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The optimum decarbonization path for a container ship company

Tao Wang

WORLD MARITIME UNIVERSITY

Dalian, China

THE OPTIMUM DECARBONIZATION PATH FOR A CONTAINER SHIP COMPANY

By

Wang Tao

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

Signature:

Date: 28-Jun-2022

Supervised by: Professor. Sun Deping

Supervisor's affiliation: DMU

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After more than ten years of sailing and becoming a container captain, I am delighted and excited to be able to return to university. MSEM's curriculum system deepened my understanding of laws and regulations, technology trends, and maritime safety and environmental management skills. At the same time, I have benefited a lot from being able to meet so many knowledgeable professors and talented classmates. Although the COVID-19 epidemic has not improved in the past two years, and we cannot listen to most of the professors' courses on-site, the lively online discussions and enthusiastic collaboration between groups have allowed us to gain a wealth of knowledge and depth of friendship comparable to offline.

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ABSTRACT

Title of Dissertation: **The Optimum Decarbonization Path for a Container Ship Company**

Degree: **Master of Science**

Today, there is a growing consensus on curbing climate change. As the main culprit of global warming, how to reduce carbon dioxide emissions from the burning of fossil fuels is the key to achieving carbon neutrality by 2050. As a major carbon emitter in the shipping industry, the container ship is critical to the IMO and the industry's ambition to eliminate its carbon footprint.

Although there are many studies and measures for decarbonization, there is rarely a decarbonization design for an entire fleet. Based on the analysis of hundreds of related papers and taking Technology readiness level, Carbon dioxide emission reduction potential, Cost-effectiveness, etc. as indicators, according to the composition of the sample container company's fleet, a cost-effective short, medium, and long-term plan to achieve net-zero carbon emissions by 2050 has been developed. This research has specific reference significance for other container companies and the shipping industry.

KEYWORDS: Decarbolization, Container ship, Cost-effectiveness.

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LIST OF ABBREVIATIONS

ABS....................American Bureau of Shipping
BIMCO ....Baltic and International Maritime Council
MBM..................Market based measures
CII ....Carbon Intensity Indicator
CMA CGM ....Compagnie Maritime d'Affrètement (CMA) and Compagnie Générale Maritime (CGM)
CO_2.....................Carbon Dioxide
COP26................26th meeting of the Conference of the Parties
COSCO ....China Ocean Shipping Company, Limited,
COVID-19 ....Coronavirus Disease 2019
DCS....................Data collection system for fuel oil consumption of ships
DNV...................Det Norske Veritas
DWT ....Deadweight tonnage
EEDI ....Energy Efficiency Design Index
EEXI ....Energy Efficiency Existing Ship Index
E.U ETS. ....European Union Emissions Trading System
FAME.................Fatty Acid Methyl Esters
GDP ....Gross domestic product
GHG ....Greenhouse gas
HFO ....Heavy fuel oil
HVO...................Hydrotreated Vegetable Oils
IMO....................International Maritime Organisation
LNG ....Liquified natural gas
LPG....................liquified petroleum gas
MAN B&W........Maschinenfabriek Augsburg-Nurnberg.Burmeister & Wain
MARPOL...........International Convention for the Prevention of Pollution from Ships
MDO ....Marine diesel oil
MEPC.................IMO Marine Environment Protection Committee
MGO ....Marine Gasoil
MRV...................Monitoring, reporting and verification of CO2 emissions for vessels
MSC ....Mediterranean Shipping Company
NASA ....National Aeronautics and Space Administration
NMFT ....No more favorable treatment principle
NOAA ....National Oceanic and Atmospheric Administration
OCCS ....Onboard Carbon Capture and Storage
OOCL ....Orient Overseas Container Line

PM ....Particulate matter
SCR ....Selective catalytic reduction
TEU....................Twenty-foot-equivalent unit
ULCV.................Ultra Large Container Vessel
UNCTAD ....United Nations Conference on Trade and Development
UNFCCC ....United Nations Framework Convention on Climate Change
U.S. ....United States of America

CHAPTER 1 - BACKGROUND INTRODUCTION AND LITERATURE REVIEW

1.1 Shipping Decarbonization Background

The Paris Agreement claimed that climate change could be the greatest threat to humankind in thousands of years. For a long time, climate change was something that scientists predicted would happen in the future. But with more and more extreme weather, Greater storms, more significant floods, more incredible heat waves, and excessive sea level rises, all of this was happening far faster than many scientists thought possible.

What's causing more and more extreme weather? Scientists first became concerned about these steady and unremitting temperature trends, but nobody could be sure exactly what was driving them. So, scientists have on land, at sea, and in the far reaches of our atmosphere, a large number of observations and studies have been carried out. With the deepening of research, the causes of climate change have become more apparent and unequivocal. Our climate is changing because of one simple fact. Our world is getting hotter.

In the summer of 1988, Dr. James Hansen testified to U.S. Congress. He stated that 1988 was the hottest year on Earth in the history of instrumental measurements; the Earth is warming by an amount that is too large to be a chance fluctuation, an actual physical effect of the increasing carbon dioxide. This is the first-time scientist trying to reach the public and politicians on climate change on the international agenda. As shown below, it's not just Japan Met Office records showing this trend; data from the U.S. climate center, NOAA, the BERKELEY EARTH, and NASA all show the same sharp rise in temperatures.

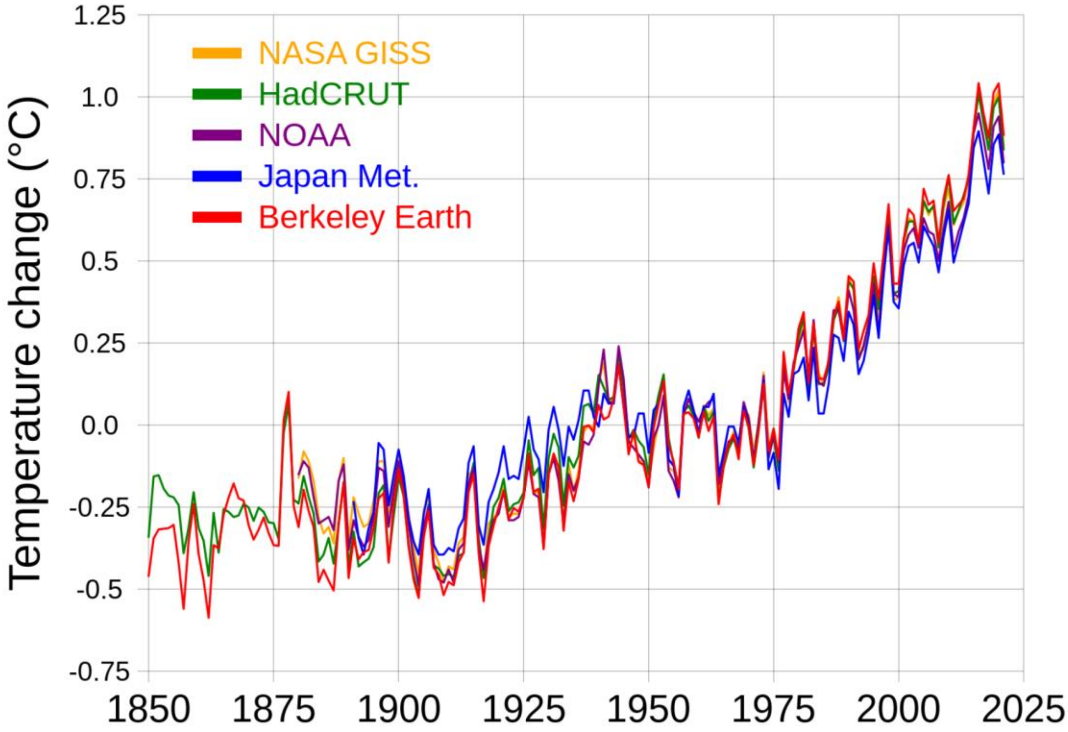

Figure 1-Graphs show the correlation of measured global average temperature from five scientific organizations.（Source: en.wikipedia.org, 2022)

Carbon dioxide acts as a blanket, absorbing the heat radiation from the Earth's surface, which keeps the surface warmer than it would be otherwise. As more and more additional carbon dioxide and other greenhouse gas emissions into the atmosphere, it is equivalent to increasing the thickness of this blanket. Industrial Revolution at the end of the 18th century, we started to burn coal extensively; the amount of carbon dioxide in the atmosphere was about 280 parts per million; it's now over 400 parts per million. According to research, most carbon emissions are caused by human activities, in particular, by the use of fossil fuels. Today's human life is highly dependent on fossil fuels. Various sea, land, air transportation, heating, power generation, etc., consume millions of tons of fossil fuels yearly. The graph below shows carbon dioxide emissions from fossil fuels today are seven times higher than in 1950, seventy years ago.

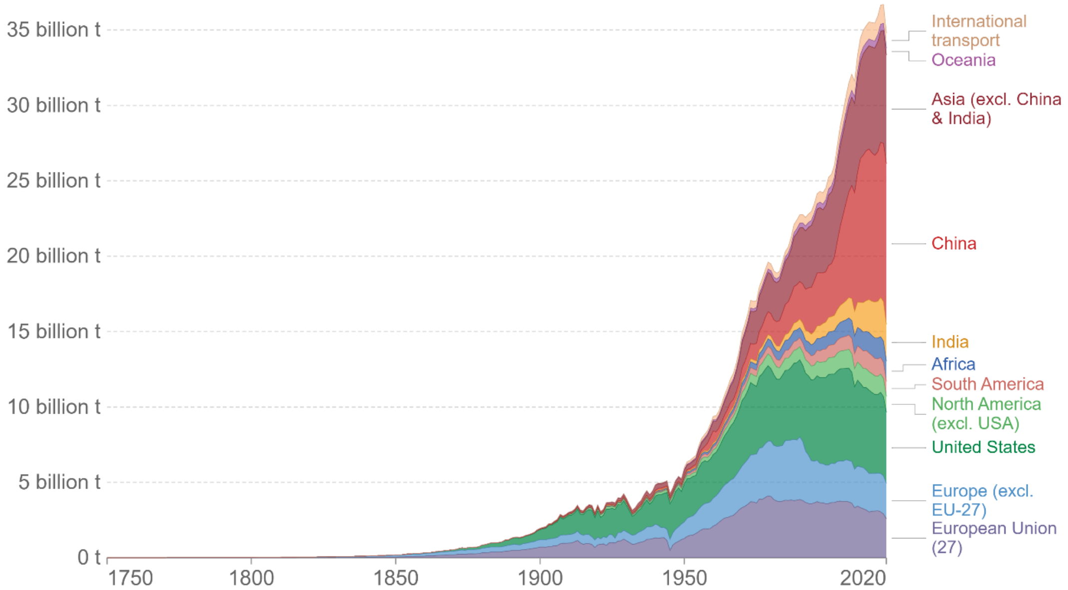

Figure 2-Annual CO_2 emissions from fossil fuels by world region(Source: Global Carbon Project-2021)

Global warming will not only bring about more frequent and severe extreme weather but may also lead to more serious consequences(Wyns & Beagley, 2021). First, Scientists believe that 8% of species are now at threat of extinction solely due to climate change. With the loss of even the smallest organisms, we destabilize and ultimately risk collapsing ecosystems, the networks that support the whole of life on Earth. Second, food production will be more problematic with increased storms, floods, droughts, and heat waves. In addition, thousands of scientists worldwide use compelling climate models, and they predict that if we continue as we are now, we will hit 1.5 degrees global warming between 2040 and 2050. By the end of the century, our planet will be somewhere between three and six degrees hotter. Some models predict that if we don't do anything to curb climate change, we could be looking at 80 centimeters of sea-level rise by the end of the century. This means that many coastal residents will lose their homes. Again, according to the research was done by Carlson, C.J., Albery, G.F., Merow, C. et al.（2022）, climate change and land-use changes will potentially result in a large number of novel cross-species virus transmissions due to species congregating at high population densities areas such as Asia and Africa. Surprisingly, such an ecological shift is likely already underway, and even limiting global temperature rise to 2°C this century will not slow the spread of the virus in the future. The last but also the most important, the big fear is that there may be other, more extreme dangers lurking beyond those we already know. Scientists call these tipping points. A tipping point is where in a part of the climate system, just a little bit of extra warming could nudge it into a different state, an irreversible change, and it's going to get even hotter because you've triggered something that you can't undo. One of the potential tipping points scientists have identified involves a greenhouse gas locked underground in the arctic. If permafrost starts to unfreeze, the methane trapped underneath will bubble up. Methane is 21 times more potent as a greenhouse gas than CO_2. They were burping out of the permafrost, causing the acceleration in global warming.

