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UNDERSTANDING FUEL SAVING AND CLEAN FUEL STRATEGIES TOWARDS GREEN MARITIME

Van Nhanh Nguyen [1]
Krzysztof Rudzki [2]
Marek Dzida [3]
Nguyen Dang Khoa Pham [4]
Minh Tuan Pham [5*]
Phuoc Quy Phong Nguyen [4]
Phuong Nguyen Xuan [4*]
[1] Institute of Engineering, HUTECH University, Ho Chi Minh City, Viet Nam
[2] Gdynia Maritime University, Faculty of Marine Engineering, Poland
[3] Gdansk University of Technology, Poland
[4] PATET Research Group, Ho Chi Minh City University of Transport, Ho Chi Minh City, Viet Nam
[5] School of Mechanical Engineering, Hanoi University of Science and Technology, Hanoi, Viet Nam

* Corresponding authors: *phuong@ut.edu.vn (Phuong Nguyen Xuan)*
tuan.phamminh@hust.edu.vn (Minh Tuan Pham)

ABSTRACT

Due to recent emission-associated regulations imposed on marine fuel, ship owners have been forced to seek alternate fuels, in order to meet the new limits. The aim of achieving low-carbon shipping by the year 2050, has meant that alternative marine fuels, as well as various technological and operational initiatives, need to be taken into account. This article evaluates and examines recent clean fuels and novel clean technologies for vessels. The alternative fuels are classified as low-carbon fuels, carbon-free fuels, and carbon neutral fuels, based on their properties. Fuel properties, the status of technological development, and existing challenges are also summarised in this paper. Furthermore, researchers have also investigated energy-saving devices and discovered that zero-carbon and virtually zero-carbon clean fuels, together with clean production, might play an important part in shipping, despite the commercial impracticability of existing costs and infrastructure. More interestingly, the transition to marine fuel is known to be a lengthy process; thus, early consensus-building, as well as action-adoption, in the maritime community is critical for meeting the expectations and aims of sustainable marine transportation.

Keywords: Marine engine; Alternative fuel; Green maritime; Fuel savings; Low-carbon strategy

INTRODUCTION

ASo as to meet climate change goals, as well as reduce greenhouse gas (GHG) emissions, it is crucial for the shipping industry to drastically decarbonise and transition to an eco-friendlier future [1], [2]effectively promoted the marine low sulfur diesel fuel (MLSDF. Obviously, important international protocols and events, as well as academic and government agendas, all contribute to triggering and responding to the issues which this sector encounters as it strives to become more environmentally friendly and sustainable [3], [4]Most importantly, awareness of the definition of ‚decarbonisation' is critical, since it refers to the ‚reduction or entire removal of CO_2 emissions' according to reports of International Maritime Organization (IMO) [5], [6]. The fourth GHG Survey, which was released in August 2020, established significant goals for the shipping industry, including a 50% reduction in yearly GHG emissions by 2050, compared with those in 2008 [7], [8]. It is not hard to see that the IMO will attempt to reach the above-mentioned goals by using energy efficiency approaches and novel methods such as using alternative fuels that could be applied in the short, medium, and long-term [9], [10]. Fig. 1 shows the IMO's ship-enhancement strategy for reducing CO_2 emissions between 2013 and 2050 [11].

Fig. 1. IMO agreement for reduction of CO2 emission from ships [11]

In fact, international shipping's decarbonisation has been slow because of the sector's stakeholders' disparate and diversified aspirations and interests. Arguments at the IMO have been marked by sharp disagreement over how and whether this field should conform with the Paris Agreement's aims. The existing IMO GHG reduction roadmap suggested a slow decision-making process in the implementation of critical actions and regulations [12], [13]. With no precise, ambitious, and enforceable aims, the industry would have no motivation to invest in low-carbon techniques on a large scale. This could be explained by the significant risk and uncertainty related to investment in low-carbon methods, which are generally more expensive. As a result, policy uncertainty might hinder innovation in low-carbon techniques and fuels. Regarding the primary factors impeding progress in establishing an aggressive target, the lack of rigorous investigations, analysing the technical feasibility of decarbonising international maritime transportation, was mentioned, particularly in light of the Paris Agreement's more ambitious target of 1.5°C temperature limitation [14]. Significantly, shipping was identified as a substantial source of anthropogenic NOx and SOx emissions in recent research, accounting for 15% and 13% of global NOx and SOx emissions, respectively [15]–[18]. Furthermore, maritime shipping is also known as the principal source of black carbon in the Arctic Circle [19], as well as a considerable source of CO_2 and particulate matter, released through human activities [20]. For the aforementioned reasons, the IMO established goals targeted at gradually decreasing the ships and ports' carbon intensity, with general goals of decarbonising the marine field by the end of the century [21]–[23]. It has been noted that stakeholder-led initiatives, along with the regulations mentioned above, were compelling ship-owners to change their operational practices, to install on-board air contamination control devices, such as SOx scrubbers and selective catalytic reduction, as well as to diversify their fuel categories to include alternative low-carbon and low-sulphur fuels [24], [25]. Hence, the newly discovered demand for alternative fuels offers exciting potential for investment in the expansion and diversification of the blend of maritime fuels [26].

The combination of improvements in energy efficiency and a shift to energy carriers with low or zero-carbon could lead to a high probability of achieving very low (even zero) GHG emissions discharged from shipping [27]. Electricity, biofuels, and electrofuels derived from renewable sources of energy (e.g. solar, wind and biomass) are examples of energy carriers that emit little or no GHG during their life cycle [28], [29]. Energy efficient approaches, on the other hand, are those that need to go hand-in-hand with operational measures, such as:

- capacity utilisation and voyage optimisation,
- technical approaches,
- enhancements in hull design and changes in propulsion and power systems.

The emission reduction potential of various strategies have been examined and the findings show that one of the best and most gratifying approaches to achieve the required potential emission reduction is a shift to alternative fuels and the use of energy-saving techniques [30], [31]. The primary goal for this work was to look at the role of alternative fuels, as well as energy-saving measures, in decarbonising maritime transportation, which requires providing not only short-term GHG reductions but also engine solutions and tank arrangements, that could easily be adjusted to run on fuels with very low or zero carbon (if available) and are efficient in utilising fuel or technological ship operation solutions, to decrease GHG emissions.

SOLUTIONS TO MANAGE CO_2 EMISSION FROM SHIPS

Previous studies have asserted that a target of at least 50% emissions reduction should be possible at zero net cost by 2030, if low-cost energy savings were to be fully exploited in supporting investments in more costly solutions [32]. The above difference, between the energy efficiency potential and the level of realised energy efficiency, is referred to as the energy efficiency gap [33], [34]. This is an important issue that needs to be thoroughly considered if the shipping industry is to make a substantial effort in working towards a low-carbon future for global maritime transport [35], [36]. Indeed, if all available energy efficiency and carbon mitigation measures are to be implemented, the projected growth in shipping activities could achieve remarkable results, in terms of decreasing energy demands and zero-net reduction in CO_2 emissions. In other words, the reduction in emissions achieved by measures taken by various shipping companies effectively cancels out the growth in energy consumption resulting from the sector's growth [37]–[39]. To further highlight the sector's role in combating climate change, the European Commission has recently called for the global shipping industry to set a target for 2050: to achieve 40-50% CO_2 emissions reduction compared to 2005 levels [40].

