Analysis for Decarbonization Pathways for Shipping

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Abstract. As regulations and goals for reducing carbon emissions in shipping become increasingly clear, decarbonization will become the top priority for the development of shipping industry in the coming decades. Currently, the main source of CO_2 emissions from marine engines comes from the combustion of fossil fuels, while the operation of merchant ships typically requires striking a balance between equipment investment costs and the efficiency of CO_2 emissions reduction. Thus, choosing a more suitable approach for ships is a hot topic of concern. This article summarizes three decarbonization methods, including reduction of energy consumption by speed reduction and air lubrication, using low-carbon and carbon-free fuels to substitute conventional marine fuels, and carbon capture. These methods are analysed for their technical feasibility, decarbonization capacity, safety, economy, and technical readiness. To achieve the short-term CO_2 emissions reduction goal, there are various technologies to be applied, individually or in combination. Carbon-free fuels internal combustion engines can meet the long-term goal and its fuel cells will be the ultimate choice for net-zero scenario.

1. Introduction

As a response to climate worsening, more than 60% of the countries have declared “net-zero” on target. The topic of greenhouse gas (GHG) emissions reduction in international maritime transport has been initiated by the International Maritime Organization (IMO) since 1997. After two decades, the concrete pilot strategy was confirmed in 2018 through the 72nd session of the Marine Environment Protection Committee (MEPC) of two targets respectively. The short-term target is to reduce global average CO_2 emissions per unit of transport activity from maritime transport by at least 40% by 2030 compared to the 2008 baseline, and the long-term target is to reduce emissions to 50% by 2050 and pursue a 70% GHG reduction. For this reason, there is an estimate that at least 70% of marine engines will need to be changed or modified to meet these IMO regulations [1].

The world trade derives 80% of its freight from ships, which is by far the least carbon-intensive method for commercial transport in terms of emissions by weight [2]. However, based on the statistics from International Energy Agency (IEA) 2021, transport accounts for 21% of global CO_2 emissions, with shipping contributing 11%. In addition, if no mitigation measures are considered while maritime transportation continues to develop under business-as-usual, the share of GHG emissions from shipping will reach 17% by 2050 [3]. Such a situation is far from the IMO's 2050 ambition, and the whole shipping industry is facing severe challenges to reduce emissions.

Shipping is recognized as one of the ‘hard-to-abate’ sectors, primarily due to the regulation difficulties and insufficient technical readiness of green technologies. Because of the mobility of ships, which consume fuel both during their voyages and in-port times, it is difficult to determine the exact amount of GHG emitted by ships within the jurisdiction of the coastal state, port state or flag state, or in areas not under the control by any competent authority, thus the carbon emissions from shipping are not incorporated into the low carbon reduction schemes of the Kyoto Protocol and the UN Framework Convention on Climate Change. Although IMO has conducted regulations such as Energy Efficiency Design Index (EEDI), Energy Efficiency Existing ship Index (EEXI) and Carbon Intensity Indicator (CII) in 2023 to limit CO_2 emissions from ships, very few ships are able to meet the regulations on the continuous basis. According to the Det Norske Veritas (DNV) data for fuel types uptake in the world fleet 2022, 98.8% of the ocean-going vessels in service use conventional fuels to provide the primary propulsion. Moreover, conventional fuel type vessels account for around 75% of new shipbuilding orders in 2022 [4]. It is evident that in maritime transportation there is a gradual shift from conventional fuels to low-carbon applications, but this transition needs to be carefully weighed as the priority of shipping is based on safe operations.

This article provides three general categories of the net-zero transition that are widely discussed in the shipping industry, which are reduction of energy consumption, alternative fuels and carbon capture onboard. The aim of energy consumption reduction is to consume less fossil fuel. For alternative fuels, there are two types, low-carbon fuels such as methanol, methane, etc. and carbon-free fuels such as ammonia and hydrogen, these reduce carbon emission from the combustion

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process. Another option for merchant vessels carbon neutral transition is an aftertreatment measure, for decarbonization, carbon capture is an incipient technology for maritime applications which had been proven at onshore applications.

This article is structured as follows. In Section 2 to 4, the mentioned three types of technologies will be elaborated with technical principles, analysis of the decarbonization potential and notation of deficiencies. Two typical energy efficiency improvements are described in Section 2. The current status of research into low and zero carbon fuels in marine applications is presented in Section 3. The research progress on carbon capture system onboard is illustrated in Section 4. In Section 5, the conclusions and outlooks for the strategies for decarbonizing the shipping industry are raised.