As more and more scientists and politicians realize we are facing a manufactured disaster on a global scale, the scientific evidence is that if we have not taken dramatic action within the next decade, we could face irreversible damage to the natural world and the collapse of our societies. As a result, 154 countries signed the United Nations Framework Convention on Climate Change in 1992(UNFCCC). It aims to stabilize the global greenhouse gas concentration and build a basic legal framework for the international community to address climate change jointly.

Subsequently, the "Kyoto Protocol" adopted in 1997 further stipulated the responsibility and timetable for the quantified emission reduction of carbon dioxide and other greenhouse gases for major industrialized developed countries. The six greenhouse gases controlled in the Kyoto Protocol are CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. CO_2 accounts for 75% of all greenhouse gases and contributes the most significant proportion to global warming, so controlling carbon dioxide emissions has become the top priority. Greenhouse gas emissions are also considered carbon emissions(Young & Stokke, 2020). Given the importance of international maritime transport in the economic structure, Article 2.2 of the Kyoto Protocol explicitly authorizes the IMO to control greenhouse gas emissions in the industry.

The Paris Agreement adopted in 2015 put forward the goal of keeping the global average temperature rise within 2°C of the pre-industrial level and striving to keep it within 1.5°C and to put forward common but differentiated responsibilities principle; the signatory countries will participate in the global response to climate change in the form of "Independent Contributions." However, as shown in Figure 3, the shipping industry is crucial for the economic development of many developing countries. Therefore, developing countries do not support the inclusion of maritime transport texts in the Paris Agreement, resulting in the absence of maritime transport in the Paris Agreement.

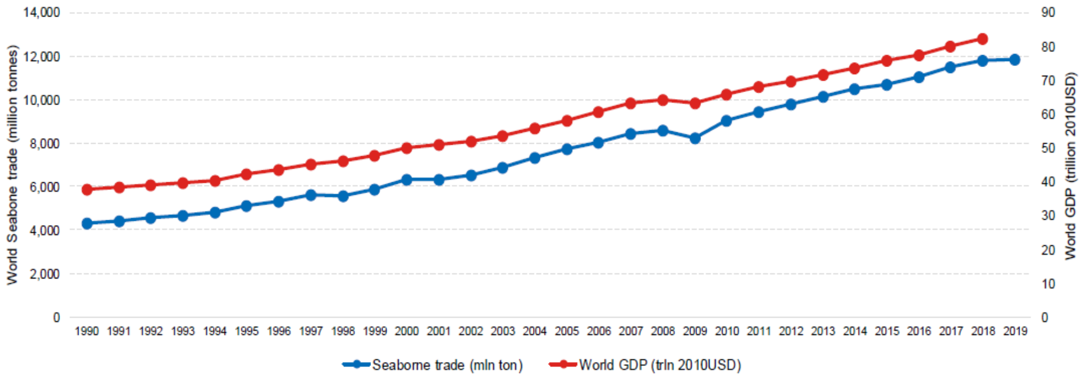

Figure 3-Correlation between world GDP and seaborne trade (Source: World Bank-2021)

On November 13, 2021, the 26th meeting of the Conference of the Parties (COP26) to the UNFCCC concluded in Glasgow, UK, with 197 countries reaching a Glasgow Climate Convention. The agreement aims to achieve carbon neutrality by mid-century at the latest and limit global warming to 1.5 degrees Celsius, preventing the world from suffering the severe consequences of catastrophic climate change. The International Energy Agency (IEA) forecasts that if all climate commitments announced at COP26 are met on time, global temperatures will rise to 1.8 degrees Celsius by 2100.

In the context of reaching a consensus on global greenhouse gas emission reduction targets, in April 2018, the 72nd session of the IMO Marine Environment Protection Committee (MEPC) adopted the IMO Initial Strategy. However, unlike the 2015 Paris Agreement, the IMO adopts no more favorable treatment principle (NMFT). As shown in Figure 4, the Initial Strategy takes time as the dimension and proposes a list of 20 short-term, medium-term, and long-term alternative measures. The Initial Strategy sends a solid signal to the international community to speed up the transition to the low-carbon shipping industry and, at the same time, push green shipping on the fast lane, which will undoubtedly have a revolutionary impact on the development of the entire shipping industry. The initial strategy proposes a 40% reduction in the intensity of greenhouse gas emissions from shipping by 2030, a 70% reduction in emissions intensity in 2050, and a quantified goal of reducing total annual greenhouse gas emissions by at least 50% compared to 2008, and vision to eliminate shipping GHG emissions as quickly as possible.

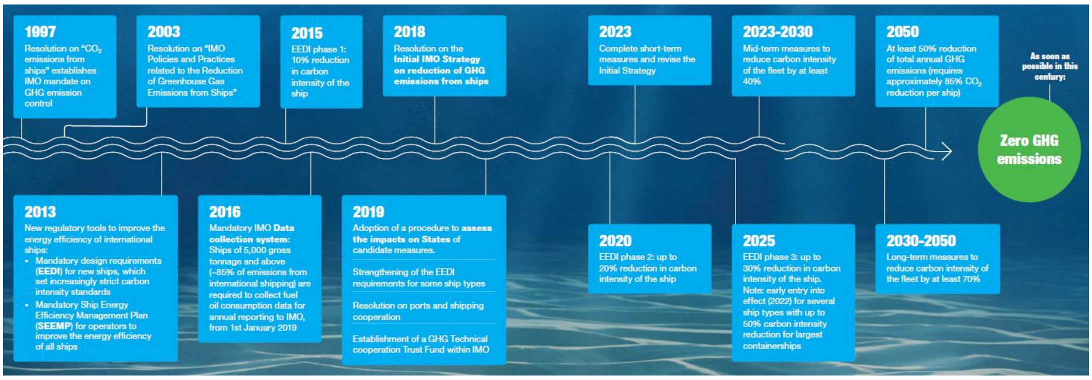

Figure 4-The timetable of IMO action to reduce GHG emissions from ships (Source: IMO initial strategy-2018)

As shown in Figure 5, there is still a particular gap between the 2050 goal of a 50% reduction in greenhouse gas emissions set by IMO and the Paris Agreement and the Glasgow Climate Convention(Chae & Kim, 2020). During COP26, U.N. Secretary-General Gutierrez, many national governments, industry organizations, and large shipper companies expect IMO to target zero-emission shipping by 2050. In addition, on July 14, 2021, the European Commission officially released a package of legislative and policy proposals ("Fit for 55"), which aims to ensure that E.U. GHG emissions in 2030 are reduced by at least 55% from 1990 levels, and plans to include the international shipping industry in the EU-ETS. Based on the above pressures, the MEPC of the IMO agreed at its seventy-seventh session (MEPC77) to initiate the revision of its Greenhouse Gas Reduction Strategy work; the final draft of the modification will be considered at the MEPC80 meeting in spring 2023.

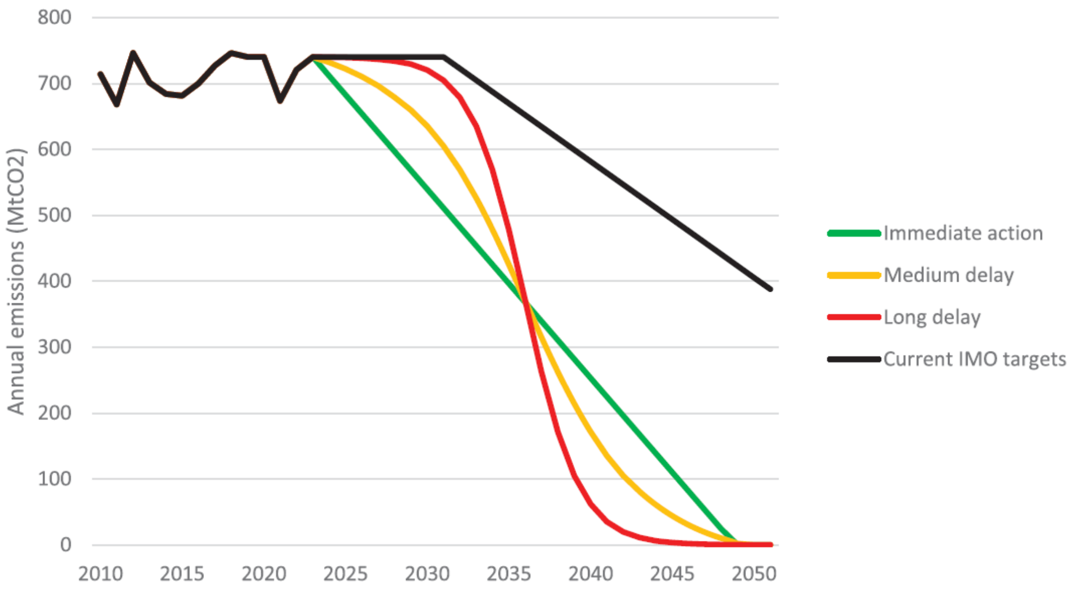

Figure 5-The IMO's targets and Paris-compatible 1.5°C pathways (Source: The urgent case for more vital climate targets for international shipping-2021)

1.2 The importance of container ships in the decarbonization of the shipping industry and the significance of this paper

According to 2020 data from the IMO, the global shipping industry's greenhouse gas emissions have exceeded 1 billion tons, accounting for nearly 3% of global anthropogenic emissions. If the control measures are not implemented in time, it is expected that the worldwide ship carbon emissions will soar by 150%~250% in 2050, and the proportion will increase to 18%. Among them, as shown in figures 6 and 7 below, although container freight only accounts for about 13% of global shipping freight, it contributes almost 26% of carbon emissions, and according to EU MRV 2019 data, container ships contribute 30% of carbon emission(Godet, Panagakos, & Barfod, 2021). Therefore, the success of the decarbonization of container ships will be the key to whether IMO can achieve its 2050 zero-carbon ambition.