Indeed, the problem of handling CO_2 emissions in current world shipping conditions is not only a technological one, but is intertwined with highly sophisticated and multifaceted governmental factors. As the main intergovernmental body governing international maritime activities, the IMO adopted two key policy measures during the 62^{nd} meeting of its Maritime Environment Protection Committee (MEPC) in July 2011. More importantly, in order to lower CO_2 emissions released from ocean-going vessels, the EEDI (Energy Efficiency Design Index), applying exclusively to novel vessels, and the SEEMP (Ship Energy Efficiency Management Plan) needed to persuade vessel owners and operators to take CO_2 emission-cutting measures for their fleet. Unfortunately, the rise in emissions is likely to continue, despite these actions [41]. While emission reduction is affected by other actors (e.g. port authorities) [42], [43], a substantial portion of the expected reduction is likely to come from improvements in ship compliance to the standards set by SEEMP (i.e. operational and retrofit measures to increase ship energy efficiency) [41]. When considering the goal of CO_2 emissions reduction in the shipping industry, the entire vessel and its operation should be subjected to analysis. Therefore, detailed discussions are provided on emission reduction strategies through reviewing emission control mechanisms for marine diesel engines, as the main ship engine propulsion, using the concept of EEDI given in Eq. (1). This indicates the amount of CO_2 emissions from diesel engines with CF as the conversion coefficient for CO_2 [44].

$$\text{EEDI}(g(CO_2/\text{ton/mile}) = \frac{\text{Engine power (kW) x Fuel consumption rate (g/kWh)x } C_F}{\text{DWT (ton) x Speed (mile/h)}} \tag{1}$$

In fact, the IMO implemented various technical methods to achieve the long-term goal of reducing GHG, which included the EEDI and SEEMP [45]. Notably, the EEDI required all vessels built after 2013 to have a certain minimum energy efficiency, assessed in grams of CO_2 emitted per capacity-mile. Indeed, EEDI was a regulatory measure designed to reduce the carbon intensity and enhance operating efficiency of a ship; nevertheless, the EEDI only concentrated on gate-to-gate ship emissions [46]. Significantly, critics expressed concerns that the EEDI might understate carbon reductions [47] and comprehensive systems analysis, such as the production of feedstock, raw materials acquisition, and the conversion and consumption of fuel in maritime vessels, was essential to evaluate the environmental impacts on a broad scale, as well as the advantages of alternative marine fuels [48], [49]. This life cycle viewpoint captured environmental externalities that traditional measurements could not and it could assist in offsetting unforeseen environmental implications of marine fuel usage, such as transferring environmental challenges between supply chain segments or pollutant classifications. While EEDI established performance criteria for novel ship design and construction, the SEEMP primarily addressed energy-saving options at the operating level of both current and new ships over 400 GRT. Similar to EEDI, SEEMP was made mandatory, requiring fleet owners and companies to take immediate action to improve the energy efficiency of their operations following a four-step process: i) planning, ii) implementation, iii) monitoring, and iv) self-evaluation and improvement. Moreover, the IMO created the EEOI (Energy Efficiency Operational Indicator) as an operational measuring tool to assess the energy efficiency and CO_2 emissions of vessels, in order to monitor compliance with SEEMP. Lower EEOI values indicate better ship energy efficiency and are calculated by Eq. (2):

$$\text{EEOI} = \frac{\text{Eactual } CO_2 \text{ emission}}{\text{performed transport work}} \tag{2}$$

More interestingly, with the creation of the EEOI, vessel owners and operators could access an indicator used to monitor individual ship operations in real time. As a result, any prospective alterations to the ship's structural design and operation could be evaluated according to their effects on the general efficiency performance. Although the EEOI was usually used to evaluate the energy efficiency of vessels under the SEEMP framework, there was controversy in the shipping industry because utilising such an indicator to compare ship performance was thought to be incorrect and inaccurate [50]. The IMO introduced the IMO Data Collection System in MEPC.278 (70), which came into force in 2018. This data collection system provides information about the fuel consumption of vessels. Measuring the actual transport work, in terms of tonne miles, requires information about the distance travelled and the cargo mass. The cargo on the ships is generally viewed as sensitive information and so this information is not included in the DCS. Therefore, the Annual Efficiency Ratio (AER), known to be a simple component, quantified the vessels' energy efficiency regarding GHG emissions per transportation work, which assumed a constant cargo value based on the ship's deadweight tonnage.

$$\text{AER} = \frac{\text{actual } CO_2 \text{ emission}}{\text{DWT*distance}} \tag{3}$$

In order to comprehensively evaluate the reduction measures of GHG emissions, the 5th GHG Working Group and MEPC-74 discussed the methods of approach to reduce GHG emissions given in Table 1.

Tab. 1. Measures for reducing GHG emission of IMO [51]

Measures	Main measure	Remarks
Technical measures	• Energy efficiency such as light advanced materials,waste heat recovery, optimisation of design, improvement of propulsion devices, reduction offriction. • Green/renewable/alternative energy such as biofuels, H_2, NH_3, LNG, fuel cell, renewable energy sources (solar, wind, wave and tide, geothermal); electricity.	EEDI framework
Operational measures	• Optimisation of ship speed and size, improvement of ship-port interface, enhancement of on-shore power.	SEEMP/ EEOI/EEXI
Market-based measures (MBM)	• Emission trading, efficiency incentive, GHG fund or tax.	MBM

APPLICATION OF CLEAN AND RENEWABLE ENERGY FOR SHIPS

Reducing the reliance of marine vessels on fossil fuels is part of the strategy to attain a more sustainable and low-carbon future for the global shipping industry. This is achieved via introducing alternative and cleaner fuel options to power ships [52], [53]. Ship propulsion systems (aboard commercial ships) are mostly powered by gas turbines, diesel engines, or steam, in which diesel engines accounts for the vast bulk of the available fleet [54]. In spite of their rarity, electric generators running on diesel and oil-fired boilers can be observed on several vessels. Besides this, several kinds of vessel propulsion power systems, including gas turbines, traditional reciprocating internal combustion engines, and boilers, are investigated in the following section, for the employment of low-carbon fuels, and with the aim of replacing traditional fossil fuels. Researchers have shown interest in the possible applications of more appealing alternative fuels (such as H_2, LNG, ammonia, and biofuels) in propulsion systems of vessels and such prospective low-carbon fuels have been examined in the laboratory, as well as at pilot scales. It was noted that the fuel coefficient is determined by the carbon concentration (CC, m/m) of the fuel; this is the product of the carbon concentration and carbon fuel coefficient ($C_{FF} = C_{FC}$*CC) [55]. Fig. 2a illustrates the coefficients for various alternative and marine fuels. Among the fuels used for ships, Bouman et al. [30] discovered that biofuels had the single greatest potential in lowering CO_2 emissions among all the methods investigated. Fig. 2b depicts the life cycle GHG emissions of a variety of bio-based fuel and fossil-fuel approaches and these are documented in the paper as a series of boxplots. In spite of the wide range of results, biofuels showed a considerable ability to decrease life cycle GHG emissions, when compared to HFO, as well as fossil alternatives [56].