2. Reduction of energy consumption

Limited means of retrofitting for the majority of existing ships can be used to enhance their hull shape or propulsion systems [5]. Reducing energy consumption is the friendliest to existing vessels, these methods can often be achieved through computational refinements or small-scale modifications. Thus, reducing energy consumption would be more acceptable for shipowners to reduce CO_2 emissions since they require less investment. This section will focus on two typical engineering applications: speed reduction and air lubrication.

2.1 Speed reduction

Technically speaking, reduction in speed is one of the most immediate ways for ships to reduce CO_2 emissions in the short term, supervision and mandatory regulation are indispensable. For ocean-going vessels, the prediction of fuel consumption per unit distance over the sailing speed can be demonstrated by a cubic function [6, 7], thus reducing speed can considerably reduce fuel consumption. A study conducted by CE Delft shown that if only the speed reduction is considered, the CO_2 emissions reduction potential of the three mainstream ship types including Container, Dry bulk and Crude & product tanker ranges from 10% to 38% by reducing their speed by 10%~30%, as shown in Figure 1 [8].

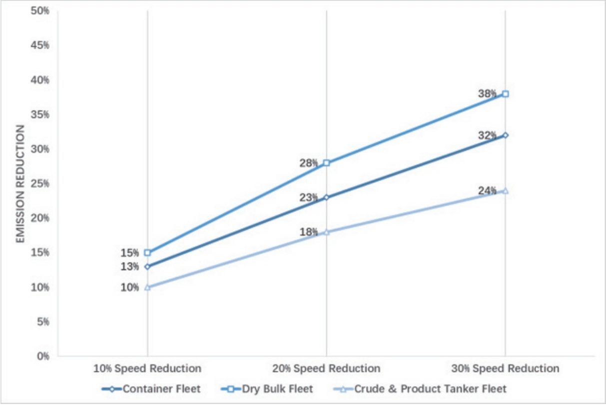


Fig. 1. Potential of speed reduction for CO_2 emissions reduction (Picture credit: Original)

To make detailed illustration, a specific case study for a 7,000 DWT bulk carrier quantifies its CO_2 emissions, sailing time and total costs based on a minimum sailing cost scenario (Scenario 1) and a minimum carbon emissions scenario (Scenario 2) with the same fuel price, as shown in Figure 2 [9].

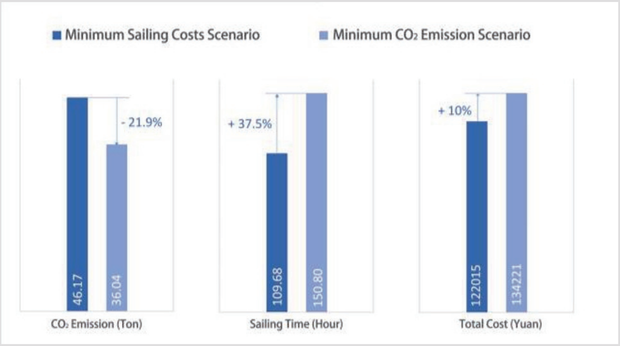


Fig. 2. CO_2 emissions, sailing time and total costs on two scenarios of a 7,000 DWT bulk carrier *Total cost include fuel cost and operation cost (Picture credit: Original)

Scenario 2 has a lower speed, 37.5% longer sailing time and 21.9% lower CO_2 emissions compared to Scenario 1, confirming that speed reduction can reduce CO_2 emissions to a certain extent. From an operating standpoint, despite the reduction in speed also reduces fuel consumption and fuel cost, the operating cost increase significantly due to the longer sailing time, resulting in 10% higher in total cost.

For shipowners, profitability is the priority. Thus, the primary motivation for the reduction in speed is not environmental, but economical. The minimum CO_2 emissions scenario is eco-friendly. However, if fuel price decreases or market demand increases, there will be less incentive to reduce speed. When this occurs, it will be essential for the government to regulate shipowners through increased carbon taxes, mandated slowdowns and etc.

2.2 Air lubrication

Reducing ship speed can decrease CO_2 emissions, but it also brings a series of additional problems, such as extended voyage duration and increased costs. Unlike speed reduction, air lubrication technology utilizes the reduction of friction between the ship's body and seawater to enhance energy efficiency without bringing the counter-effect caused by speed reduction.