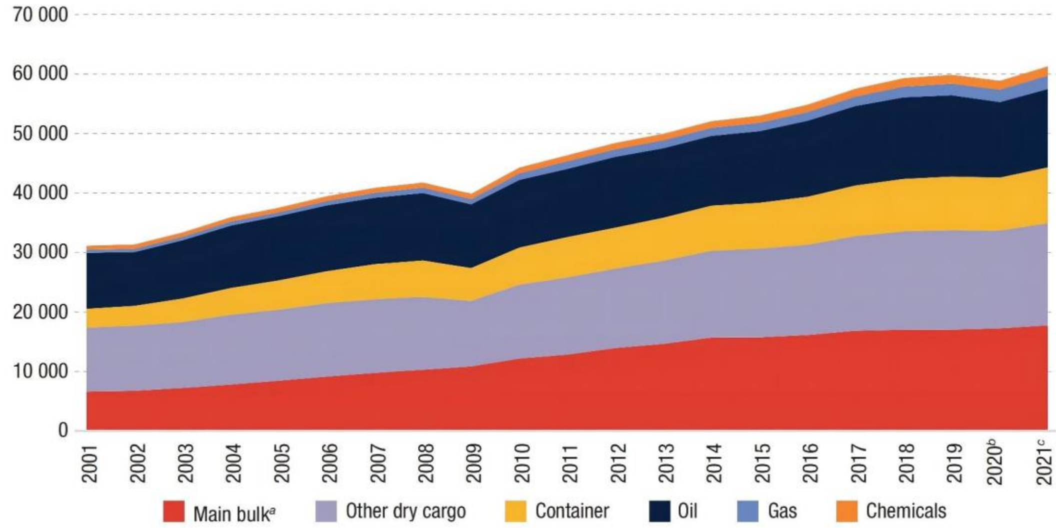

Figure 6-International maritime trade in cargo, ton-miles, 2001-2021(Source: UNCTAD, REVIEW OF MARITIME TRANSPORT 2021)

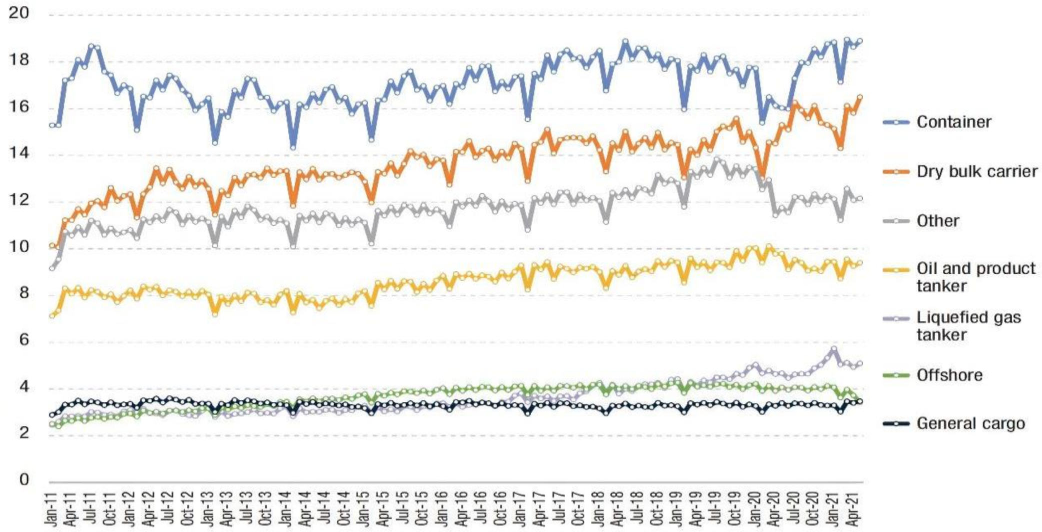

Figure 7-Carbon dioxide emissions by vessel type, million tons,2011-2021 (Source UNCTAD, REVIEW OF MARITIME TRANSPORT 2021)

As shown in Figure 8 below, Shipowners' willingness to reduce carbon emissions is mainly affected by three aspects. To meet increasingly stringent international and regional regulations and cater to the expectations of cargo owners and capital, container shipping companies are forced to accelerate their decarbonization efforts (Heiskanen, Kivimaa, & Lovio, 2019). But there are many paths to lower their carbon footprint, with different opinions, and the methods currently adopted by the major container shipping companies are also different. So among these, which direction is the most economical, efficient, and practical under the premise of complying with international and regional regulations? This paper will select a medium-sized container company as a sample under the assumption of achieving net-zero emissions by 2050. At the same time, combined with 17 years of sailing experience, the author is trying to find the most economical and practical path for short-term, medium-term, and long-term action through various decarbonization measures. This article has excellent reference significance for existing container companies, and the best decarbonization path is also the answer that major container companies have been looking for.

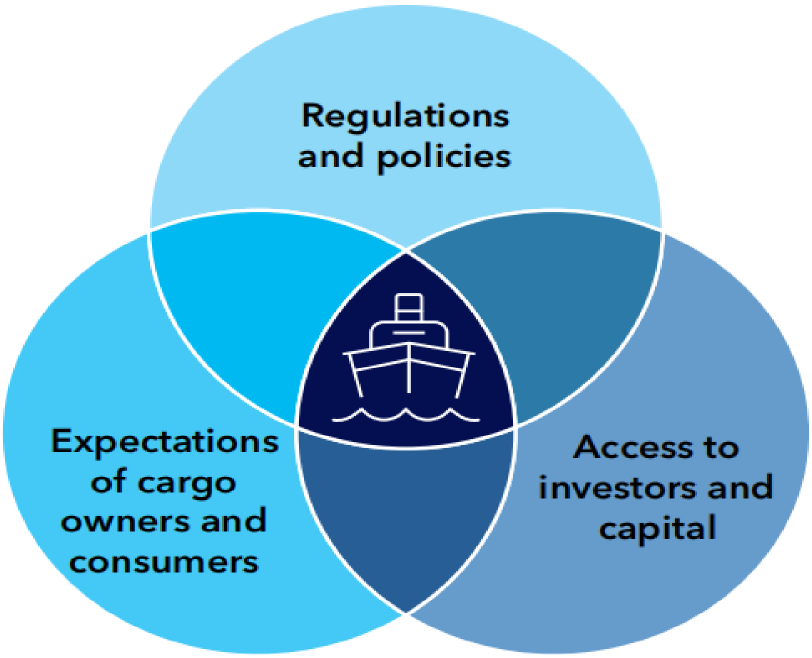

Figure 8-Key drivers influencing ship decarbonization(Source: DNV Maritime Forecast to 2050,2021)

1.3 A review of research worldwide

As the decarbonization of shipping becomes increasingly urgent, experts and scholars in the maritime industry worldwide have carried out a lot of exploration, practice, and research. Various countermeasures to reduce carbon emissions have been put forward to achieve the decarbonization requirements of IMO and other regions. And action plans, discussing the concepts, methods, characteristics, barriers to implementation, and prospects of different emission reduction measures. To complete this paper, the author has collected more than 150 Chinese and foreign papers related to shipping decarbonization measures, such as SCI, SSCI, CPCI, and JCR, through the database. The research associated with this paper is roughly divided into four aspects: international and regional rules affecting the decarbonization of ships; improving energy efficiency by optimizing operation management; using new technologies to reduce carbon; the feasibility and economics of using new alternative fuels and zero-carbon fuels to decarbonize.

In terms of policy, although the IMO is orderly in introducing short-term, mid-term, and long-term decarbonization measures. But at the same time, other international organizations have become more determined to achieve net carbon emissions by mid-century, and the E.U. is more likely to include shipping in carbon emissions trading. The larger the scale, the more significant uncertainty exists about IMO's current decarbonization goals and corresponding supporting measures(Halim, Kirstein, Merk, & Martinez, 2018). As shown in Figure 9 below, while there are a wide variety of CO_2

reduction options, the technical, operational, commercial, and legal framework to help container ship owners meet IMO decarbonization ambitions and regional carbon emissions requirements remains unclear. There are doubts, and the answers given by the maritime industry so far on how to deal with CO_2 reductions appear to be vague. In addition, it is necessary to determine which measures are the highest priority measures.

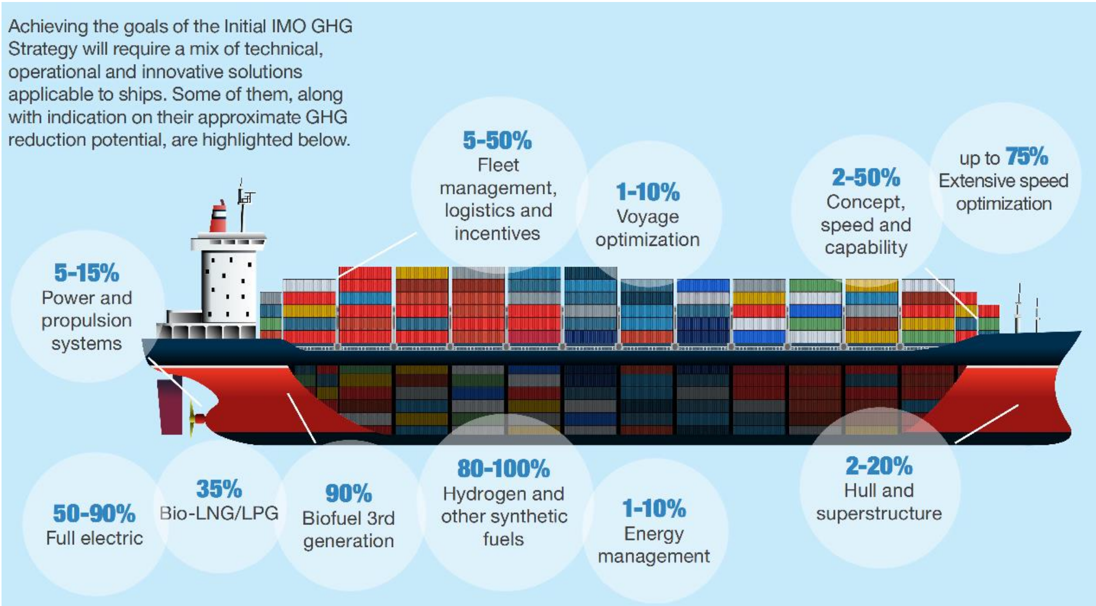

Figure 9-A wide variety of design, operational and economical solutions (Source: IMO action to reduce GHG emissions from international shipping,2020)

Moreover, the potential CO_2 emission reduction effects claimed in most literature are mainly for individual actions. There is no in-depth explanation and discussion on the interdependence and superposition effects of different criteria, which means that the impact of various combinations of actions is uncertain. Besides, few short-, medium- and long-term decarbonization solutions are designed for an entire container company's fleet. The related content will be discussed in detail in the following chapters.

CHAPTER 2 - CURRENT REQUIREMENTS AND FUTURE TREND FORECASTS

2.1 EEDI AND SEEMP

The issue of greenhouse gas emission reduction from shipping has been discussed at the IMO since 1997, and its negotiation has gone through several stages of development. At the 62nd MEPC meeting held in July 2011, the requirements for ship energy efficiency were officially incorporated into MARPOL Annex VI. For the first time, technical emission reduction measures - Ship Energy Efficiency Design Index (EEDI), and operational emission reduction measures - Ship Energy Efficiency Management Plan were included for the first time. SEEMP is incorporated into the MARPOL as a mandatory requirement. EEDI applies to new buildings after January 1, 2013, and SEEMP applies to existing ships. To meet the needs of new shipbuilding in various stages.