LNG

Because liquefied natural gas (LNG) has low carbon content, it is considered a potentially appealing fuel for the maritime sector. Furthermore, methane (CH4) is the primary chemical molecule found in natural gas, which contains a higher density of energy compared to diesel fuel derived from petroleum [63], [64]. In addition, natural gas is known to be a cleaner-burning fuel compared with diesel and HFO because it emits less SOx, NOx, and PM [26], [65]. Apart from that, because LNG has high energy density, compared to other hydrocarbons or

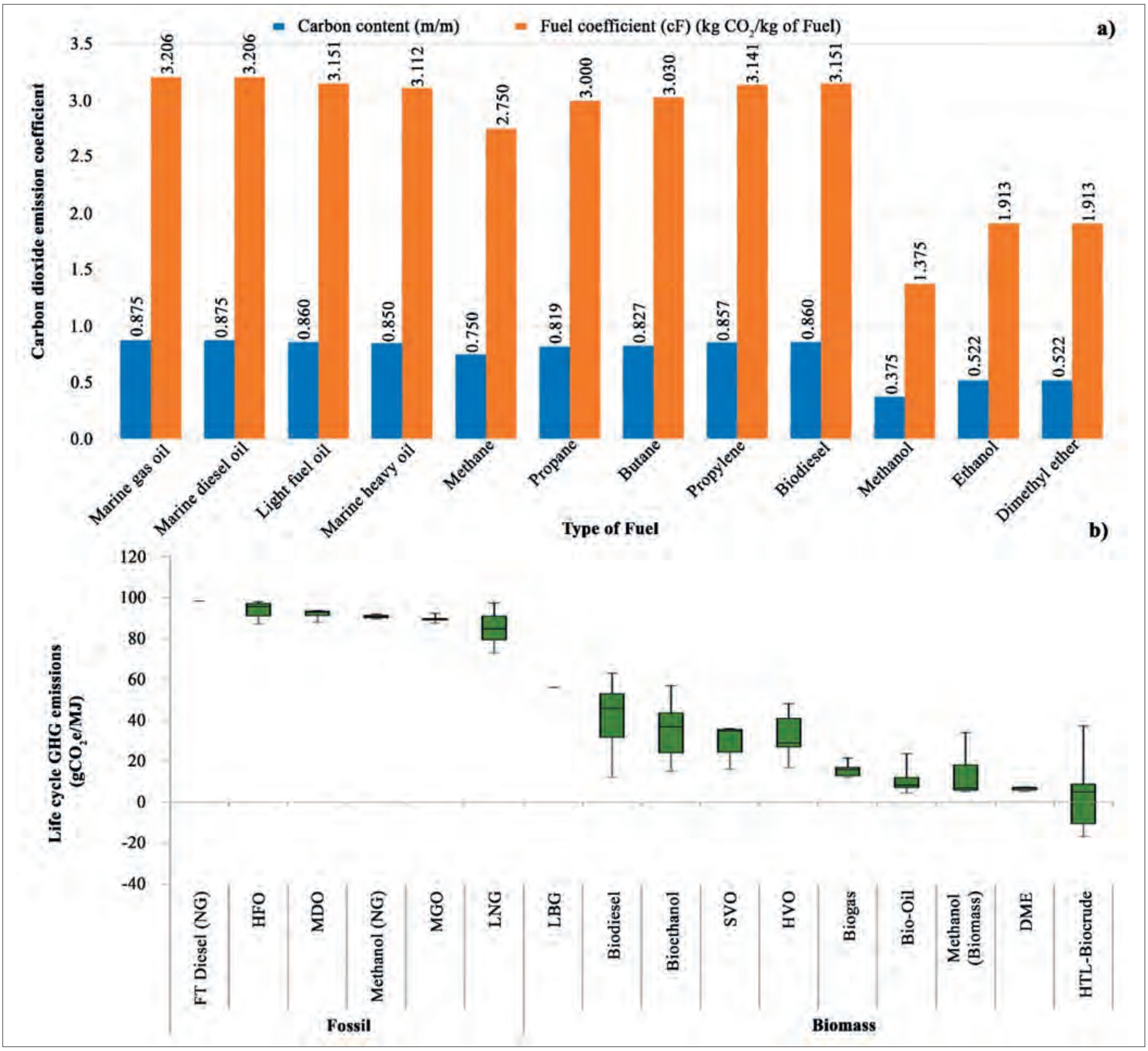

Fig. 2. (a) – CO_2 emission coefficient for various fuels used for ships [55]; (b) – Life cycle GHG emissions of various fuel types used for ships [56]–[62]

alcohol-sourced fuels, it plays a vital part in progressing the final aims. Indeed, LNG was identified as the best fossil alternative for the replacement of MGO and HFO, since it emits 30% less GHG and contains no NOx or SOx [66]. It should be noted that, although the first ship running on LNG was built in 2000, there are now 55 operating around the world; because of ECA laws, their activities are primarily in North America (38%) and Europe (57%). More importantly, for internal combustion engines running on LNG, the gas has to be stored at a temperature of −162°C [67], [68]. Nonetheless, LNG is still mostly derived from fossil fuels, so bio-LNG was suggested as a potential renewable decarbonisation source, in the document. In fact, biomass could be converted into biomethane in two ways: thermochemical gasification, known as bio-synthetic natural gas (bio-SNG), and bio-methane [69], [70], which can be liquefied and stored in tanks, to be utilised in LNG terminals [71].

The conversion of the main engine of a vessel from diesel fuel to dual-fuel (diesel and LNG) is capable of lowering CO_2 emissions by up to 10% [72]. Anderson et al. [73] studied the emission properties of a ship running on LNG with four dual-fuel engines rated as 30,400 kW at various loads. LNG's CO_2 emissions were reported to be lower, compared to those of marine fuel oils. The combustion of LNG, on the other hand, caused greater HC and CO emissions. Li et al. [74] obtained similar results with a maritime dual-fuel diesel engine at high speeds. Thus, LNG not only has a good environmental impact because of its lower CO_2 emissions, but it also brings a significant cost benefit [72], [75]. In addition, evaluating the environmental advantages of switching from HFO to natural gas by changing the average emission parameters of NOx, SOx, PM, and CO_2, for both LNG and HFO, for diesel engines with two strokes and using the same power and operating hours (in the case of an engine running on dual-fuel) were also found in studies of Banawan et al. [72] and Gerilla et al. [76]. With the use of statistical analysis, researchers discovered that switching from HFO to LNG reduced PM, SOx, CO_2, and NOx emissions by approximately 96%, 98%, 11%, and 86%, respectively [77].