The total resistance R_T of a ship is mainly caused by frictional resistance R_F, wave resistance R_W, eddy resistance R_E and air resistance R_A, as shown in Formula (1) and Figure 3.

$$R_T = R_F + R_W + R_E + R_A \qquad (1)$$

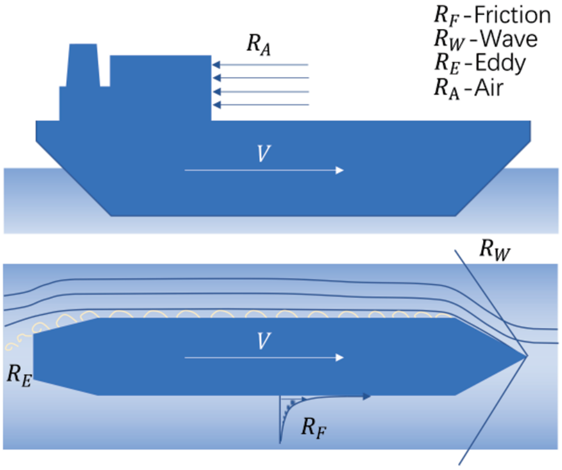


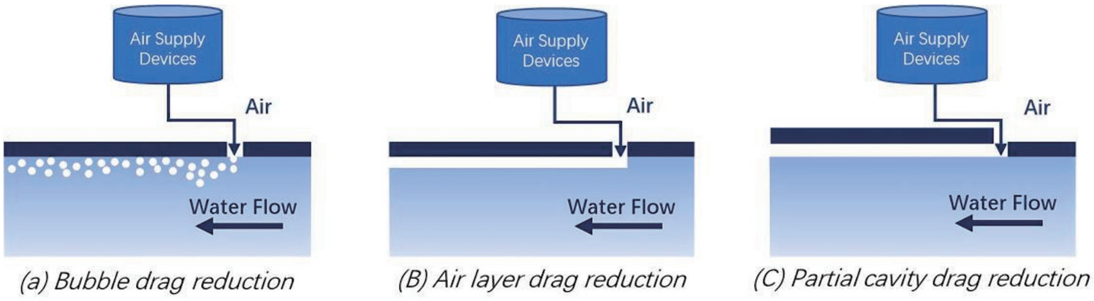
Fig. 3. The composition of the total resistance of a ship (Picture credit: Original)

According to research conducted by MAN et al., the largest composition of R_T for low-speed ocean-going vessels comes from the friction generated through sea water and the wetted area of the hull, which typically ranges from 70% to 90%, as shown in Table 1 [10].

Table 1. Share of total resistance by different type

Resistance type	Share of total resistance	
	High speed ships	Low speed ships
R_F	$45-90$	
R_W	$40-5$	
R_E	$5-3$	
R_A	$10-2$	

Ships being design at a certain speed, requiring energy to overcome resistance, air lubrication is mainly designed to reduce the R_F, thus less energy required. When the ship's thrust output remains constant, a decrease in resistance means a higher sailing speed. Furthermore, a decrease in resistance at a given design speed can reduce the power required, thereby reducing fuel consumption and CO_2 emissions. Currently, several manufacturers have begun to supply air lubrication systems, such as Mitsubishi Heavy Industries and Sliverstream. The equipment mainly includes air supply devices, air layer/bubble generators, and air escape prevention devices, etc. The principle of air lubrication involves pumping air below the ship's hull to create a continuous layer of air or a series of discrete bubbles to reduce the wetted area and friction coefficient, thus reduce R_F. There are three types: bubble drag reduction, air layer drag reduction, and partial cavity drag reduction. The basic working principle is shown in Figure 4.



(a) Bubble drag reduction (B) Air layer drag reduction (C) Partial cavity drag reduction

Fig. 4. The basic working principle of three types of air lubrication (Picture credit: Original)

Silverstream together with the University of Southampton had made the tank test to prove that the air lubrication system can reduce the fictional resistance up to 50% and make net energy saving by 4%~8%, additionally, the bubble didn’t cause any corrosion issue to hull coating and propeller [11]. The maximum emission reduction ability of air lubrication system is not high, but its irreplaceable advantage lies in low investment and almost no side effects.

Ways to reduce energy consumption or energy loss on ships also include installing shaft generators, waste heat recovery systems, etc., all of which aim to reduce fuel consumption and thus decrease CO_2 emissions. However, the reduction rate of these applications generally does not exceed 15% [12]. Combining with speed reduction and air lubrication, it can be proven that reducing fuel consumption is a relatively low investment and effective method for short-term net-zero transition, but for long-term goals, this method is still far from enough.