The designed model establishes the connection between the container ship deadweight and the EEDI calculation at each stage. Figure 10 is drawn, which provides a good reference for the new container ship construction. Based on the ship design energy efficiency requirements in 2011, the IMO completed the review in 2020 and passed the revision of the third stage of the EEDI requirements for new buildings. The enhanced requirements will take effect on April 1, 2022. From the aspect of ship design, all classification societies actively research ship optimization design in response to EEDI, such as Lloyd's Register of Shipping and the American Bureau of Shipping, etc. Reference for ship owners, designers, and builders. Some scholars also use EEDI to apply it to optimize the shape line of ship design and study the optimal selection design of ship power plants. In addition, many scholars have conducted research on using new technologies such as OCCS and alternative fuels in the shipbuilding stage(S. Lee, Yoo, Park, Ahn, & Chang, 2021). In general, new technologies or new alternative fuels can effectively reduce the EEDI of ships. Still, their technological maturity and economic availability are affected by many factors, and each container company has different attitudes and choices in using new technologies and new fuels.

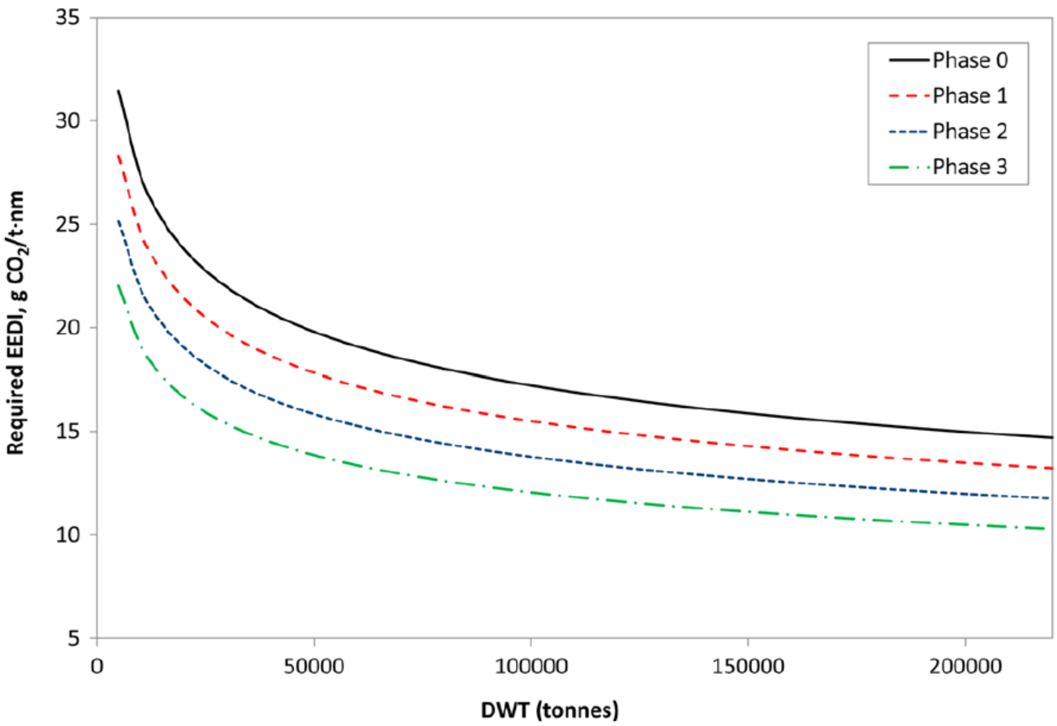

Figure 10-EEDI reference lines for container ships according to MEPC.203(62) (Source: Effect of ship size on EEDI requirements for large container ships-2021)

SEEMP is one of the maritime greenhouse gas emission reduction tools developed by the IMO to meet the UNFCCC requirements. The history of the formulation and revision of SEEMP is the history of the development process of the IMO's operational ship greenhouse gas emission reduction technology route, from vague to clear, from voluntary to mandatory, from qualitative to quantitative, after 24 years! In March 2012, MEPC 63 amended Annex VI, which included SEEMP into the Convention of compulsory implementation for the first time. Article 22 of the rules requires each ship to keep a ship energy efficiency management plan on board and, at the same time, formulate the 2012 Ship Energy Efficiency Management Plan (SEEMP). Guidelines for Compilation, MEPC.1/Circ.683 is abolished, and SEEMP has changed from voluntary to mandatory. In October 2016, MEPC 70 amended Annex VI, and Regulation 22 added the requirements for data collection (DCS) of ship fuel consumption.

Energy efficiency management can reduce greenhouse gas emissions and save fuel. The cost of fuel oil accounts for a large proportion of the operating expenses of ships. Therefore, before the implementation of SEEMP, various shipping companies, and research institutions had already done a lot of work in this area and summarized many ways to improve energy efficiency. For example, they increased sailing time by optimizing network settings, reducing ship resistance by regularly cleaning the hull and using antifouling paint, reducing ballast water by optimizing stowage and adjusting the best trim, etc. However, due to the many uncontrollable factors involved in the implementation process, insufficient crew training and attention, and no corresponding punitive measures, the results of SEEMP implementation are uneven.

2.2 EEXI and CII

It can be seen that the implementation of EEDI and SEEMP has indeed played a specific role in reducing the carbon emissions of ships. Still, it is difficult to achieve a limited effect on the short-term goals of IMO. To improve the energy efficiency level of existing vessels above 400 gross tonnages built before January 1, 2013, Japan proposed the concept of the Existing Ship Energy Efficiency Index (EEXI) at the

MEPC74 meeting held in 2019. IMO adopted EEXI and the Carbon Intensity Indicator (CII) at its 76th MEPC meeting in June 2021, with EEXI addressing ship technical efficiency; the CII rating scheme addressing operational efficiency; the Enhanced SEEMP for the management system. Existing ships' technical energy efficiency requirements are generally equivalent to the design energy efficiency requirements for new vessels in 2022. A reduced rate of 2% per year will be implemented from 2023 to 2026 (relative to the 2019 CII baseline value). And in 2026, operational carbon intensity requirements will be reviewed to ensure that IMO emission reduction targets are met. The existing ship energy efficiency-related provisions have been incorporated into the MARPOL amendments, which will enter into force at the end of 2022 and take effect on January 1, 2023.

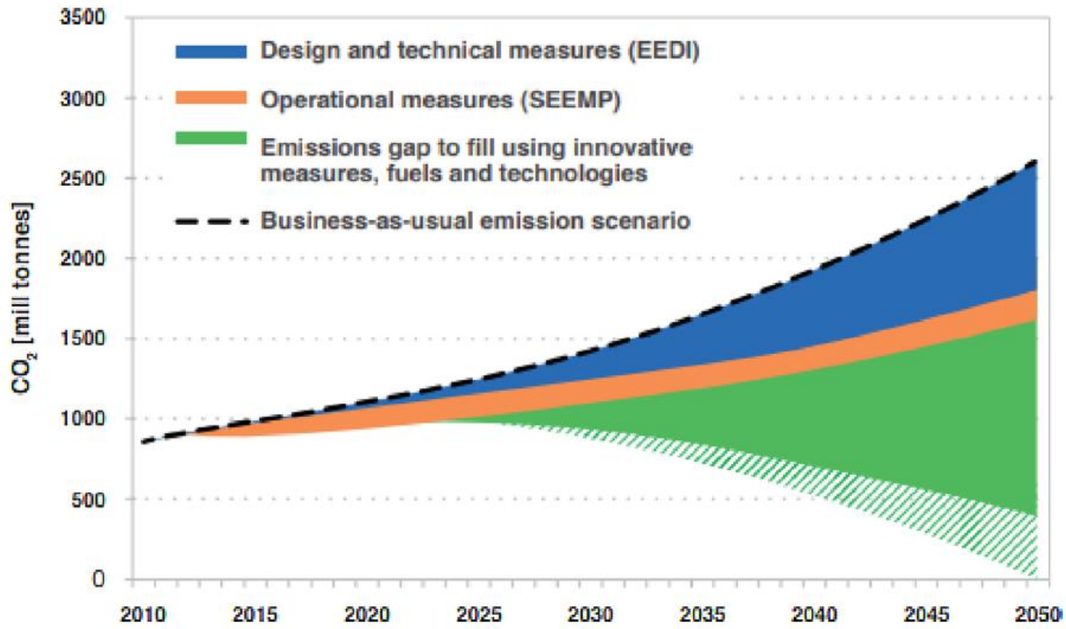

Figure 11-Overall GHG reduction pathway to achieve the initial IMO strategy (S. Lee et al., 2021)

EEXI is the theoretical carbon emission intensity, a technical indicator, while CII is the actual carbon emission intensity, an indicator in the IMO 2030/2050 carbon reduction plan. A critical MEPC 76 decision was to clarify the calculation of the CII reduction rate relative to the 2019 base year. (Psaraftis, 2021) IMO's fourth greenhouse gas research report shows that between 2008 and 2019, the global carbon emission intensity of ships above 5,000 gross tons decreased by 23.6%. IMO's goal is to reduce carbon emission intensity by 40% by 2030 compared with 2008. This means that carbon intensity needs to be reduced by 16.4%.(Ahn, Lee, Jeong, & Choi, 2021; Tokuslu, 2021)

The relationship between stock and increment should be comprehensively considered for the technical path of existing ships to achieve IMO emission reduction requirements. The current set requirements of EEXI are generally equivalent to the provisions of EEDI in 2022. For vessels built after 2022, EEDI has already met the requirements of EEXI, and no special consideration is required if the conditions of EEXI are not further improved. For existing ships, especially Pre-EEDI ships, it is difficult for some vessels to meet EEXI requirements without any adjustment or modification from the current analysis. In general, the implementation of speed reduction is the preferred measure for Pre-EEDI ships to meet EEXI requirements, except that ships that have been considered in the early design stage and adopted the "dual fuel" preset scheme can complete the practical application of "dual fuel" in the future. In addition to the renovation, other relatively economical and easy-to-implement energy-saving technologies can be used for renovation under conditions. The feasibility of technical transformation and the sufficient capital and time costs need to be further analyzed according to different ship conditions.

The Carbon Intensity Index (CII) measures the efficiency of ships in transporting cargo, measured by the deadweight of each vessel and the grams of carbon dioxide emitted per nautical mile. Annual operating CII involves baseline determination, discount rate, and rating. The calculation formula is (1−Z/100) X CIIR, where CIIR is the reference value or baseline value, and Z is the discount rate; the rating is based on the annual operating CII achieved by the ship. Compared with the yearly operating CII required by the boat, the energy efficiency ranges from A-level excellent to E-level poor. The median value of the C-level range is the required annual operational CII value, which is the basis for determining other energy efficiency rating boundaries. When the CII comes into force, around 45% of ships are expected to be in category D and another 16% in category E, according to calculations from Finnish technology group Wärtsilä's CII Insight tool. The company further predicts that if nothing is done, and assuming the IMO path remains the same, 80% of the containership fleet will be in category E by 2030.

For ships rated A and B, IMO recommends that the competent port and shipping stakeholders provide incentives, and for ships ranked D for three consecutive years or rated E in the current year, a correction plan that reaches the required annual operational CII needs to be formulated and incorporated into SEEMP implementation after approval. For ships rated D for three consecutive years or rated E in the current year, what should we do if the corrective plan is implemented and the requirements are still not met? After all, at the beginning of the formulation of the rules, 16% of the ships were at the E-class level. Through their efforts, it is still impossible to meet the requirements of improving energy efficiency year by year, and the default is also a high probability. From 2026, the IMO will assess the implementation of the rules and then formulate corresponding penalties.