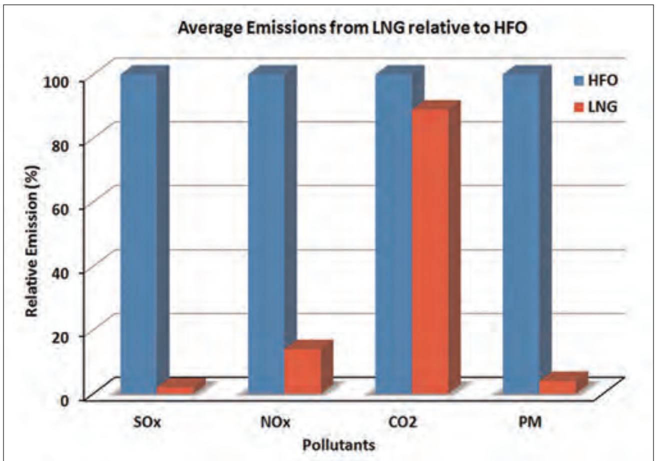

Fig. 3. Pollutants from ships using LNG compared to HFO [77]

More significantly, because of the costlier propulsion plant, related technology and procurement issues, the capital expenses for LNG-powered vessels are likely to be greater than those for conventionally powered ones. Interestingly, the LNG tank was considered the most expensive component of the additional expenditure required for all ships. According to market sources, the additional capital cost could range from 5-20 million USD, based on the tank and engine capacity [78], [79]. The key elements affecting payback time included (i) - ECA exposure, and (ii) - the price of LNG fuel. Even though the limit of global sulphur in the year 2020 or 2025 would enhance the business case, by requiring mandatory compliance for the whole journey, the uncertainty of the LNG fuel's availability and pricing makes vessel owners and operators cautious. In general, the additional expenses for a ship running on LNG (mostly applying to merchant ships like tankers, bulkers, and containers) was 15-30% of the cost of a newly built conventional ship [79]. In spite of the regulatory momentum, most major impediments to LNG adoption as a marine bunker are the financial and commercial uncertainties related to the LNG fuel price and its availability (bunkering facilities), and the considerable additional investment required. According to the current market status, the only ships that are likely to apply LNG as a fuel are those running on fixed routes such as containerships, or RoRo, and rather large ships participating in regional trades, particularly in ECAs [78], [80], [81]. Furthermore, the global sulphur restriction, which would come into effect in 2025, as well as the EU's sulphur limit for EU waters (2020), bolstered LNG's position as a marine fuel. When the afore-mentioned laws took effect, it was envisaged that larger ocean-going ships (namely tankers and bulkers) would investigate LNG as a compliance choice [79], [82].

BIODIESEL

As reported, biodiesel is considered to be one of the renewable sources of alternative energy and it has been studied by the world's oil industry because demand for fossil fuel is increasing, leading to high prices [83], [84]. Interestingly, biodiesel has nearly the same functional features as fossil fuels but is environmentally friendly, so it is regarded as a superior alternative [85]–[87]. Besides the sustainability of biodiesel production, its benefits also include a significant reduction in carbon emissions, more environment related job opportunities, a reduction in the requirement for imported fossil fuel, and a decrease in fuel costs. Furthermore, biodiesel can be used in diesel engines directly, with no modification required although some drawbacks of biodiesel should be overcome [88], [89]. It is easy to see why biodiesel gained favour as a greener alternative fuel and, recently, most scientists and researchers utilised edible and non-edible feedstocks to create more cost-effective bio-based diesel mixtures and boost the physicochemical features of the blends [90]–[93].

In fact, the study of biodiesel fuel in the marine field has been ongoing since 1998. The Great Lakes Environment Research Group conducted extensive biodiesel testing on board the NOAA Huron Explorer research ship, which was the first US vessel powered by alternative fuel and operated entirely without the use of petroleum products [94]. After eight years, the Great Lakes Maritime Research Institute conducted investigations on various technical issues related to the biodiesel fuel employed in marine engines. They stated that biodiesel served as a solvent and might harm the rubber and elastomer components used in the engine. Moreover, in 2003, the Annis Water Research Institute carried out another investigation on Detroit and Cummins' diesel-fuelled engines, utilising the same feedstock. They claimed that using B20 soybean would have a small effect on the engine, while causing no harm to machinery equipment [95]. The BioMer Canada research team employed neat bio-based diesel on several sizes of marine ships, in October 2004; their testing resulted in a successful outcome, with a rise in engine performance of 2-3% with the use of bio-derived diesel [96]. Moreover, BV energy tested biodiesel on a MAN diesel engine with 975-kW, placed on a luxury boat in 2007. Consequently, they stressed that before transitioning from marine gasoline to bio-originated diesel, fuel filters should constantly be adjusted and fuel tanks should be cleaned [97]. The Royal Caribbean Cruise Line fleet's biodiesel initiative began with the testing of 5-100% bio-based diesel on their GE LM2500 gas turbine. The findings showed that biodiesel gasoline, soot and other pollutants greatly decreased [98], [99]. Notably, MAN Diesel Company, which is a global designer and engine manufacturer, has been working with biodiesel since 1994. They investigated various biodiesel feedstocks in order to figure out the best fuel for their engines. In Copenhagen, Denmark, the first biodiesel experiment on their low-speed engines with two strokes was conducted in 2006 [100]. In 2007, MAN Diesel utilised palm biodiesel in their medium speed engine with four strokes in Belgium, marking a new milestone. MAN Diesel currently offers a large selection of marine engines which can be ideally used with biodiesel fuel with no changes. Apart from that, Rolls-Royce, the world's largest maker of medium-speed engines, indicated that they had no experience with bio-derived diesel on their engines, but biodiesel needed to be suitable for marine engines in general. In addition, following multiple buyer requests, they wanted to devote greater attention to alternative fuel in future [94]. Caterpillar Incorporated, a marine engine manufacturer in the US, has considerable experience with the use of biodiesel. Investigations on Caterpillar ferry engines suggested that biodiesel could be utilised smoothly in the short term. Hence, additional research was conducted to determine the potential implications of using bio-derived diesel in marine engines in the long run. Most of Caterpillar's novel and older marine diesel engines could now employ up to 30% biodiesel with no adjustment [65], [99].

METHANOL

Methanol is another widely used alcoholic fuel [101], [102]. Indeed, methanol can be manufactured from natural gas or derived by gasifying biomass on an industrial scale. Because of its low CO_2 and other air pollution emissions, methanol, especially bio-methanol, was seen as a more environmentally friendly and more sustainable fuel for the maritime sector [103]. In the case of large marine engines, not only the transformation of existing engines, but also the fabrication of novel dual-fuel engines, aiming to operate methanol, was completed successfully in a few cases [104], [105]. In fact, methanol was extensively examined and utilised in spark-ignited car engines for many years, with minimal modifications necessary [106]. These days, bio-methanol and bio-ethanol generation from biomass could take advantage of a well-established supply network. Nonetheless, there are still economic hurdles that have to be solved in order to allow the afore-mentioned alternative fuels to compete with conventional petroleum-originated fuels [106]. More importantly, since the world's supply of alcoholic fuels taken from renewable resources has increased, bio-methanol and bio-ethanol have tremendous potential in the shipping sector. However, more storage space would be required because methanol has a lower energy density than fossil fuels. As reported, there are presently 13 ships running on methanol worldwide [107]. Methanol combustion, as the major fuel employed to power marine boats, has been observed to release less CO_2 and other air contaminants than HFO or MGO [108], [109]. In 2015, the MS Stena Germanica became the first marine ship to be powered by recovered methanol.