3. Alternative fuels

Effective utilization of low-carbon and carbon-free alternative fuels are necessary measures for the carbon-neutral transition of the shipping industry. According to IMO, starting from January 1, 2023, all ships must meet both the technical energy efficiency requirements (EEDI, EEXI) and the operational requirements (CII). These regulations have affirmed how to calculate the mass of CO_2 emissions from ships. Based on Huang et al.'s integration, this can be summarized as Formula (2) [13].

$$M = FC_j \times C_{F_j} \tag{2}$$

In the formula, M represents the amount of CO_2 emitted per unit time, j represents the type of fuel, FC_j represents the total mass of j type fuel emitted per unit time, and C_{F_j} represents the conversion factor between fuel consumption and CO_2 emissions.

Different carbon content in different fuels determine the quantity of CO_2 emitted after combustion. MEPC 76 listed the current mainstream C_F values for marine fuels, shown as Table 2 [14].

Table 2. C_F values for marine fuels

Type of fuel	Lower calorific value (kJ/kg)	Carbon content	C_F (t-CO_2/t-Fuel)
Diesel/Gas Oil	42,700	0.8744	3.206
Light Fuel Oil	41,200	0.8594	3.151
Heavy Fuel Oil	40,200	0.8493	3.114
Liquefied Petroleum Gas (LPG)	46,300	0.8182	3.000
	45,700	0.8264	3.030
Liquefied Natural Gas (LNG)	48,000	0.7500	2.750
Methanol	19,900	0.3750	1.375
Ethanol	26,800	0.5217	1.913

Through the comparison of different fuels in the table, it can be observed that the lower the carbon content in the fuel, the lower the C_F, which indicates a lower level of CO_2 emissions.

3.1 Low-carbon fuels

A hypothesis, without altering the engine output power, which means the engine produce the same total heat value, by replacing the conventional fuel with LNG. Assuming that the thermal efficiency of a marine engine remains constant, the diesel consumption required for 3000 kW is 180 g/kWh, and thus the calorific value of diesel produced is 7686 kJ/kWh, 577 g/kWh CO_2 emitted. In conditions where the same calorific value is required and no ignition oil is used, the LNG consumption is 160 g/kWh, 440 g/kWh CO_2 emitted. CO_2 emissions level by LNG-powering reduced 24%. Wang et al.'s research provides more comprehensive results, using LNG as fuel can reduce CO_2 emissions by 20%~30% [15]. However, it should be noted that when using LNG as fuel, methane leakage can reach 2%~3%, as methane's global warming potential is much greater than CO_2, if the leakage exceeds 5.5%, the advantage of LNG as a low-carbon fuel compared to conventional fuels will be negated [16]. Methanol is another popular low-carbon fuel applied onboard. However, because of its low Lower Calorific Value (LCV), in order to achieve the same power output, it is necessary to burn more methanol, which results in small CO_2 emissions reduction compare to burning diesel [17]. From an economic perspective, a common shortage for LNG and methanol is that to storage the same amount of energy, the space required for storing either of them is approximately twice that of traditional diesel fuel [18, 19]. Furthermore, in practical applications, the flammability of LNG and the corrosiveness of methanol to pipelines must be taken into consideration, additional equipment is necessary for monitoring to ensure safety.

For short term, Low-carbon fuels, represented by LNG and methanol, can make certain contributions to CO_2 reduction, but are insufficient to achieve the longer-term goal [20]. For long term, the pathway for low-carbon fuels' production should shift from fossil fuel energy to renewable energy to enhance the carbon-neutral potential.

3.2 Carbon-free fuels

Hydrogen and ammonia, as carbon-free fuels, are becoming the trend for ships in replacing conventional fuels. Since hydrogen and ammonia molecules do not have carbon elements, their theoretical value of C_F is zero. However, it is crucial that the sources of these energy must be sustainable and green.

Currently, over 95% of hydrogen production comes from fossil fuels, primarily natural gas, oil, and coal [21]. Moreover, hydrogen is typically present in the form of compounds, implying that extracting hydrogen requires additional energy consumption. This method of acquisition is known as grey hydrogen, and it results in significant carbon dioxide emissions. The production of green hydrogen primarily comes from electrolyzing water to produce hydrogen, with the electricity used in the process coming from renewable sources. The study conducted by Li et al. provides the cost and CO_2 emissions under current technology of producing grey, blue, and green hydrogen, shown as Table 3 [22].

