An Analysis on the Development Direction and Trend of the Application of Clean Energy for Ships

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The impact of global climate change and greenhouse gas emission reduction policies on the energy development of countries and industries is becoming more and more profound, especially since the United Nations Climate Change Summit reached the Paris Agreement in 2015, when countries started to actively submit their Intended Nationally Determined Contributions regarding GHG emission reduction. Meanwhile, the progress of greenhouse gas emission reduction and energy decarbonization in the international shipping industry has also been greatly promoted. The International Maritime Organization (IMO) released a preliminary strategy for greenhouse gas emission reduction from ships in April 2018, proposing an ambitious emission reduction target of reducing the global shipping industry's total greenhouse gas emissions by 50% and reducing the intensity of carbon emissions by 70% by 2050 compared to 2008. Facing the regulatory pressure of future GHG emission

Table 1: Main physicochemical properties of marine fuels

Property	Fuel		LNG	Methanol	Dimethyl ether	Biodiesel	Hydrogen	Ammonia
	HFO/LSFO	MGO						
Main component	C_{20}-C_{70} heavy hydrocarbon	C_{10}-C_{22} light hydrocarbon	CH_4	CH_3OH	CH_3OCH_3	FAME	H_2	NH_3
Physical state	Liquid	Liquid	Liquid	Liquid	Gaseous	Liquid	Gaseous	Gaseous
Calorific value (MJ/kg)	39	42.8	48.6	19.9	28.43	35-37	120	22.5
Boiling point (°C)	--	175-650	-160	65	-25	--	-253	-33
Flash point (°C)	>60	>52	-175	12	-44	150-160	--	11
Density (kg/m³)	989	900	448 (-160°C)	796	660	887	70.8 (-253°C)	680 (-33°C)
(-33°C)	38.2	36.6	20.8	15.8	18.8	33.3	8.49	12.7
Liquid energy density (MJ/L)	38.2	36.6	20.8	15.8	18.8	33.3	8.49	12.7
Cetane number	--	>40	0	5	55-60	47-65	--	--
Self-ignition point (°C)	>300	250-500	650	464	235	370-450	571	630
Flammability limit (%)	--	0.3-10	5-15	6-36	3.4-17	--	4-75	15-28

reduction, the shipping industry is focusing on exploring feasible carbon reduction technology directions from the aspect of clean energy, and has carried out different levels of research and practice centering on low/zero carbon energy; however, we have yet to form a clear technical direction or solution on how to achieve the IMO's preliminary strategy on GHG emission reduction, and that hinders the shipping industry's strategic choice of low-carbon transformation and the achievement of GHG emission reduction goals. This paper examines the technical direction and development trend of feasible emission reduction technologies from the perspective of clean energy and power technology, taking into account the initial strategic goals of IMO on GHG emission reduction and the current energy efficiency and emission status of the global fleet, in order to provide a reference for the shipping industry to seek the correct path of decarbonization transition.

The shipping industry embarks on the decarbonization process

In the process of decarbonization transition of the shipping industry, various degrees of marine research and practices have been carried out on ships' application of clean energy resources represented by low carbon energy (natural gas, alcohols, ethers, etc.), carbon neutral energy (biofuels, electric fuels), and zero carbon energy (hydrogen, ammonia, electricity, etc.), providing a variety of possible development directions from the energy level to achieve carbon reduction goals.

1. Low-carbon energy

Liquefied Natural Gas (LNG). The natural gas becomes more and more prominent in the global energy mix; specifically, natural gas accounts for 23% of the global energy mix in 2019, mainly used in industrial fuels, municipal gas and power generation. In addition, the global natural gas market is basically in a situation where "production and sales are both flourishing, while regulations are overall loose", so that in 2019, there was a global LNG supply surplus of about 70 million tons. Thus, LNG has a solid foundation on the supply side to serve as a marine fuel. The further development of marine LNG fuel also needs concerted efforts to be made in both upstream and downstream of the industry chain with the upstream improving the construction of LNG refueling infrastructure and the downstream carrying out R&D and application for methane emission control technology.

