and historically there has been a dearth of trustworthy information regarding the costs and possible savings associated with certain operational measures or renewable energy solutions for the specific industry.

Concerning market obstacles, the main issue is that incentives differ between shipowners and charterers, restricting shipowners' incentives to engage in clean energy solutions because the advantages are not always realized by the investor and the savings cannot be fully amortized. After the collapse of the maritime industry's expansion in 2006, investors are reluctant to invest in the sector. The shipping industry is rarely visible to the general public, resulting in less social pressure on the industry to switch to sustainable energy sources. Among the hurdles unrelated to the market, the varying classes and sizes of ships, the markets and trade routes covered, and the lack of access to financing are crucial obstacles that must be addressed.

In conclusion, shipping plays an essential part in the global population's health, economy, well-being, and sustainability. We know from the past that the shipping sector had to adjust to changes in commerce as well as ongoing pressures for safe navigation and adherence to environmental regulations. However, when the global community is confronted with issues such as climate change, the greenhouse effect, the decrease of global trade, the impoverishment of individuals owing to social inequities, etc., sustainability has become the operative term.

Through imports and exports, international trade through shipping plays an essential part in the global economies of nations. The vast majority of goods and commodities that are bought and sold are transported by ship, which enables nations to expand and thrive in their trading activities.

Additionally, shipping's impact to society is significant. In modern civilizations, the contribution of shipping is reflected in the development of jobs on ships, in offices, in shipbuilding repair facilities, and in ports. Furthermore, the contribution of shipowners through their private philanthropy and charity organizations is equally significant. However, shipping contributes both favorably and negatively to the evolution of society. Specifically, air pollution causes several health concerns and even mortality among humans. In addition to casualties caused by atmospheric pollution, workers, primarily aboard ships, are susceptible to illnesses and accidents due to their severe working conditions and environment.

Given the aforementioned negative effects, modern shipping must promote the concept of sustainability. In times of economic downturn, the concept of sustainable shipping might be an enticing alternative. Multiple energies are necessary for the sustainability of shipping. As indicated previously, these efforts include reducing CO2 emissions, taking all necessary precautions to prevent accidents, hence reducing pollution and loss of life, assuring the safety of the ship and its crew, etc. Regarding the notion of marine sustainability, we would infer that it is one of the most critical concerns affecting the global community; nevertheless, due to the uniqueness of the marine sector, the marine stakeholders that deal with it confront challenges and uncertainty.

Overall, the transition to these low-carbon fuels is not straightforward. There are numerous things that must be taken into account. It is possible, though, if the proper incentives and investments are implemented to make alternative fuels more commercially feasible. It is essential for a "cleaner" world that we adopt a more sustainable method of transportation and, by extension, living.

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