Table 3. Comparison of three types of hydrogen

	Green H_2	Blue H_2	Grey H_2
Source	Renewable energy	Fossil fuel + Carbon capture	Fossil fuel
Cost / kg·Yuan^{-1}	30~41.6	11.5~15.4	7.7~11.5
CO_2 emissions during the production of 1 kg of H_2 /kg	0	1~5	11~21

Achieving net-zero emission in the production side of H_2 is a key factor for the development of downstream applications. Although green hydrogen is currently much more expensive to produce than grey and blue ones in terms of manufacturing costs, it is considered green precisely because of its low environmental cost. Continuous investments in the upstream of the supply chain are inevitable.

On the application side, H_2 can be mainly used in ships in two forms: one is the traditional internal combustion engine (ICE), and the other is the fuel cell (FC) [20]. In ICE applications, when hydrogen is combusted with a stoichiometric ratio, only H_2O is produced. Existing experimental data show that the thermal efficiency can reach over 35%, and a maximum of 50%, large-scale commercial applications have yet to be realized [23]. Additionally, due to the small molar specific heat capacity of H_2, the combustion temperature increases significantly. The intake air contains N_2 and O_2 which can easily form thermal-induced NO_X [24]. However, the selective catalysis reduction (SCR) technology is mature enough to reduce NO_X post-combustion, thus will not become a technical difficulty.

The low energy density of hydrogen poses the largest obstacle to its application in ship propulsion. To generating the same amount of energy, compressed hydrogen and liquefied hydrogen for marine fuel require 10-20 times and 4-5 times more volume respectively compared to traditional fuels [20]. The conditions of high pressure and extremely low temperature can also bring safety risks and higher operating energy consumption.

When hydrogen is used in FC, the energy efficiency can reach 30%~50% in practical applications, with only H_2O as by-product [24]. Although polymer electrolyte membrane (PEM) FC using hydrogen as fuel has matured in terms of technology and application, its low output power per module limits its use as auxiliary or propulsion power only for small ferries or commercial yacht, and FC with higher energy density such as molten carbonate FC and solid oxide FC power systems are believed to be more suitable for ocean-going transportation [25]. However, the technology readiness level and excessive costs have greatly limited the industrialization of H_2 FC, not suitable for marine propulsion currently [24].

Ammonia, similar to hydrogen, can only maintain its advantage as a zero-carbon fuel when renewable energy is used in the process of synthesis.

Ammonia can also be used with ICE or FC to provide power to ships. When ammonia is applied to ICE, the thermal efficiency can reach 35%~40% [26]. However, due to its high spontaneous ignition temperature and slow flame propagation speed, conventional fuels are typically needed as ignition enhancer, and thus CO_2 emissions remain [27]. In FC applications, no GHG would emit, but the power output from ammonia FC is too small to fit marine applications [27]. Compared to hydrogen, ammonia fuel has advantages in terms of safety and cost. The advantages of ammonia include its higher volumetric energy density (1.5 times higher than that of liquid hydrogen), ease of liquefaction (at standard pressure, -33℃ or 0.9 MPa, whereas hydrogen liquefies at -253℃ at standard pressure), and ease of storage and transportation (regular liquefied gas cylinders can be used, while hydrogen can experience hydrogen embrittlement).

In summary, LNG as a low-carbon fuel can be used to achieve short-term carbon reduction goals, while renewable LNG, methanol, and ammonia fuels will be needed in the medium term. The development of hydrogen and fuel cell technologies will be key to achieving long-term zero-carbon scenario in shipping.

4. Carbon capture onboard

Although alternative fuels have the potential for zero carbon emissions, Xing et al. have conducted a multi-dimensional and multi-criteria decision analysis of the prospects of alternative fuels, there are various advantages and disadvantages of alternative fuels in different aspects, no fuel that can completely replace traditional fossil fuels [20].

Carbon capture on conventional fuel-powered ships is set to become a transitional solution for net-zero transformation in the shipping industry. 98.8% of the global ocean-going fleet and over 75% of new ship is driven by conventional fuels [4]. Normally, the service life of an ocean-going merchant ship is not less than 20 years. These vessels mentioned above need to face the IMO's emission reduction regulations. Simply using reducing fuel consumption means cannot achieve the target of reducing emissions by 40% by 2030. However, switching to alternative fuels means a large-scale modification of the engine room. Therefore, the use of carbon capture on ships has become a popular solution.