For inspections related to shipping energy efficiency, in the past, PSCOs were limited to inspecting ships' IEEC certificates, SEEMP documents, and SOCs issued based on DCS. After implementing the shipping carbon intensity rules, the SOC is superimposed with the energy efficiency rating label. When checking the compliance of the SOC, the PSCO will pay more attention to the energy efficiency rating status. For ships with poor ratings, the PSCO is given greater authority to check whether the ship has been thoughtfully implemented SEEMP, which may lead to a more detailed inspection by the PSCO. The "Port State Inspection Procedures" being revised have added operational carbon intensity inspection requirements, lack of SOC, COC (SEEMP), and crew unfamiliar with how to implement SEEMP, including corrective plans and implementation with a rating of E or a rating of D for three consecutive years, are defects that may lead to the detention of the ship.

The carbon intensity rules of ship operation will break the existing ship management model and prompt ships to take measures to improve energy efficiency continuously. After 2008, the shipping market tended to be in a long-term downturn after experiencing a wave of high freight rates, and ships generally adopted speed reduction measures to reduce operating costs. The fuel consumption data collected by IMO 2019 is precisely after sailing at a reduced speed. Therefore, the carbon intensity baseline in 2019 is a baseline value based on low-speed sailing and low emissions. Taking this as a benchmark, the calculation of emissions in 2008 is a redistribution of the carbon intensity indicators that have been reduced. Compared with the emission reduction targets that have been increased year by year until 2030, today's energy efficiency management is informative and intelligent, adequate measures are weak, and the expected targets can be achieved. There is a lot of uncertainty about whether it will be implemented. Fortunately, as an independent individual, the rating mechanism of ships is not affected by other ships. Ships that lose to the starting line can still achieve the ideal level of energy efficiency through measures such as improving energy efficiency management level, technology, and clean energy application.

2.3 MBM(Market based measures)

At present, MBM is a promising carbon reduction tool. According to the analysis of the World Bank, implementing fuel tax through a global agreement is the most effective shipping carbon reduction policy.(Lagouvardou, Psaraftis, & Zis, 2020; Psaraftis, 2021). Taxes based on market carbon prices can help countries reduce costs, stimulate the research and development of alternative energy and low-carbon or zero-carbon technologies, accelerate emission reductions, and effectively avoid carbon leakage(Psaraftis, Zis, & Lagouvardou, 2021). As spot carbon prices increase and higher percentages of emissions fees are applied, optimal vessel speeds are thought to decrease. In the $100/t and 100% application scenarios, an increase in emissions prices or a higher emissions percentage will not affect the variable margin as it can reduce CO_2 emissions by nearly 50%, thus significantly contributing to an environmental greenhouse Gas target. (Cariou, Parola, & Notteboom, 2019; Goicoechea & Abadie, 2021) But a tax on marine fuel will directly lead to increased transportation costs, especially for companies with weak technology and financial resources. Therefore, the MBM strategy may not be supported by the relevant shipping organizations and countries, as these shipping companies or governments will put their interests first. (Chae & Kim, 2020; Elliott, Schumacher, & Withagen, 2020; Heiskanen et al., 2019; Matewos, 2019)

Among all the regional MBM measures, the EU-ETS system is the earliest and the most influential. The European Union's revision of the EU ETS Directive aims to match its 2030 climate targets (55%) and achieve a 61% reduction in GHG emissions from 2005 in ETS-covered industries. This is mainly achieved by reducing quota issuance, strengthening the "market stability reserve" mechanism, and further expanding ETS coverage. Among them, it is planned to partially incorporate the shipping industry in 2023 and fully incorporate the shipping industry into the existing carbon market by 2026 (shipping companies will pay carbon allowances based on 20%, 45%, and 70% of their actual emissions each year, and by 2026 100% performance is required from now on). The ETS implementation process is similar to the current Maritime MRV Regulations (2015/757), with emissions monitoring, reporting, and verification carried out per the revised Maritime MRV Regulations and related implementing regulations. At the same time, to adapt to the EU ETS, targeted clauses have been added, mainly including the identification of the management authority of the shipping company, the submission of the verified cumulative emission data of the company to the management authority, the imposition of fines on companies and their ships that fail to pay sufficient quotas, Expulsion, prohibition of entry, detention and other measures. As seen in Figure 12 below, the carbon emissions of container ships account for 30% of the carbon emissions of the entire shipping industry, so container ships that need to call at European ports will be seriously affected by the inclusion of the shipping industry in the EU-ETS system. According to estimates by the Baltic Shipping Council (BIMCO), if the E.U. does not issue free quotas, assuming a carbon price range of 25 to 60 euros per ton, container ships entering and leaving the E.U. are expected to pay 900 to 200 million euros.

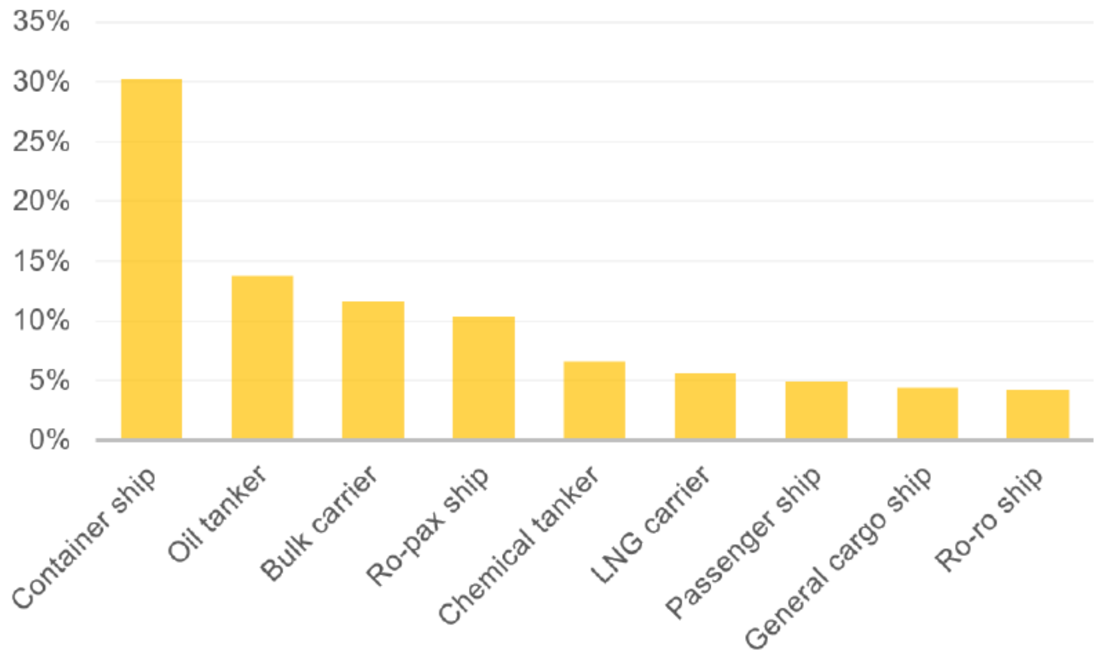

Figure 12-Share of different ship types in total CO_2 emissions reported under EU MRV for 2019(Zhao, Ye, & Zhou, 2021)

The MEPC meeting held at IMO in March 2012 reviewed the proposal on MBM submitted by the GHG Emissions Working Group Intersessional Meeting, analyzed the advantages and disadvantages of MBM, and emphasized the urgent need to establish MBM at the IMO level. The global MBM needs to comprehensively consider many factors, such as the difficulty of implementation, the efficiency of raising funds, the probability of absolute carbon reduction, the stimulation of new technologies, the likelihood of preventing carbon leakage, etc. One is the pricing of carbon emissions. On the other hand, the progress of MBM at the IMO level has been plodding because the IMO has been committed to using technologies to reduce emissions. However, the rapid advancement of the global carbon emissions trading market and the E.U.'s new legislative measures will undoubtedly speed up the review process of the IMO GHG emission reduction medium-term measures. They will also highlight the position of carbon emissions trading in the market mechanism. At the same time, coordinating the MBM carbon reduction strategy formulated by IMO and the other regions will also be a problematic issue to succeed. IMO needs to find a viable path between institutional reductionism and institutional overload(Young & Stokke, 2020).

2.4 Decarbonization Trend Forecast

The growing likelihood of IMO taking the initial strategy set in 2018 to zero carbon emissions by 2050 in 2023(Wada, Yamamura, Hamada, & Wanaka, 2021). The initial decarbonization strategy formulated by the IMO lags behind the latest Glasgow Climate Pact signed by the European Union and the United Nations(Bullock, Mason, & Larkin, 2021). During the COP26 meeting, the U.S. President's special envoy on climate issues, John Kerry, and the Danish Prime Minister announced that they are urging the IMO to set more ambitious goals to achieve zero emissions from shipping by 2050(Sheather, 2021). Kerry said complete decarbonization of the shipping industry is achievable and would contribute to the goal of limiting global warming to 1.5°C. In addition, according to research, when cargo owners have low-carbon preferences, regardless of whether the government provides emission reduction subsidies, the profits of shipping companies in the green shipping supply chain are always better than those in the ordinary shipping supply chain(Elliott et al., 2020). Therefore, many large container companies have set their decarbonization goals to achieve zero carbon emissions by the middle of this century. Maersk even declared that it will reach completely green shipping by 2040. Undoubtedly, in the face of these pressures, the IMO is more likely to show greater ambition in decarbonization(Doelle & Chircop, 2019).

The MBM formulated under the guidance of IMO will contribute to the realization of the shipping industry's mid-and long-term decarbonization goals. The International Monetary Fund and the World Bank hold the same view. Both believe that the fuel tax is relatively stable, which is conducive to the decision to regulate transportation and the long-term development of carbon emission reduction technologies(Halim et al., 2018). The Congressional Budget Office also believes that taxes have apparent advantages and are the most effective means of stimulating emission reductions. The shipping industry is not only highly differentiated but also has unique characteristics. Considering the environment in which it works, its role in global trade, and the nature of its business model, It is not difficult to see that GHG emission reduction needs to pass a globally unified fuel tax policy(Godet et al., 2021; H. Xing, Spence, & Chen, 2020). In this way, it will be the most direct and effective measures to reduce carbon emissions and avoid carbon leakage, stimulate the research and development of alternative energy and low-carbon or zero-carbon technologies, thereby assisting the realization of global GHG emission reduction goals and jointly curbing the impact of climate change.

CHAPTER 3 - DECARBONIZATION MEASURES FOR CONTAINER SHIPS

3.1 Design-build stage decarbonization technology

At present, shipowners in the market pay special attention to fuel consumption indicators, and at the same time, the requirements for EEDI of new ships are also constantly increasing. Therefore, newly developed ship types must focus on energy efficiency optimization. This is a standard requirement and a market demand for ship owners to reduce operating costs. The traditional ship energy-saving design mainly includes hydrodynamic optimization, equipment improvement and upgrading, and ship size optimization. These three technical energy efficiency measures have relatively high emission reduction potential. Still, the investment cost is also high, and there are differences in the types of ships applicable to different technical energy efficiency measures.

3.1.1 Hydrodynamic optimization

Hydrodynamic energy-saving design is the traditional method, with low input cost, good energy-saving effect, and reliable technology. The ship's hydrodynamic energy-saving design is mainly reflected in two aspects: one is to reduce the vessel's resistance; the other is to improve the propulsion efficiency of the ship.