Methanol. As an important chemical raw material, methanol is mainly produced from coal and natural gas, and currently, its production capacity can ensure global supply. The use of methanol fuel in internal combustion engines can reduce about 10% of carbon emissions and 60% of NOx emissions. In terms of energy resources, China is rich in coal reserves, and thereby in a good position to produce methanol. Therefore, promoting the application of methanol fuel in the shipping industry has strategic significance in reducing China's dependence on oil and gas resources and ensuring China's shipping energy security.

Dimethyl Ether (DME). DME is mainly produced from methanol dehydration, so its production still depends on coal, natural gas and other fossil energy resources, and has no advantage over methanol in this regard. Compared with diesel fuel, DME has higher cetane number and lower auto-ignition temperature, so it has better ignition performance and can be used in compression-ignition engines as an alternative fuel to diesel. The low viscosity and poor lubrication characteristics of DME also pose a challenge to the application, for which the fuel supply, injection and control systems of internal combustion engines need to be modified and adjusted. In terms of carbon emission reduction effect, DME is almost the same as methanol.

2. Carbon neutral energy

The CO_2 released from the combustion of carbon-neutral energy resources comes from the naturally occurring CO_2 in the atmospheric system and does not contribute to the increase of the total amount of CO_2. For example, biofuel combustion is the reverse process of photosynthesis, the CO_2 released to the atmospheric system cycles back into the biomass through photosynthesis, and so on so forth, to achieve "carbon neutrality". However, "carbon neutral" does not exist in an absolute sense, because the production, storage and transportation of carbon-neutral energy resources require energy consumption, and the production and use of such secondary energy also emit greenhouse gases. Therefore, carbon-neutral energy is a relative concept.

Biofuels. Biofuels including biodiesel, biomethane, biomethanol, etc. are mainly produced from energy crops, agricultural wastes, and forestry products and refuses through chemical conversion, anaerobic digestion, gasification and other processes. Biofuel is also called "drop-in fuel", because it can be used in existing marine equipment and fueling infrastructure without technical transformation of facilities or equipment as its energy density, combustion characteristics and other physicochemical properties are similar or the same as those of corresponding fossil fuels. Due to the unstable source and fluctuating price of biomass raw materials, existing marine biofuel projects are mainly on research and testing bases, and there is still a considerably long way to go before commercial operation.

Electrofuels. Electrofuels are produced by the carbon neutral route, using renewable electricity as the energy source, and H_2 and CO_2/N_2 as raw materials for synthesis. Depending on whether or not it contains carbon, electrofuels can be divided into carbon-based fuels (methane, methanol, dimethyl ether, etc.) and non-carbon-based fuels (hydrogen, ammonia, etc.). Electric fuels are also "drop-in fuels", which can be blended with or used in replacement of conventional fuels in the existing ship power system. Currently, the existing electrofuels projects worldwide are mainly in the pilot stage, with small production scale and high cost. According to estimation, the price of methane, methanol, dimethyl ether and other electric fuels is more than 10 times that of the corresponding conventional fuels.

3. Zero carbon energy

Hydrogen. So far, the main way to produce hydrogen is still based on fossil energy (coal, natural gas), and a large amount of CO_2 will be released as a by-product. In the future, the development trend is the green way of hydrogen production, such as offshore wind power based hydrogen production. For storage, the high-density hydrogen storage technology that can meet the requirements of the ship's endurance needs to be further developed. At present, the industry has carried out a series of application research and pilot demonstrations on the application of hydrogen fuel on ships, but conditions are not yet met for large-scale application and a lot of investment and efforts still have to be put in marine technology, standard and infrastructure in the coming decades.

Ammonia. Ammonia is an important feedstock for the fertilizer industry and is produced synthetically from hydrogen and nitrogen, of which the former is still largely dependent on fossil fuels and the latter is derived from air separation. For application of ammonia fuel in internal combustion engines, the problems still need to be solved such as low flame propagation speed, narrow combustion range and NO_x and N_2O emissions. In addition, ammonia has certain toxicity and strong irritating odor, and therefore strict safety protection measures need to be adopted for its use as a marine fuel, for which there is not any supporting technical standard yet. Research and development on ammonia-fueled internal combustion engine, ammonia-fueled fuel cell and ammonia-fueled ship type are being carried out in the industry. Compared with liquid hydrogen (-253°C), liquid ammonia (-33°C) is relatively easy to store and supply, and has an energy density about 1.5 times that of liquid hydrogen, thus suitable as a carrier of hydrogen energy for marine transportation.