After investigating the use of methanol in a diesel engine with dual-fuel mode operations, Song et al. [110] gained great fuel economy and engine power, as well as lower levels of particulate and nitrous oxide emissions. Furthermore, Wärtsilä, a marine engine manufacturer, studied different methanol combustion methods for engine conversion on the Stena Germanica ferry and chose one in which the methanol was burnt using a moderate amount of pilot fuel [111]. Since 2015, retrofitted engines based on this design have been functioning satisfactorily [111]. The MAN engine manufacturers also tested methanol in low speed two-stroke LGI engines, employing a pilot fuel ignition approach, and the experiments were deemed a success. In 2016, the engines were mounted aboard seven novel chemical tankers [112]. In fact, methanol engines installed in smaller ships (pilot boats, road ferries, and commuter ferries) were not yet commercially viable but were being developed. Some proposals for the use of methanol in small marine engines (with power ranging from 250 to 1200 kW) were evaluated as part of the Swedish study project SUMMETH [113]. The 'Billion Miles' company, located in Singapore, developed a 100% methanol engine for harbour craft, with the prototype engine being assessed at a technical readiness level of 8-9 of 10 [114]. Therefore, various engine manufacturers, programmes and other efforts have evaluated methanol engines for marine applications, including large and small engines, with promising technical outcomes [106]. In assessing the potential application of methanol/ethanol as alternative fuels for marine vessels, an evaluation was conducted by the European Maritime Safety Agency on the benefits and challenges of these resources, in terms of the technical, operational, and economic factors, supply availability, environmental impacts, and safety regulations [115]. Despite the potential positive environmental effects, both methanol and ethanol still face considerable obstacles in their application to marine vessels, due to the lack of adequate safety instructions, operational experience, and capable infrastructure to satisfy the need for bunkering.

HYDROGEN AND HYDROGEN CARRIERS

Because of the near-zero emissions (such as PM, CO_2, and SO_2, etc.) throughout the combustion process, hydrogen (H_2) is regarded as a clean type of fuel and so it has the potential to become a cleaner alternative to traditional fossil fuels [116].

Moreover, H_2 fuel could be used in boilers, gas turbines, and internal combustion engines [117]–[119]. Spark-ignition engines, in particular, could better tolerate H2 fuel because the temperature of auto-ignition is really high (about 585°C) [120], [121].

All of the existing major shipping fuels are hydrocarbons. The H_2/carbon ratio is considered to be an important factor since a greater proportion can lead to a fuel that is more energy-efficient and discharges fewer CO_2 emissions [122], [123]. Thus, H_2 or H_2 carriers could become a zero-emission alternative for future transport [124]–[126]. Currently, the majority of vessels utilise combustion technologies in the form of diesel engines. Although H_2 could be utilised to power a diesel engine, retrofitting would necessitate major changes due to the dissimilar combustion rates of H_2 compared to the currently employed fuels [127]. However, with the proper infrastructure, de-Troya et al. [128] proposed that H_2 engine performance might outperform oil-derived fuels because of its high gravitational energy density and flammability. Significantly, a fuel cell was considered the most efficient way to extract energy from H_2. Several small vessels running on H_2 have been built with relatively low energy consumption, e.g. the Energy Observer or the Hamburg Ferry [129], [130].

In the shipping industry, H_2 has been the focus of studies into viable ship engine types, investigating the benefits from the fuel's increased power density, as well as the lower emissions of pollutants. More importantly, taking the evaluation of the life cycle into consideration, H_2 utilised in marine transportation (even as a fuel employed in a dual-fuel engine mixed with other types of fossil fuel) was observed to have the potential to decrease CO_2 emissions by up to 40% per unit of transport task [131]. Even though H_2 is largely accepted in maritime fuel cell applications, the applications of marine motors powered by H_2 remain rare. Wärtsilä tested spark-ignited engines fuelled by LNG and H_2 in two modes, including single fuel and dual fuel, and discovered that current dual-fuel marine engines could only operate with the largest amount of 25% H_2 mixture with no modification [132]. Hence, the engine had to be modified if the H2 ratios exceeded 25%. CMB's passenger ship 'Hydroville' has been recognised as the first sea-going ship fitted with dual-fuel engines, such as H_2 and diesel, in the world. More intriguingly, HyMethShip created a technique for ships to use H_2 and generate methanol through storing only methanol and CO_2 aboard, with the goal of eliminating the obstacles related to storing H_2 [133]. For liquefied H_2 storage, it demonstrated that the tank capacity for liquid H_2 was double that of LNG. Hence, with engine technologies based on methanol, the disadvantage mentioned above for H_2 marine engines can be solved, as shown in Fig. 4.

Ammonia had a pre-existing worldwide supply chain but mostly in the field of fertilisers, with a total annual production of 176 million tons in 2018 [134]. As a result, pre-existing worldwide safety regulations were considered advantageous and production scaling might be less difficult. Current ammonia generation methods typically employ fossil fuels to generate H_2 feedstock, followed by the Haber-Bosch process, which is extremely energy intensive because high pressures (20 MPa) and high temperatures (500°C) are required [135]–[137]. Consequently, ammonia generation now comprises 2% of the

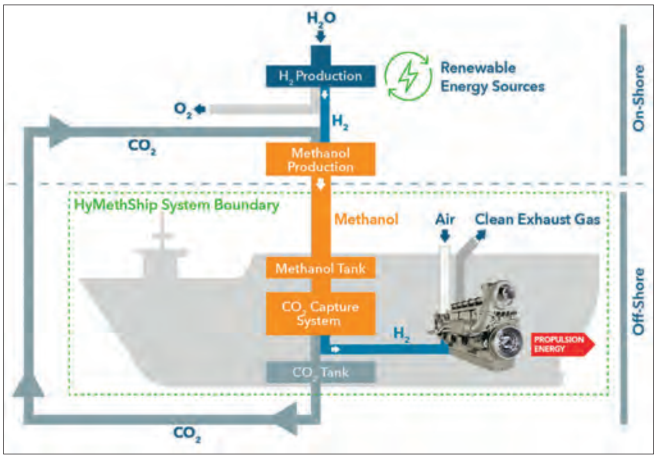

Fig. 4. HyMethShip with the engine running on H_2 and integrated in a methanol production system [133]

world's energy consumption and 1% of CO_2 emissions, making it the most energy-consuming chemical product [136]. Thus, expanding ammonia manufacturing for applications in maritime propulsion might lead to an enormous increase in emissions, unless the process can be decarbonised [130].

In dual-fuel mode, diesel fuel is mixed with ammonia fuel in order to start combustion and ammonia is partially broken to create a H_2 gas mixture. Even though ammonia can be utilised directly as a fuel in fuel cells under high temperature, the ammonia cracking process has broadened its applicability in internal combustion engines [138]. Furthermore, the ability to partially split ammonia allows internal combustion engines to operate more flexibly. In terms of maritime transportation, employing ammonia as a marine fuel in traditional marine engines is still being researched and developed, but with limited uses [139]. Indeed, the power which could be produced by a four-stroke diesel engine with ammonia acting as the fuel could match that produced by the same engine when fed conventional diesel fuel [140]. More interestingly, the world's largest diesel engine manufacturer has been developing a two-stroke diesel engine that would run on ammonia as its principal fuel [141]. According to the statistics released by the European Transportation and Environment Group, the quantity of ammonia needed for conventional marine engines aboard vessels would be in the region of 1230 MWh annually by 2050 [142]. Moreover, Bicer et al. [143] highlighted the overall environmental benefits of employing ammonia in traditional marine diesel engines without providing any particular results. Meanwhile, MAERSK [144] has stated, in a technical report, that ammonia could become one of the greatest positioned fuels for conventional marine power factories to achieve zero net emission goals.