3.1.1.1 Reduce ship sailing resistance

Reducing the resistance of ships during sailing is the basis of energy-saving optimization design. The resistance of ships in navigation mainly comes from water and wind resistance, so the following methods are used primarily to reduce the navigation resistance of ships. (Halim et al., 2018). (1) Through the optimization of the line shape, the resistance of the ship in still water and waves is reduced; (2) Ensure the best overall performance through multi-objective optimization based on operating profiles; (3) Ensure that the ship sails in the best energy-saving attitude through trim optimization; (4) Reduce frictional resistance under the waterline through low-resistance paint or air layer resistance reduction; (5) The wind resistance of the ship is reduced by optimizing the wind resistance of the superstructure.

3.1.1.2 Improve ship propulsion efficiency

The ship propulsion efficiency is improved mainly through propeller optimization and applying hydrodynamic energy-saving devices. The propeller design has been very mature. In addition to taping the propeller's design potential, the propeller's efficiency is mainly achieved by matching the large-diameter propeller with the low-speed main engine. Hydrodynamic energy-saving devices are also a meaningful way to improve the propulsion efficiency of ships. The energy-saving effect varies with ships and propellers, so different customized energy-saving device designs should be adopted for different ship types, line types, and propellers.

3.1.2 Waste heat recovery improvements and upgrades

Except for a small amount of fuel carried by ship, the rest is used for combustion and becomes the form of primary heat energy. About half of this heat energy becomes the input energy of power devices such as internal combustion engines. Heat engines convert it into mechanical energy, driving power generation. According to the second law of thermodynamics, heat energy always flows from a high-temperature heat source to a low-temperature heat source. It degrades from high-grade to low-grade but cannot spontaneously return to its original grade of unusable thermal energy. As far as the thermal efficiency of the heat engine is concerned, as shown in Figure 13 below, even the most efficient marine diesel engine is only about 50%. Generally, more than 50% of the thermal energy of the maritime power plant is discharged into the atmosphere by exhaust gas or cooling. Utensils are directly discharged into the river and sea(Singh & Pedersen, 2016).

Therefore, the so-called energy saving is the problem of how to increase the effective utilization of the available energy in the energy system. The thermal efficiency of marine diesel engines is the highest among the major main engines, around 50-55%, and there is now little opportunity to improve engine efficiency further. However, since about 25-30% of the energy is lost through the exhaust gas and about 10-15% is lost through the cooling water, recovering the waste heat from the exhaust gas and cooling water can significantly improve the overall thermal efficiency. In addition to conventional exhaust gas turbocharging and exhaust gas economizers, organic Rankine cycle WHR powertrains have great potential for offshore applications. (Singh & Pedersen, 2016) However, the fuel-saving potential reported by different published studies varies widely(Kim, Park, Lee, Chun, & Lee, 2018).

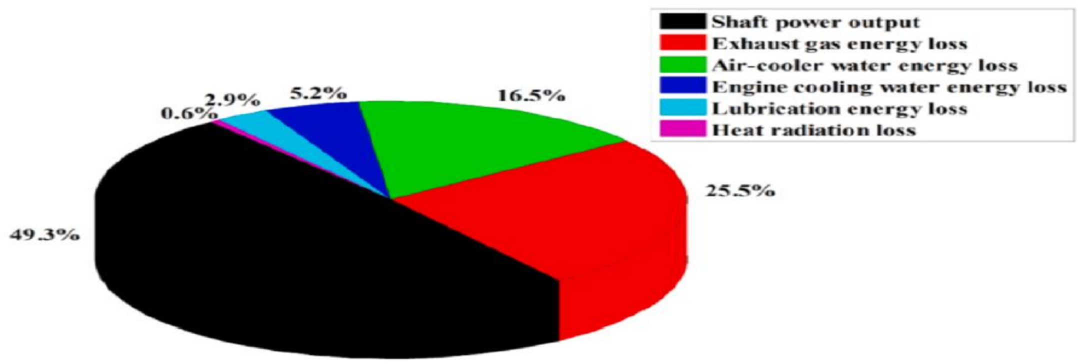

Figure 13-Energy balance of a low-speed two-stroke marine diesel engine(Pan et al., 2020))

The improvement and upgrading of the main engine can be directly reflected in the reduction of unit fuel consumption, mainly relying on the development of new high-efficiency models. For example, the new high-efficiency main engine (G-type machine, X-type machine) with ultra-long stroke and low speed has higher efficiency and lower unit fuel consumption(Ahn et al., 2021; Civgin & Deniz, 2021). At the same time, the optional range of the power point of the main engine is more comprehensive, and the speed is lower. The power point (SMCR) should be selected as close as possible to the lower-left corner of the optional range with the most downward mean adequate pressure, which not only reduces the unit fuel consumption of the main engine but also reduces the rotational speed, increases the optimal diameter of the propeller, improves the propulsion efficiency, and effectively reduces the total fuel consumption(Ammar & Seddiek, 2021). The choice of NOX emission Tier III solutions will also affect fuel consumption, such as EGR, EcoEGR, HPSCR, etc.

The energy consumption of the main engine accounts for the vast majority of the energy consumption of the whole ship. Still, optimizing auxiliary systems also has energy-saving potential and cannot be ignored. The optimization of the auxiliary system mainly includes the following. According to (Pan et al., 2020), the modified dual TAC S- CO_2 RBC waste heat recovery system can effectively reduce the EEDI of auxiliary machines by 1.01% and 1.02% and can improve the energy efficiency of the main engine by 3.23%.

(1) Shaft generator;

(2) Waste heat recovery system;

(3) Frequency conversion equipment;

(4) Intelligent energy efficiency management system.

3.1.3 Ship size optimization

The ultimate goal of civil transport ship design is to achieve specific transport functions at the most economical operating cost. Optimizing the ship size will often significantly reduce the unit cargo transportation cost and bring about significant energy-saving effects, such as larger ships and customization of ship shapes. In the case of sufficient cargo transportation volume, the economies of scale brought about by large-scale ships can significantly improve the energy efficiency of unit cargo transportation, thereby reducing the total amount of greenhouse gas emissions. A typical example is the international super-large-scale competition of container ships in recent years.

3.2 Decarbonization of existing ship technology retrofits

Technical energy efficiency measures can reduce fuel consumption and carbon emissions by lowering ships' resistance and improving propulsion devices' efficiency. The main measures for retrofitting existing ships include hull coating, air film resistance reduction, and wind energy-assisted propulsion. In addition, technologies such as marine carbon capture and collection have also received increasing attention in recent years. For existing ships, hull coating, air lubrication, wind boosting, and other energy efficiency technologies with significant energy saving and emission reduction effects are feasible solutions.

3.2.1 Hull coating

The hull coating is mainly composed of two parts, one is to reduce the adhesion of marine organisms through the layer, and the other is to increase the smoothness of the hull surface. Biofouling, corrosion, and deformation on the surface of the hull and propeller will also significantly impact the energy efficiency of ship operation, especially since biofouling is the most significant. According to MAN Diesel & Turbo, the fouling organisms may increase the sailing resistance by 25%-50% during the entire operation of the ship; every 25 microns thickening of the fouling organisms requires an increase of 2-3% in power consumption to maintain the speed. Failure to do so will result in a 1% reduction in speed. The American Bureau of Shipping (ABS) calculation results show that every 10-20 microns of fouling organisms on the hull increase the resistance of high-speed skinny ships by about 0.5%. Taking a typical propeller as an example, with the help of computational fluid dynamics simulation studies, found that fouling organisms can lead to a 30% reduction in propeller efficiency. Through empirical analysis, it was found that regular cleaning of hull fouling can reduce the daily fuel consumption by 9%-17%. Compared the differences of different antifouling coatings in inhibiting biofouling, and pointed out that the ship's sailing speed, berthing time, and the salinity and temperature of the sailing waters all have a particular influence on the degree of fouling. Biocide-free paint with a hydrogel coating can slow down the fouling of the hull, thereby reducing ship resistance. Other advanced hull coatings reduce frictional and are claimed to deliver fuel savings of over 10%.

3.2.2 Air lubrication

Air lubrication has attracted some attention in recent years. It works by forming an air film on the part of the hull to reduce friction and thus fuel consumption (Kumagai, Takahashi, & Murai, 2015). In November 2021, British clean technology company Silverstream Technologies announced that it had won a significant order from Mediterranean Shipping Company(MSC) to install the Silverstream R air lubrication technology system for its more than 30 large container ship new build projects. It claims the Silverstream R system will directly reduce carbon emissions by 1.6 million tonnes over the vessel's life – equivalent to the annual emissions of 350,000 cars. As a result, MSC can save about 257.5 million euros in fuel costs. Silverstream technology creates a rigid blanket of air bubbles between the hull and the water to reduce friction, reducing fuel usage and carbon emissions. Independent third-party agencies prove savings as high as 5-10%. The system works effectively in all sea conditions and has the highest utilization or range effective working rate of any air lubrication technology available on the market. Silverstream technology is equally applicable in new build and retrofit projects.

3.2.3 wind-assisted propulsion

Wind energy has neither cost nor emissions. Using it as a supplementary power to assist propulsion can achieve sound energy-saving effects under specific environmental conditions. For example, the rotating wind turbine using the Magnus effect and the wing-shaped sail that can be raised and lowered. Currently, the most popular and least risky WAPS technology on commercial ships is the rotary-wing sail, also known as the Freightliner sail, which was introduced in the 1920s. Inventor named.

The installation of rotor sails on small ships has achieved fuel savings of 4.5% and up to 25% through advanced computer control technology. But for container ships, the rotating wind drum is unsuitable because it will affect the loading of deck cargo. Wingsails and kite sails are one of the few wind-assisted propulsion systems suitable for container ships. Wingsail manufacturing company Zéphyr & Borée used a tool that uses statistical weather and routing to predict vessel performance and estimate fuel levels, enabling the selection of routes in optimal wind conditions. The wind booster can be used with energy-saving, and emission reduction means such as hydropower and alternative fuels, which is beneficial for ships to reduce EEDI. Regardless of whether it is a new ship or a refitted operating ship, the wind-assisted rotor of the vessel is applicable, the investment is small, and the payback period is short for the ship owner.

3.2.4 Marine carbon capture and recovery device

In addition, carbon capture technologies that are already commercialized and applied to offshore plants are a more suitable option for bridging the gap until more advanced fuel and propulsion system technologies are developed. But the EEDI regulations proposed by the IMO by 2022 do not reflect the introduction of the OCCS system (S. Lee et al., 2021). At ISWG-GHG 12, the issue of incorporating carbon capture technology into the EEDI/EEXI formula using revision coefficients proposed by South Korea was discussed. The conference invited interested parties to continue to submit proposals for subsequent consideration regarding the maturity of the technology and practical application. But at present, although carbon capture and collection technology have many operating projects on land, there are still many obstacles to marine use, such as laws and regulations, economics, and technical feasibility (d'Amore, Romano, & Bezzo, 2021; S. Lee et al., 2021; Weng, Cai, & Wang, 2021; Zhang, 2021).

3.3 Strengthening decarbonization of operations management

Optimizing operations reduces energy requirements and increases energy efficiency without using any new technology by optimizing processes during sailing, maneuvering, and berthing phases, which the management company can do, crew, or is implemented by port service providers. Various operational carbon reduction measures have been listed in many research reports, which can be divided into the supply chain and logistics optimization, low-speed sailing, voyage optimization, maintenance optimization, and improving the energy-saving awareness of relevant staff. Among them, the optimization of container network design and schedule arrangement accounted for the most significant proportion.