Battery. By using pure battery power, zero emissions can be achieved during using the ship, but to achieve zero emissions in the whole life cycle, it is necessary to use clean energy generation (renewable energy, nuclear energy), or the application of carbon capture and storage (CCS) technology in the power plant. At the present stage, due to energy density constraints, the use of pure battery power is mainly limited to small and short-haul vessels. Considering both energy density limitations and emissions reductions, a compromise in between can be achieved by using hybrid power systems based on battery energy storage.

Table 2: Comparison of major ship power units

	Internal combustion engine	Gas turbine	Fuel cell	Stirling engine	Brayton cycle power
Fuel adaptability	Diesel, natural gas, methanol, biodiesel, hydrogen, etc.	Marine Gas Oil, natural gas, hydrogen, etc.	Hydrogen, natural gas, methanol, etc.	Various forms of fossil fuels (gaseous, liquid and even solid), solar energy, etc.	Various forms of fossil fuels (gaseous, liquid and even solid), solar energy, waste heat, etc.
Power range	<80MW	<50MW	<500kW	<800kW	<15MW (engineering prototype)
Thermal efficiency	<50%	<42%	<60%	<40%	<45% (heat source 500°C)
Technology maturity	High	High	Medium	Low (not yet industrialized)	Low (not yet industrialized)
Propulsion mode	Direct (diesel) propulsion/ electric propulsion	Direct (diesel) propulsion/ electric propulsion/water jet propulsion	Electric propulsion	Electric propulsion	N/A (waste heat generation)

Dawn of an age of evolution and change in ship power technologies

The application of various clean energy sources on board ships promotes the diversification of ship power technologies. In addition to internal combustion engines, fuel cells and power cells based on electrochemical reactions, as well as power units based on external combustion heat cycles, are increasingly used in ship propulsion/power systems.

1. Internal combustion engine

The internal combustion engine has significant comprehensive advantages in terms of power range, thermal efficiency, economy and reliability, and will not likely be replaced by other new power units in the near future. In addition, development and application are under way for alternative fuel adaptability, energy efficiency improvement, and emission control to consolidate its dominant position in the marine power field. In terms of alternative fuels, the industry is exploring the safe and efficient application of new fuels such as methanol, dimethyl ether, biodiesel, hydrogen and ammonia for the internal combustion engines of ships. The adaptability of internal combustion engines to different fuels will be further enhanced. In terms of energy efficiency improvement, cylinder break/variable cylinder technology, integration and development of electric motors, and waste heat recovery and utilization will further optimize the efficiency of the internal combustion engine power system. In terms of emission control, there are ongoing researches and application of key post-treatment technologies for black carbon, methane and other emission substances with greenhouse effect.

2. External combustion engine

Marine external combustion power units mainly consist of Stirling engines and Brayton cycle power units. The Stirling engine is mainly used in special or military fields other than the advantageous areas of internal combustion engines, and its sealing, reliability and durability are yet to be further improved through the development and application of new technologies, new processes and new materials. The thermal efficiency of the closed Brayton cycle engines is lower than that of diesel engines, and according to current research and application cases, its application on board ships is all about using the waste heat of the exhaust gas from the main power unit to generate electricity. Overall, the external combustion power units have better fuel adaptability, but cannot compete with internal combustion engines in terms of thermal efficiency, reliability, technical maturity, cost and other aspects.

3. Gas turbine

Compared to internal combustion engines, the gas turbines main have the advantages of power density and emission reduction performance, the combustion engine is 1/5 to 1/10 the volume of a diesel engine with the same power rating, and the use of "Gas-Steam Combined Cycle Electric System (COGES)" can meet the IMO Tier III emission requirements. The main disadvantages are higher investment costs and poorer fuel adaptability. The cost of gas turbines for power output is about $400-500/kW, while that of a two-stroke diesel engine is about $300/kW. For fuel adaptability, marine gas turbines primarily use marine gas oil (MGO) or natural gas. In the field of gas-fired power generation, breakthrough has been made in the technology of 50% hydrogen mixed fuel (hydrogen - natural gas) turbine, and 100% hydrogen fuel gas turbine is being developed, but the application in the marine field is not foreseen in the short term.