LPG

It should be noted that the components of LPG are similar to those of LNG; however, unlike LNG, LPG liquefies at an ambient temperature and steady pressure, without the necessity for low-temperature cooling to −162°C. Apart from that, LPG has been demonstrated to be economically attractive, in terms of shorter payback periods [145], [146], lower investment expense, and less vulnerability to fuel price variations [147], [148]. Furthermore, because most materials employed in fuel supply systems and LPG storage tanks are considered appropriate for ammonia storage, it is conceivable to reduce the compulsory methods for future conversion into ammonia fuel storage tanks [149]. There are significant commercial examples of its use in huge vessels utilising the ME-LGIP engine, built by MAN-ES and powered by LPG fuel [147], [150]. According to the World LPG Association, 71 LPG-fuelled ships were scheduled to be in operation by 2022. As for vessels of small and medium size, technological development and commercialisation is underway, with a focus on small boat outboard motors in the US and Europe. Despite this, the level of development of LPG engines that could be commercialised for ships of small to medium size, is still low [151]. In terms of volume, the small and medium vessel market is equivalent to the large vessel industry; however, it copes with significant technological challenges in the deployment of LPG in vessels, [152].

Nowadays, utilising LPG as an alternative fuel for internal combustion engines has gained popularity, despite the fact that LPG plays a trivial role in the marine industry and the shipping domain. The vast majority of diesel engines continue to use CNG and LNG as alternative fuels [153]. Nevertheless, since the 2020 IMO mandate was put into effect, LPG has received some attention because the use of LPG in marine engines powered by mono fuel lowered CO_2 emissions by roughly 10-20%, although a diesel-powered marine engine has greater thermal efficiency. Speaking of dual-fuel marine engines, it was noted that a small amount of diesel fuel is still utilised to start the ignition before switching to LPG combustion [146]. As reported, marine engines can operate using up to 3% diesel and 97% LPG fuel, resulting in low CO_2 emissions. More importantly, dual-fuel diesel engines were thought to be more efficient since they have excellent performance and dependability when compared to diesel engines that only run on diesel fuel. Wärtsilä and MAN undertook an investigation, employing LPG for tri-fuel engines that were powered by LNG, diesel, and LPG, according to a recent report. Furthermore, Wärtsilä conducted the first experiment on a container vessel with 7300 TEU. Even though these studies were preliminary, applying LPG could be a viable method for decreasing CO_2 emissions [154]. More intriguingly, the MAN B&W engine manufacturer developed a method to reduce CO_2 emissions by using both ammonia and LPG in marine engines [155]; they claim that a small adjustment to the LPG system for applying ammonia would be made, as depicted in Fig. 5.

ENERGY AND FUEL SAVINGS FOR SHIPS

As a general assumption, the relationship between the required power and the speed of the ship can be portrayed in a cubic function. For example, a 10% decrease in the ship's speed corresponds to a 27% drop in the amount of required power. Hence, it is logical to assume that by decreasing the design speed one could save on potential fuel consumption and CO_2 emissions from ships. Moreover, maintaining slower engine speeds can provide better propeller efficiency and further realise additional cost savings. As a potential strategy in reducing shipping emissions, ports can establish regulations and policy incentives to reduce vessel speeds upon entering ports that could result in lower fuel consumption and emissions [156]. Indeed, decreasing ship speed can result in an approximately 8-20% reduction in CO_2 emissions [157]. Other studies have also reached similar conclusions, in which reducing speed by as much as 10% and 20% leads to a potential fuel saving of 15-20% and 40%, respectively [158], [159]. A recent study by Ammar [160] investigated the effects of ship speed on the reduction of CO_2 emissions and the cost-effectiveness of a RO-RO cargo vessel. They indicated that approximately 78.39% of CO_2 emissions, with 287.6 $/ton CO_2 cost-effectiveness, could be reduced when

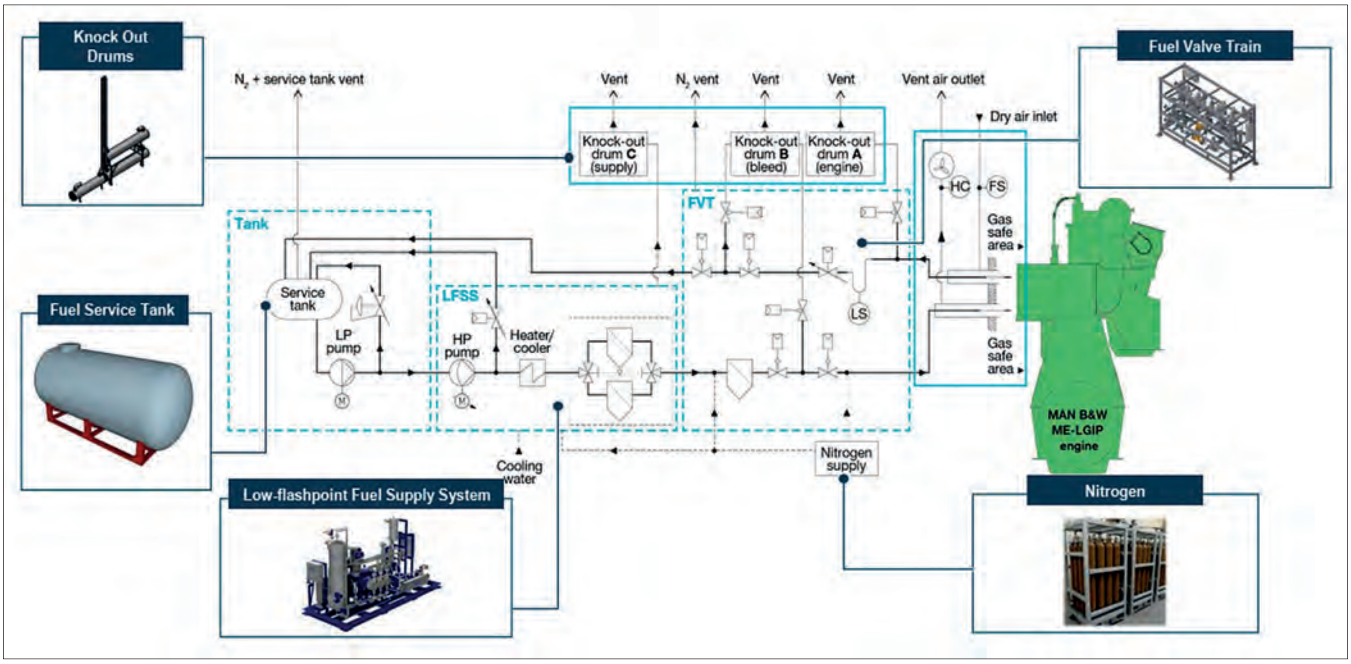

Fig. 5. Scheme of LPG and ammonia system for marine engine suggested by MAN B&W [155]

the ship speed decreased by 40%. In order for the optimisation strategy for ship speed to achieve minimum emissions in the port area, Chang et al. [161] presented a method to estimate the most suitable ship speed. They detected that 12 knots can be considered as the optimised speed to attain both low CO_2 emissions and cost-effectiveness, as shown in Fig. 6a. When combining the slow speed approach with power supply from the onshore grid, potential emission reductions can be as high as 71-91%, as ships are subjected to a 20 nautical mile speed limit within the designated area of the Port of Kaohsiung, Taiwan [161].