The navigation resistance of the ship is mainly affected by the underwater shape of the hull, the surface area, the degree of smoothness, the speed over the water, the weight of the ship's loaded cargo, and the wind-affected area above the water surface. The above factors mainly depend on the ship's speed, angle of the trim, smooth surface condition of the underwater hull, propeller, and rudder blade(Farkas, Degiuli, Martić, & Vujanović, 2021), deck cargo stowage(Yu et al., 2021), weather and sea conditions(Trapp, Harris, Sanchez Rodrigues, & Sarkis, 2020) and so on. Therefore, optimizing the above factors will effectively improve the energy efficiency of ships and reduce their carbon emissions.

Among all the factors that affect the carbon emissions of ships, as a rule of thumb, the output power of the vessel's main engine is proportional to the cube of its rotational speed, so the change of sailing speed has the most apparent impact on fuel consumption. Moreover, as a significant expenditure item in ship operation, reducing fuel consumption can reduce carbon emissions and operating costs. Hence, the research on it is also the most popular. Because the schedules of liner companies are relatively fixed, the study of how to maximize the route time and reduce the sailing speed by optimizing the arrangement of the fleet network has become the focus of the research. These studies are analyzed through statistical analysis(Cariou et al., 2019), algorithm optimization, Fleet Network Dynamic Optimization(Herrera Rodriguez, Agrell, Manrique-de-Lara-Peñate, & Trujillo, 2022; Jiang et al., 2021), dynamic adjustment of port order(Poulsen & Sampson, 2020; Zheng Wan et al., 2021). By optimizing the bunkering port, as shown in Figure 14 below (De, Wang, & Tiwari, 2021; Wang & Chen, 2017), combined with regional emission control rules and charter party (Ammar & Seddiek, 2020; Dirzka & Acciaro, 2021; Dong & Tae-Woo Lee, 2020; Goicoechea & Abadie, 2021; Lashgari, Akbari, & Nasersarraf, 2021), use collapsible containers(Goh, 2019), etc. Verifies the significant effect of optimizing fleet network and using economical speed in reducing fuel consumption and operating costs, found that optimal speed can reduce average fuel consumption cost by 4.41%. Profits will be maximized when applying a reduction of individual port calls while slowing sailing. A system consisting of ocean-going container liners and feeder containers can increase earnings by 4.05% and reduce carbon emissions by 19.70% (Yu et al., 2021)。

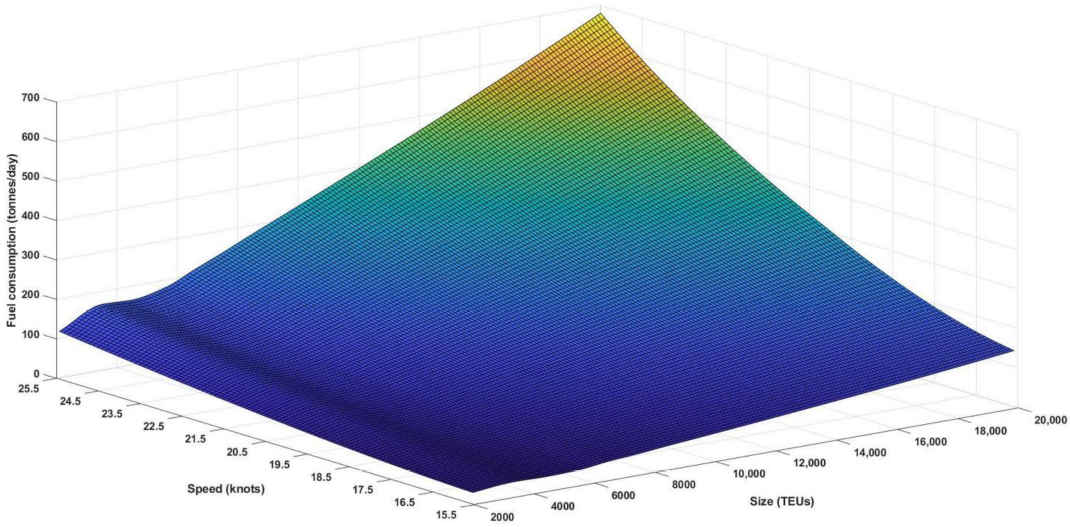

Figure 14-Fuel consumption (FC(VS,SS)) as function of size (TEUs) and speed (knots) Optimal behaviour for selected vessels(Goicoechea & Abadie, 2021)

In addition, it can be seen from Figure 15 below that container ships have a higher proportion of sailing time than other ship types. Hence, another popular research is to optimize transoceanic routes through meteorological navigation, maximize the use of wind currents and avoid bad weather. During the entire voyage, the engine speed is dynamically adjusted through algorithms to optimize fuel savings and reduce emissions. According to(Cariou et al., 2019; Goicoechea & Abadie, 2021), It was found that with the increase in the spot carbon price or the application of a higher percentage of the emissions price, the optimal vessel speed was thought to decrease. In the $100/t and 100% application scenario, an increase in emissions price or applying a higher emissions percentage would not affect the variable margin as it could reduce CO_2 emissions by almost 50%, thus significantly contributing to the achievement of an environmental greenhouse gas target (Dirzka & Acciaro, 2021). But if freight rates remain high as in 2021, fuel prices will have little effect on changes in container shipping rates(S.-Y. Lee, 2021).

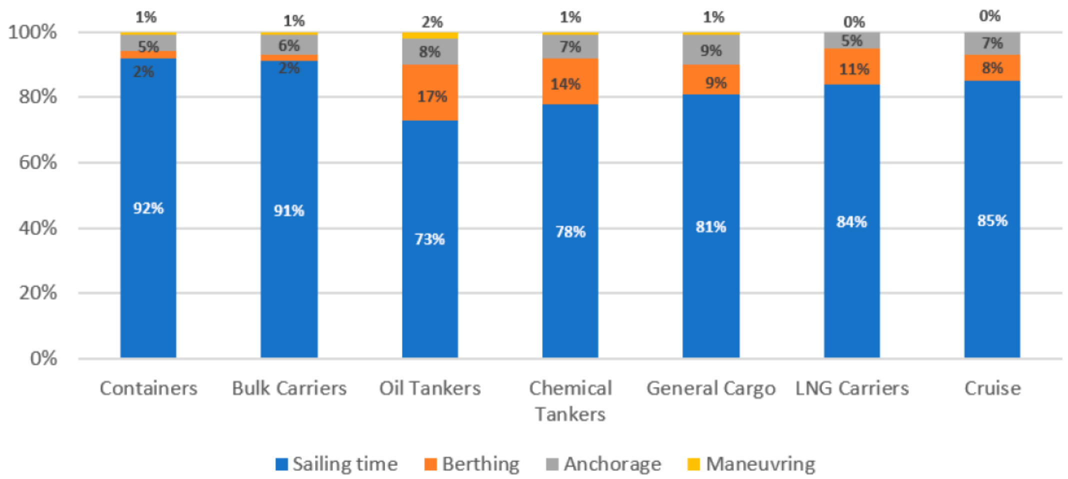

Figure 15-Energy consumed by ships according to the stage of voyage and type of fleet (Source:An Energy Consumption Approach to Estimate Air Emission Reductions in Container Shipping-2021).

Furthermore, the specific environmental emission reduction potential of each measure is derived from multiple different references, so it does not make sense to look at the emission reduction potential of particular actions in isolation, especially when introducing characteristic emission reduction policies such as the EU-ETS, the ship type, route, and operational characteristics should be taken into account(Zheng Wan, Ge, & Chen, 2018). For example, despite Arctic shipping's high CO_2 reduction potential, very few ships sail through the Arctic shipping lanes. Studies have shown that compared with the 16,000 TEU container ships sailing through the Suez Canal, not all ship types can reduce fuel carbon intensity by switching to the Northeast Arctic route. Factors such as ship speed and space utilization also need to be considered. When the speed of ships in normal waters is set to 23 kn and ships in ice waters are set to 14 kn. Compared with the 16 000 TEU container ships navigating the Suez Canal, the seven types of container ships sailing the Northeast Arctic route have the same CO_2

emissions per voyage. But only the 14 000 TEU and 16 000 TEU ship types have a lower carbon intensity of sailing fuel, and the advantage is not considerable. The reason: Compared with navigating the Suez Canal, as shown in Figure 16 below, although the Arctic Northeast route can shorten the voyage, due to the low space utilization rate, the accumulated cargo turnover does not gain an advantage. When ships are navigating the Northeast Arctic route, the carbon intensity of fuel can be reduced by further reducing the speed of vessels in ice waters or improving the utilization of space(Ding, Wang, Dai, & Hu, 2020).

Figure 16-The Shipping Route of SCR and NSR(Ding et al., 2020))

On the premise of ensuring the safety of navigation, according to different ship draughts, adjusting the ship to a certain trim condition has a positive effect on improving the propulsion efficiency. When the ship has a certain displacement, changing the trim angle, the geometry of the underwater part of the ship changes, the shape and length of the waterline of the hull, the position of the center of buoyancy, the inflow from the bow and the outflow from the stern also change accordingly. The change is more remarkable when pitching, resulting in a change in resistance when the ship is sailing. Compared with the state of flat draft, when the ship is in the state of bowing, the total resistance increases with the bowing. When the ship is in the state of tailing, the total resistance decreases first with the increase of the state of the tailing; when the tail tilt exceeds 0.02 m, the total resistance begins to increase significantly. The optimum trim value is 0.02 m tail tilt, and its resistance is reduced by about 45.48% compared with the maximum resistance, and the opposition is reduced significantly. Considering the ship's tail tilt, its propeller propulsion efficiency is higher, and its energy-saving and emission reduction effect is better. Through the simulation of an 8000TEU container, it is found that the optimal trim under the premise of safe navigation can reduce the hydrostatic resistance by about 1.9%, thereby increasing the operating energy efficiency of the ship by about 0.8%. With the help of navigation simulator research (Zhou, Wang, & Yuen, 2021) and others found that the ship's fuel consumption can be reduced by nearly 10% by providing relevant skills training and energy-saving awareness training to the crew.

In addition to retrofitting existing ships through technology or optimizing operations, phasing out old ships is also a decarbonization option. The China Shipping Prosperity

Index Compilation Office of the Shanghai International Shipping Research Center surveyed what measures shipping and port companies will take to meet the "30/60 carbon peak/carbon neutrality" goal. According to the survey report, 19.78% of enterprises indicated that they would mainly use clean energy fuels to achieve emission reduction targets; 18.68% of enterprises indicated that they would choose engines with higher combustion efficiency to reduce carbon emission intensity; 17.03% of enterprises indicated that they would adopt additional installations; way to reduce carbon emission devices; 15.38% of the companies said they would slow down the fleet; 21.43% of the companies said they would take measures to speed up the dismantling of old ships.

In general, as shown in Figure 17 below, due to the complex composition of the shipping fleet and the significant differences in size and performance of similar ships, the conclusions obtained from these studies cannot necessarily be generalized as general laws. These research results show that different energy-saving and carbon-reducing effects are often produced when specific technologies or measures are applied to other ships, under different operating conditions, or affected by various external environmental conditions. However, since these constraints are seldom explicitly mentioned, the evaluation results are often uncertain. In addition, although existing research provides several performance evaluation methods for specific technologies when multiple measures are applied to the same ship, there is no mature method to evaluate the superposition effect.