4. Fuel cell

Fuel cells are mainly divided into low-temperature fuel cells represented by proton exchange membrane (PEM) and high-temperature fuel cells represented by solid oxide fuel cell (SOFC). PEMs are characterized by low operating temperature (50-90°C), good dynamic characteristics, and ability to operate independently with load, but they require high purity of hydrogen, precious metals as catalyst and complex hydrothermal management system. At present, a medium temperature (about 200°C) HT-PEM technology route has been developed, which effectively solves the problems of easy CO poisoning of catalyst and complexity of hydrothermal management systems. As for high-temperature fuel cell, SOFC is adaptable to LNG, methanol, ammonia and other hydrogen-rich fuels, and its thermal efficiency is better than that of low-temperature fuel cell (and the use of waste heat recovery can further improve the thermal efficiency of the system), so it is a more suitable fuel cell technology route for marine operation, although key technical issues such as start-up time and dynamic characteristics have yet to be solved in the next step.

5. Battery power

There are two main technical routes for battery power, namely lithium iron phosphate battery and ternary polymer lithium battery. As lithium iron phosphate battery has a higher intrinsic safety level than ternary polymer lithium battery, it is especially suitable for large-capacity lithium battery applications, while the large-scale use of ternary polymer lithium battery poses higher requirements on BMS, battery module protection, thermal management system, and other application technologies. Considering the actual higher safety requirements and moderate space weight requirements of marine power, lithium iron phosphate is a more balanced technical route at this stage. All-solid-state lithium batteries with non-combustible, thermally stable solid electrolyte to replace the flammable and explosive organic liquid electrolyte could be an effective way to comprehensively address the high energy density and battery safety in the future.

The development direction and trend to achieve carbon reduction goals

For the whole shipping industry, the analysis of carbon reduction effects takes the total carbon emission amount as a reference indicator; for an individual ship, however, the analysis of carbon reduction effect should be based on the carbon emission intensity indicator. The IMO GHG preliminary strategy sets carbon intensity reduction targets of 40% and 70% for 2030 and 2050, respectively. Therefore, the possible development direction of emission reduction from the aspect of clean energy and power plant is proposed with the reduction of carbon emission intensity of the ship itself as the goal.

1. Medium-term carbon reduction development direction (2023-2030)

In 2008, the carbon emission intensity of international shipping industry was about 21.9g CO_2/ton nautical mile, and over the subsequent decade or so, energy-efficient technologies were gradually applied to newbuilds, with the carbon emission intensity falling to 15.67g CO_2/ton nautical mile in 2019, nearly 30% lower

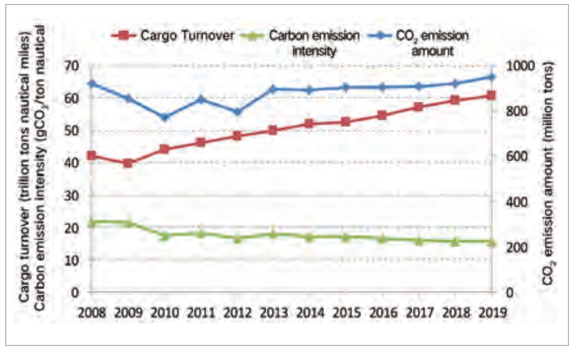

Figure 1 Carbon emission intensity of the international shipping industry (2008—2019)

than the 2008 benchmark and only 10% short of the 2030 carbon emission intensity reduction target. Given that the EEDI third phase requirements will be implemented from 2022/2025 onwards, and that old and inefficient ships will be phased out over the next decade, the 2030 carbon reduction target will be not so hard to achieve.

(1) Power units

In terms of power unit, internal combustion engines are absolutely dominant at the present stage, and will remain the mainstream choice of ship power unit in the short and medium term as research and development and optimization are being carried out in terms of thermal efficiency improvement, emission control, alternative fuel application, etc. For coastal and inland waterway vessels, which have such operating characteristics as high frequency of port calls and considerable proportion of low load conditions, it is advisable to adopt hybrid power system based on internal combustion engine and battery or DC electric propulsion system based on internal combustion generator set, so as to obtain better adaptability to the relatively complex and changing conditions and improvement in the ship's energy efficiency and emission level. For ocean-going vessels, which have longer range, relatively stable working conditions and larger propulsion power requirements, it is advisable to adopt low-speed two-stroke internal combustion engines.