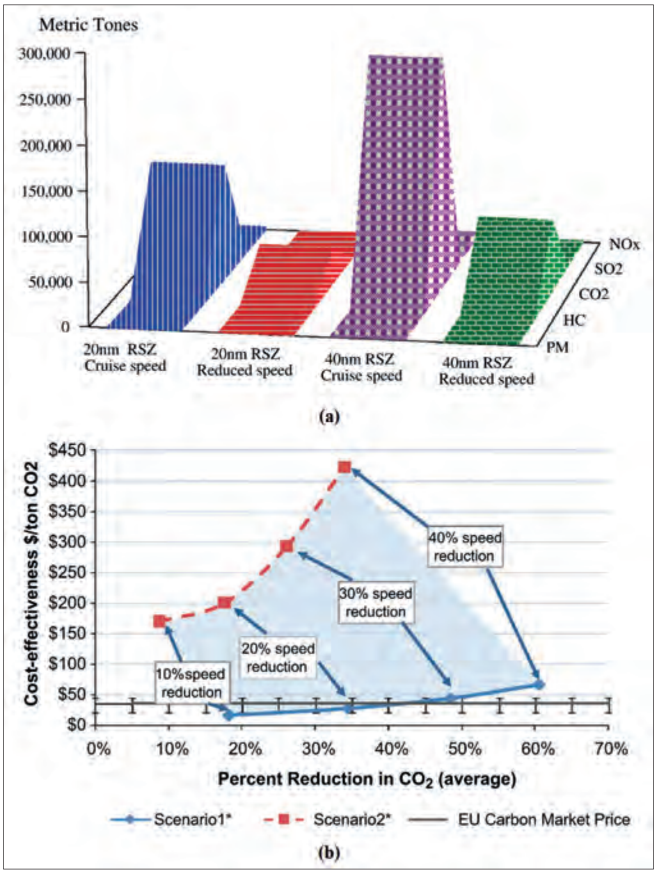

Fig. 6. (a) – Effects of the reduction of ship speed in the reduced speed-zone on emissions [161]; (b) – The marginal reduced-cost for CO_2 emissions using the change in total profit from the reduction of ship speed [162]

Moreover, Woo et al. [163] investigated the impacts of the slow steaming process on CO_2 emissions in liner shipping. They also found that more CO_2 emissions could be decreased in the case of reducing the voyage speed. More importantly, they found that around 90% CO_2 emissions could be reduced on the Asia/Europe route when the ship was operated within a speed range of 15-17 knots. Finally, the optimised result of voyage speed for CO_2 emission data and operating cost was 17.4 knots. According to Yun et al. [164], reducing speed from 24 to 8 knots could obtain up to 48.4% in CO_2 emissions reduction. However, the reduction of ship speed could negatively affect profit. Therefore, Corbett et al. [162] developed a profit-maximising function by incorporating costs relating to the ship speed reduction. They found that $150/ton for a fuel tax, combined with a reduction of ship speed of about 20–30%, resulted in a maximised reduction of CO_2 emissions of ships in US ports (Fig. 6b). In general, the reduction of speed, as well as the application of slow steaming to the ship operations in the port area, is considered a feasible approached to reduce CO_2 emissions. The effects of speed reduction or slow steaming of the ship on the decrease of CO_2 emissions in the port area are given in Table 2.

Tab. 2. Reduction level of CO_2 emissions in the port area by the application of speed reduction or slow steaming of the ship

Route/Ports	Applied strategies	CO_2 emission reduction level	References
Asia/North America	Slow steaming/ Speed reduction	29,400.10³ tons	[165], [166]
North Atlantic		5778.10³ tons	
Australasia/ Oceania		6275.10³ tons	
Latin America/ Caribbean		16,200.10³ tons	
Middle East/ South Asia		22,900.10³ tons	
Shanghai to Rotterdam		5000.10³ tons	[167]
Various ports		0 – 60%	[14], [30], [168]
Kaohsiung Port Taiwan		14% for the bulk vessel; 41% for container vessel	[169]
Port of Gothenburg		50 – 80%	[170]
North Europe–Asia		37%	[171]
Port of Rotterdam		6300 tons	[172]
Taichung Port		20 tons/1000 kW of ship power	[173]

Regarding the management of operational efficiency and emissions at the ship-port interface, measures are considered for the ports that ships are scheduled to arrive at and allowed to moor, also known as ports of call. Studies have provided comparisons of shipping GHG emissions to port emissions in the Port of Barcelona [174]: 63–78% of port emissions in the Port of Oslo [175], 61% in the Port of Gothenburg, 66% in the Port of Osaka, 8% in the Port of Sydney, 18% in the ports of Long Beach [176], and 53% of GHG emissions from the ships at berth in San Pedro Bay [177]. For UK ports, emissions from ships at berth have been observed to be ten times higher than emissions from port operations. Hence, it is suggested that ports should pay more attention and make more of an effort to reduce shipping emissions [178]. The potential of reducing shipping emissions depends on the frequency of port revisits for each vessel. The greater the number of ship calls for a particular ship, the greater the opportunity for emission reduction [176].

In most cases, the order of ships arriving and berthing at ports generally follows a first-come-first-served basis, which could lead to longer turnaround times and higher shipping emissions. In their study, Styhre et al. [176] examined four different ports and observed between 8-88% of GHG emissions from ships docking at these ports. Hence, they recommended reducing turnaround time as a potential strategy in achieving lower GHG emissions from ports. According to Moon et al. [179], a 30% reduction in turnaround time can reduce CO_2 emissions by up to 37%. In contrast, when turnaround time increases by the same percentage, annual CO_2 emissions are observed to rise by 30.7%. In the case of Johnson et al. [180], their analysis showed that a decrease of 1-4 hours in turnaround time can yield 2-8% in energy savings. Additionally, supportive port policies can facilitate the transition toward shorter ship turnaround times in ports. Other factors that can influence turnaround time include CHE efficiency and mooring operation time [164], [178], [181], [182]. In their study, Navamuel et al. [183] found that the use of an automated mooring system could reduce up to 97% in CO_2 emissions from mooring, when analysing such activities in Ro-Ro/Pax terminals. In Piris et al. [184], automated mooring systems were proposed for the Santander port, which would reduce CO_2 emissions by as much as 76%. The application of automated mooring systems have also been found among major ports in European countries, including Finland, the Netherlands, and Denmark [183]. In another study, Gibbs et al. [178] examined the integration of virtual arrival assistance to enable the exchange of information and communication in optimising the accuracy of arrival and berthing time, vessel speed reduction, and slow steaming. The authors cited a maximum potential fuel saving of up to 27%, while the average figures could be between 12-20%. Several studies have also supported the use of 'virtual arrival' as an effective strategy in reducing shipping emissions [172], [182], [185], [186].