Carbon capture has three mainstream methods: pre-combustion, oxy-fuel combustion, and post-combustion. When considering the application of carbon capture technology on ships, it is necessary to take into account the specific use case of the vessel, the limited energy and space available, as well as the low concentration of CO_2 in exhaust gases, typically only comprising 3% to 5% of the total volume. Therefore, the preferred method is through the use of chemical solvents, which is one of the post-capture methods [28]. The amine absorption method is the only carbon capture technology currently available for large-scale commercial use [29].

Carbon capture onboard has attracted significant attention from the shipping industry, due to the fact that this technology does not require any changes to the structure of the engine, and it can be adapted to all ships that need to reduce their CO2 emissions, regardless of the fuel type. Amine absorption method is a general technology, in the absorption tower lean amine solution and low concentration of CO_2 in the exhaust gas reaction to form a weak acid weak alkali salt solution, which is called rich amine solution, the rest of the gas is discharged. The rich solution is subsequently thermally decomposed to release high-concentration CO_2, forming lean liquid that is circulated to achieve CO_2 capture. This process is intuitively explained by Formula (3) and Formula (4).

$$\text{Lean amine solution} + \text{Low con.}\,\mathrm{CO_2} \rightarrow \text{Rich amine solution} + \text{Clean Exhaust} \uparrow \quad (3)$$

$$\text{Rich amine solution} + \text{Heat source} \rightarrow \text{Lean amine solution} + \text{High con.}\ \mathrm{CO_2} \uparrow \quad (4)$$

In marine applications, the exhaust of traditional fuel engines contains sulfur oxides and nitrogen oxides. Due to their stronger polarity, they are more prone to react with amine solution compared to CO_2 [30]. Therefore, additional pretreatment devices are required to reduce the consumption of amine solutions. Furthermore, after the capture process, CO_2 needs to be stored onboard during the voyage. To save space, it is usually compressed and condensed into liquid phase. The whole system requires a lot of energy.

A detailed research report from demonstrates the technical feasibility of carbon capture onboard [31]. The research conducted based on a vessel with three type of fuels, low sulfur fuel oil (LSFO), LNG and methanol. The carbon capture system has a CO_2 emission reduction capacity of 82%. However, from the entire ship, due to the energy consumption required by the system, the effective CO_2 net reduction can only reach 74% to 78%. In addition, the cost of capturing one ton of carbon dioxide is \$220~\$290, twice higher than the highest carbon tax in 2022 [32].

Although the technological feasibility of carbon capture systems onboard has been demonstrated, the excessively high costs have become a hindrance to the adoption of this application. Carbon capture systems can significantly reduce CO_2 emissions from ships. However, it can only be considered as a medium-term transitional technology because the technology cannot help to reduce the fuel consumption.

5. Conclusion

Through comparative analysis, this article has found that the three major types of emissions reduction methods can all effectively reduce the total amount of CO_2 emissions during voyage, with various emission reduction capacities.

Speed reduction and air lubrication are typical means of reducing energy consumption, which can support short-term emission reduction targets through computational simulation and small equipment investments. They can achieve carbon reduction goals without retrofitting existing vessels or by implementing minor modifications. However, a single technology within reduction of energy consumption cannot make the shipping industry achieve the IMO's 2030 target of reducing carbon emissions by 40%. It requires the integration of multiple technologies to meet longer-term carbon reduction goals.

Alternative fuels, low-carbon and carbon-free have the net-zero potential, and they are the most promising. For low-carbon fuels, lower C_F and higher LCV can bring the least CO_2 emissions, LNG is the best among them. From the perspective of combustion, the emission reduction capacity can reach 20%~30%. Furthermore, low-carbon fuels can reduce the carbon emissions of the entire fuel life cycle by synthesizing through renewable energy and sources. For carbon-free fuels, to ensure net zero emissions renewable energy synthesizing is a must. As ship propulsion, these fuels can be achieved through ICE and FC. ICE is easier to implement while FC has the potential to produce zero CO_2 emissions. However, due to these alternative fuels often require high pressure, low temperature storage and their flammability, safe utilization requires extra attention.

The technical feasibility of carbon capture onboard has been proven, which can reach over 70% CO_2 net-reduction, is capable of helping ships achieve the IMO 2050 goals. However, this posttreatment system requires further researches to find how to achieve lower energy consumption and lower cost to make it acceptable to stakeholders. Further, from a lifecycle perspective, exploring the possibility of using captured CO_2 to synthesize fuel required for shipping and achieving a closed-loop system, which could be a transition approach worth investigating.

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