(2) Fuels

In terms of fuel, considering the global sulfur restrictions have been fully implemented since 2020, low-sulfur oil will remain the mainstay of the marine fuel market in the coming years. Compared with fuel oil, LNG, methanol and other low-carbon fuels can achieve about 10%-20% carbon emission reduction, and with the EEDI third phase requirements to be implemented in 2022/2025, these low-carbon fuels will usher in new opportunity and space for development. The development of marine LNG industry chain has taken shape so far, bunkering facilities, technical support, rules and standards are being developed and improved, and the application of LNG fuel on inland waterway, coastal and ocean-going vessels will be further promoted. Methanol fuel is still in the initial stage of development in terms of infrastructure, industrial products and technical standards, and considering its low volumetric energy density, its pilot and formal application on inland waterway vessels and coastal vessels is foreseeable in the next few years.

2. Development direction of long-term carbon reduction (2030-2050)

Given that a certain amount of newbuilds delivered around 2020 will still exist by 2050, in order to achieve the goal of reducing carbon emission intensity by 70% by 2050, newbuilds after 2030 are required to have an amplitude of reduction in carbon emission intensity much higher than 70%, which compels the

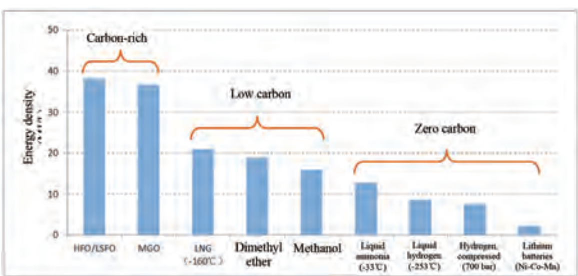

Figure 2: Comparison of fuel energy density of ships

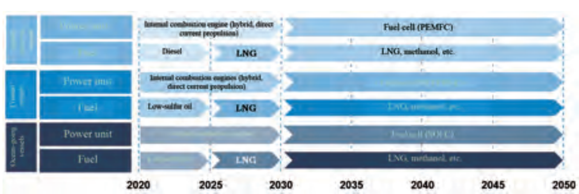

Figure 3: The development direction of carbon reduction technology for ships in the medium and long term

realization of large-scale application of zero-carbon energy and corresponding power units.

(1) Power units

In terms of thermal efficiency, the thermal efficiency of internal combustion engine is 40%-50%, while the conversion efficiency of PEM, SOFC and other mainstream fuel cells can reach 50%-60%, and the conversion efficiency of SOFC fuel cells in COGES mode can even reach 85%. In terms of power rating, the power of high-temperature fuel cells represented by SOFC is breaking through to megawatt level, and with the development of technology, its power range is expected to be further expanded to meet the propulsion power demand of large ships. Therefore, from the perspective of energy conversion efficiency improvement and power level improvement, fuel cells will lead the future development trend of ship power unit.

(2) Fuel

The choice of the specific technology route for fuel cells is closely related to the type of fuels used. For inland waterway vessels, which have a higher frequency of port calls and refilling and a relatively lower propulsion power requirement, it is feasible to use hydrogen fuel with a lower volumetric energy density. Hydrogen fuel can be used directly without any reforming unit, no CO impurities will be produced, and the purity of hydrogen can be guaranteed. Therefore, low temperature fuel cells requiring high purity of hydrogen, such as PEMFC, can be used. For coastal vessels, which require higher fuel energy density than inland waterway vessels, the use of hydrogen-rich fuels such as LNG and methanol with reformers can be considered, and since CO impurities will be present in the reformed gas, fuel cells that are insensitive to catalyst CO poisoning, such as HT-PEMFC, are required. For ocean-going vessels, which pose higher requirements on energy density and propulsion power of the fuel, it is necessary to use hydrogen-rich fuels such as LNG and methanol and high-temperature high power rating fuel cells. SOFC-based technology route is another possibility for ocean-going vessels as there has already been mature application experience of SOFC high-temperature fuel cells in onshore power generation and COGES in the hundreds of kilowatts to 10 megawatts class, where it is possible to reuse hydrogen produced from the reforming of hydrogen-rich fuels such as LNG and methanol.