The major purpose of EEDI and the plan to manage vessel energy efficiency is to reduce CO_2 emissions discharged from maritime transportation [187], [188]. As shown in Table 1, the emissions reduction targets set by EEDI are listed by each implementation phase in the future. As required by EEDI standards, the IMO regulation requires ships to comply with a minimum of 20% emissions reduction by 2020, followed by a progressive increase to a 30% reduction target, beginning in 2025. Both the vessel's structural design and operations are subject to these stringent efficiency requirements [46]. Even though the majority of current energy-saving potential is held within the improvements in the structural design of the vessel body, more attention is needed to focus on the efficient operation of marine engines and the potential use of alternative low-carbon forms of energy to power ships. Indeed, the tendency towards the reduction of CO_2 emissions in the world's shipping industry was mostly driven by increasingly more stringent international rules and advancements in alternative fuel applications. Even though there is a long way to go to fully realise the practical implementations and wide adoption of zero or low-carbon fuel in powering marine vessel engines, the progress which has been made, in both the fuel and efficiency performance of current fossil-fuel-powered engines, is highly commendable and signals a positive future trend. Hence, advances in marine diesel engine efficiency improvements are critical in the current effort to achieve future emission reduction targets. It has been observed that, insofar as the EEDI served as a goal, it was not a particularly difficult one, since the EEDI achieved by newly-built vessels vastly exceeds the existing required EEDI, although they were not compulsory until 2025. This is particularly true of general cargo vessels and containerships [189], [190]. Notably, the obtained scores frequently do not represent the employment of novel electrical or mechanical technology; however, they could be obtained simply by optimising traditional machinery or changing the hull design [189], [191], [192]. It has been noted that the influence of EEDI on reducing shipping emissions was predicted to be minor: only a negligible change in CO_2 emissions has been identified between non-EEDI and EEDI scenarios [193]. More importantly, the reference years or mandated reductions need to become more ambitious, for the EEDI law to have a greater impact. Besides EEDI, technological approaches cover the technologies used on vessels to help boost their energy efficiency [14]. The techniques described in Table 3 are usually regarded as the key technological methods to boost ship energy efficiency and are covered by a number of documents.

Tab. 3. Relationship between technological solutions and fuel saving level [14], [30], [194]–[201]

Technological solutions	Potential fuel savings
Light materials	Max 10%
Slender hull design	Max 15%
Improvement devices for propulsion	Max 25%
Bulbous bow	Max 7%
Lubrication	Max 9%
Waste heat recovery	Max 4%

CHALLENGES AND OPPORTUNITIES

The use of clean fuels for maritime applications was either confined to certain vessel types or non-existent, which limited the evaluation of alternative fuels from an environmental perspective. Obviously, this reduced the credibility of the results obtained because acquiring emissions data for such an application was incredibly difficult. Remarkably, the widespread use of clean fuels, including ammonia and H_2, might be hampered or delayed because of problems associated with these relatively novel fuels' underdeveloped infrastructure and supply chains, particularly in the maritime industry; these include high production costs, requirements for special cryogenic storage, and high fuel transportation expenses.

It was necessary for HFO and MDO to be removed steadily and it was proposed that the advancement of vessels running on LNG, LPG ought to be cautious. Thus, power systems powered by H_2 and methanol could be regarded as a primary priority for future investigations and advancement, being the power resolutions for residential and short-sea shipping. Besides, double fuel compression ignition engines were recommended to be broadly applied in order to utilise H_2, methanol, biodiesels, or bioethanol as auxiliary and, after that, essential fuel. Indeed, certain flag, coastal and fuel-generating countries need to conduct more comprehensive life cycle evaluations of more alternative fuels as soon as possible. Infrastructure construction should consider the integrated use of raw materials and the recycled use of intermediate products, with the aim of producing by-products, alternative marine fuels and the cogeneration of power, heating and cooling. It was noted that this was a significant way to lower manufacturing costs, one of the main factors limiting the widespread use of alternative marine fuels. Moreover, increasing fossil-free energy (namely solar, wind, and nuclear) in the global energy mix and increasing carbon capture, use and storage in the industrial sector on land, could directly mitigate the world's carbon emissions as well as alleviate lifecycle emissions and alternative fuel expenses. More importantly, future research assessing renewable sources of energy consisting of wind and solar power could assist in developing technological improvements to handle the obstacles that restrict the intense employment of the aforementioned energies, like energy storage resolutions, which might cause a decrease in GHG emissions released from maritime transport. Regarding the maritime community, agreement is more potent than divergent and, besides this, decisive action, with respect to the best potential methods, was more essential (as early as possible) compared to the option of waiting or hesitating. Likewise, legal frameworks at local and global scales, as well as financial incentives, need to be passed prior to other plans and, more significantly, countrywide or local regulations and pilot tasks should be prioritised.

CONCLUSIONS AND RECOMMENDATIONS

This review article provides a general overview of various approaches for lowering CO_2 emissions from ships through thorough consideration of distinct low-carbon fuels, alternative clean renewable sources of energy, and supporting regulatory frameworks. Moreover, further implementation of intelligent energy management systems, energy conversion, consumption monitoring, and battery storage could promote the potential for energy savings.

Through powerful control and operational practices aimed towards a shipping industry that was low-carbon and sustainable, ship owners could obtain effective energy, emissions mitigation and expense savings. The further deployment of clever electricity control systems, electricity transformation, battery storage, and consumption tracking could improve energy savings. Remarkably, a systematic enhancement was needed in shipping enterprises to attain energy savings. The guidelines and regulations that did not focus on the goal of decreasing emissions and obtaining electricity performance needed changing. In fact, biofuels became an appealing choice, when combined with other fuels, owing to their outstanding commercial potential. Nonetheless, the large variety of biofuels available resulted in great diversity in emissions, prices, and usability of the resources mentioned above. In spite of the numerous benefits of biodiesel, some challenges still exist, including higher expenses of generation and feedstock, cold flow features, material compatibility, fuel stability, and a shortage of marine-grade criteria. Hence, in the preceding section, effective techniques and feasible resolutions were presented to achieve the aim of this alternative fuel utilisation in the maritime sector. Also, the introduction of a novel supply of feedstock from second and third generation bio-based diesel could alleviate generation expenses and fuel economy. Recently, there has been a surge in research into novel sources, including algae and waste oil. Additionally, formal mandates from governmental and international organizations, like the IMO, could support and improve biodiesel applications in the maritime industry. Indeed, H_2 is still a viable future bunker fuel choice, since it produces more energy per unit mass, in comparison with traditional marine fuel, while emitting fewer GHGs. Nonetheless, several barriers, such as manufacturing expenses and the particular handling needs for storage and transportation, were observed, preventing the extensive use of H_2 fuel. More interestingly, ammonia is thought to be a useful H_2 storage medium because it has a greater volumetric H_2 density when compared to liquid H_2. Nevertheless, the quantity of GHG emissions related to the current ammonia manufacturing method is significant; alternative revolutionary technologies, including thermochemical processes and solid-state synthesis, are still being researched and developed. Because of their low volumetric energy densities, it was suggested that H_2, compressed natural gas, and ammonia were only suitable for domestic and short-distance transportation, while liquefied natural gas was preferred for long-distance shipping, when taking economic factors into account. In addition, one benefit of utilising ammonia fuel is that, with simple adjustments, it could readily be compatible with turbines, engines, and burners. Not only H_2 but ammonia also shows promise for totally replacing hydrocarbon fuels. In terms of both technological and economic perspectives, renewable methanol utilised in combination with a diesel engine, provided the best future world's shipping possibility. H_2 and ammonia are known as viable short-sea fuels; nonetheless, the technological routes that combine H_2 with low-temperature fuel cells and ammonia with diesel engines outperform those combining H_2 and diesel engines or ammonia with high temperature fuel cells. Obviously, the evolution of different technological paths and combinations of fuels and propulsion systems is unavoidable, and types of ships and shipping routes are considered critical elements in the majority of appropriate combinations between fuel and technology.

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