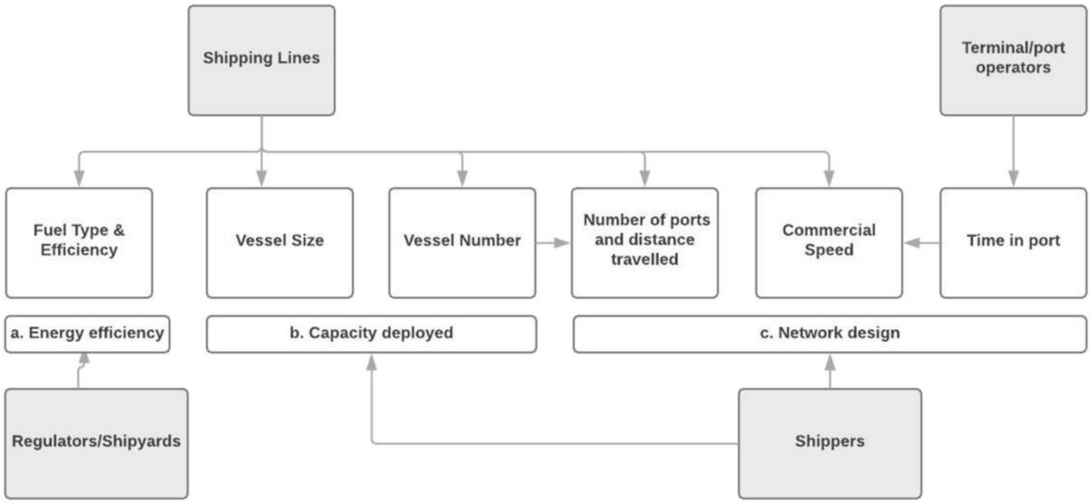

Figure 17-The actors and the decision factors influencing the variation of total CO_2 emissions in container shipping (Cariou et al., 2019))

3.4 Alternative and zero-carbon fuels

Among the main technical paths for decarbonizing shipping, carbon capture technology and alternative fuel technology can achieve a tremendous emission reduction potential, with a maximum emission reduction effect of 100%. Carbon capture and collection technology can theoretically eliminate greenhouse gas emissions, and there are also examples of practical applications on ships. However, problems include large equipment, troublesome operation and management, high cost, and the onboard storage of captured carbon dioxide that takes up the ship's cargo space. From the current point of view, the use of fuels that replace traditional fuels, especially low-carbon marine fuels, has matured in terms of technology and supporting facilities, and the economy is gradually moving closer to conventional fuels. The research development and application of zero-carbon fuels are also proceeding orderly, and commercial operations will gradually appear in the next few years. It is foreseeable that low-carbon and zero-carbon fuels will be necessary for shipping to achieve decarbonization and net-zero carbon emissions.

3.4.1 The use of low-carbon fuels has matured

LNG is regarded as the prelude to this "alternative fuel" revolution. Basic research, demonstration applications, and commercial deployment began many years ago, and now it has become the most mature alternative fuel. According to the study, compared with the traditional fuel main engine, the LNG dual-fuel main engine can achieve CO_2, NOx, SOx, PM, and C.O. are reduced by 20.1%, 85.5%, 98%, 99%, and 55.7%, respectively. In addition, LNG as a marine fuel at this stage is close to traditional energy in terms of technical maturity and very mature in production and distribution. The global infrastructure is still in the process of further expansion. More than 40 European coastal ports have LNG bunkering facilities. By 2025, there will be more than 100 bunkering facilities in the E.U., and LNG bunkering facilities in other regions are also under construction(Elkafas, Khalil, Shouman, & Elgohary, 2021). In 2018, the total global shipping LNG consumption was 11.4 million tons, the most consumed fuel in the shipping sector except for heavy fuel oil (HFO) and marine diesel (MDO).

The "full score" of technical maturity, perfect business operation model, in-depth support from diesel producers, and prices similar to traditional fuels have enabled CMA CGM Group, the world's third-largest shipping company, to expand LNG in its fleet strategically. The proportions of the LNG ship seem reasonable. Although LNG is also called a transition fuel because of its carbon emissions as fossil fuel and the problem of methane escape, it is not optimistic by some industry insiders. Still, technological progress is gradually eliminating these shortcomings. For example, the latest high-pressure diesel cycle engines can reduce methane escape to a very low level, or the emergence of bio-LNG enables a smooth transition from fossil-fuel LNG to bio-fuel, giving future LNG-powered ships a new way out (Lindstad & Rialland, 2020). Currently, the industry calls it LNG ready-to-use fuel (drop-in fuel), which means ships powered by LNG can use LNG ready-to-use fuel simultaneously in the future. For example, liquefied biomethane fuel (bio-LNG) and liquefied synthetic methane (LSM) are compatible with LNG ships without significant modifications; CMA CGM's container ship "Jacques Saade" is already used on board. Therefore, it remains to be seen whether LNG will become the ultimate alternative fuel in the future. But in any case, LNG, as the "pioneer" of alternative fuels, has been at the forefront of this new era.

While the exploration of LNG fuel is becoming increasingly mature, several low-carbon fuels have also developed rapidly, mainly LPG, methanol, and biofuels. LPG is a by-product of the natural gas production/refining process and is already available globally with a well-established production and supply path. The technological maturity of LPG used in ships is close to that of LNG, and the carbon emission reduction potential is 20%. It needs to be supplemented by LPG/dual-fuel engines. Representative solutions include MAN's ME-LGI dual-fuel engine and Wärtsilä LPG fuel supply system(LFSS). The development of LPG engines also brings new development potential for ammonia fuels, as most of the materials used in LPG storage tanks and systems are suitable for ammonia. But because LPG is a by-product, as demand for fossil fuels decreases in the future, so will LPG. Combined with the increase in renewable energy, the supply of LPG may also be constrained in the future. Given the general transition to low-carbon fuel for ships, the industry is not optimistic about the feasibility of LPG as an alternative fuel.

In February 2021, Maersk Tong officially announced that it will use methanol as a fuel for feeder container ships in 2023 and continue researching, developing, and cooperating with this goal. In March 2022, it again announced establishing a strategic partnership with several international enterprises in production, research, and development, aiming to help Maersk obtain green methanol far beyond the first batch of 12 new container ships. Such a grand strategy and layout also show Maersk's reasonable expectations for the potential of green methanol and the future feasibility of green methanol fuel. In addition to Maersk, X-Press Feeders ordered 16 1170TEU dual-fuel container ships in 2021, which can use methanol and conventional energy.

The green competitive advantage of methanol as a marine fuel is self-evident. It is a clean oxygen-containing liquid fuel with convenient storage and utilization characteristics, abundant resources, and a wide range of uses. Using it as a marine fuel will not produce sulfur emissions. PM emissions are very low, and carbon dioxide emissions can be reduced by about 20% compared to conventional marine fuel oil. Since methanol can be mixed with water, it can meet the Tier III requirements of IMO nitrogen oxide emission without installing expensive exhaust gas after-treatment equipment, effectively reducing costs. At the same time, methanol is also an excellent carrier for liquid hydrogen storage and transport.

Moreover, methanol is liquid at room temperature, contains no sulfur, and has a lower carbon dioxide content than HFO and MGO, which means that a large amount of existing infrastructure can be used to support the promotion of methanol, and also The flexibility to produce methanol from multiple feedstocks ensures a truly future-proof net-zero carbon fuel. In terms of facilities, methanol can be a distinct advantage for methanol fuel due to its extensive chemical industry infrastructure and the port's accumulated experience in handling.

In the research and development of methanol marine engines, MAN Energy Solutions has added a low-speed dual-fuel engine that can burn methanol to its engine series - the MAN B&W G80ME-C10.5-LGIM version engine, expanding shipowners' awareness of dual-fuel engines. The engine is also optionally available with exhaust gas recirculation (EGR) to ensure compliance with NOx Tier III emissions requirements. The new version of the engine will be available in 6-, 7-, 8- and 9-cylinder versions. This expansion of the engine platform will allow MAN to respond to the growing demand for methanol fuel solutions for medium-sized container ships and huge ore and crude oil carriers. Like other dual-fuel solutions recently introduced by MAN, this solution will also be suitable for retrofitting existing G80ME-C engines.

Alternative fuel powertrains. With the advancement of alternative fuel applications, powertrains dedicated to alternative fuels have also gained promising results. Wärtsilä, the world's leading power system solutions provider, has successfully developed MethanolPac, a supply system for methanol fuel. This system, combined with the recently launched Wartsila 32 methanol-fueled engine and well-proven retrofit and system integration capabilities, enables Wartsila to offer methanol-fueled supply systems and powertrains across a wide range of marine sectors. The MethanolPac includes the fuel supply system's low pressure. This includes high-pressure methanol fuel pump units, low-pressure pump modules, fuel valve manifolds, fuel filling stations, and tank gauges. The new-build Wartsila 32 methanol engine combines the time-honored methanol fuel injection technology first developed in 2015 for the Stena Germanica ro-ro passenger ship retrofit of the Wärtsilä Z40 engine with the sophisticated control and automation systems of the proven Wärtsilä 32 platform. Methanol fuel injection can also be retrofitted to more than 5,000 Wärtsilä 32 engines running on conventional fuels. The MethanolPac means this retrofit can be greatly simplified, as the same supplier provides the engine and fuel supply system. The mixed-use of multiple technologies in the hybrid system will make more effort with less effort.

Biofuels (FAME and HVO), although not currently widely used in the shipping industry, are being developed and trialed by several of the world's largest container companies, and the trend is growing. These raw materials are 100% waste or residues and cannot be used in higher-quality applications or recycled, such as used cooking oils and waste animal fats. Compared to fossil equivalents, marine biofuels can remove 80% to 90% of life cycle carbon emissions and eliminate almost all sulfur oxide (SOX) emissions(Chiong et al., 2021). The excellent carbon emission reduction effect of biofuels has also been verified. In December 2021, Eagle Bulk Shipping, a US dry bulk carrier, announced that its 63,529-DWT "Sydney Eagle" bulk carrier would use biofuels after using biofuels. CO_2 emissions have been reduced by 90%. South Korea's HMM also carried out biofuel bunkering at the South Korean port of Busan during the same period. BP and Maersk also completed trials of biofuel blending with marine fuels on two product tankers during the same period. Such speed and cases illustrate shipowners' keen awareness and action and accelerate biofuels' commercialization. It is worth mentioning that another critical advantage of biofuels is their "drop-in" capability, which means they can be used on their own in conventional engines or mixed with existing fossil fuels without any modifications.

3.4.2 Zero carbon fuel is the key to a Zero-Carbon Future for Shipping Industry

Although ammonia and hydrogen do not have the high commercial and technological maturity as marine fule, they still have been identified as the most promising fuel to ensure the shipping industry has a zero-emissions future. Perhaps because all parties in the sector clearly see that grasping the zero-carbon fuel technology may be the key to winning the future, they have made efforts in the initial stage and have the momentum to win at the starting line. The fuel options with a zero-carbon footprint are shown in Figure 18 below. Although biofuels and synthetic carbon-based fuels are also options for zero-carbon fuels, due to immature technology and unsustainable feedstock supply(Englert et al., 2021), Compared with ammonia and hydrogen, ammonia and hydrogen can be produced by electrolysis of water and air. As the technology matures and raw materials are unlimited, hydrogen and ammonia are currently the most viable options as carbon-free fuels.

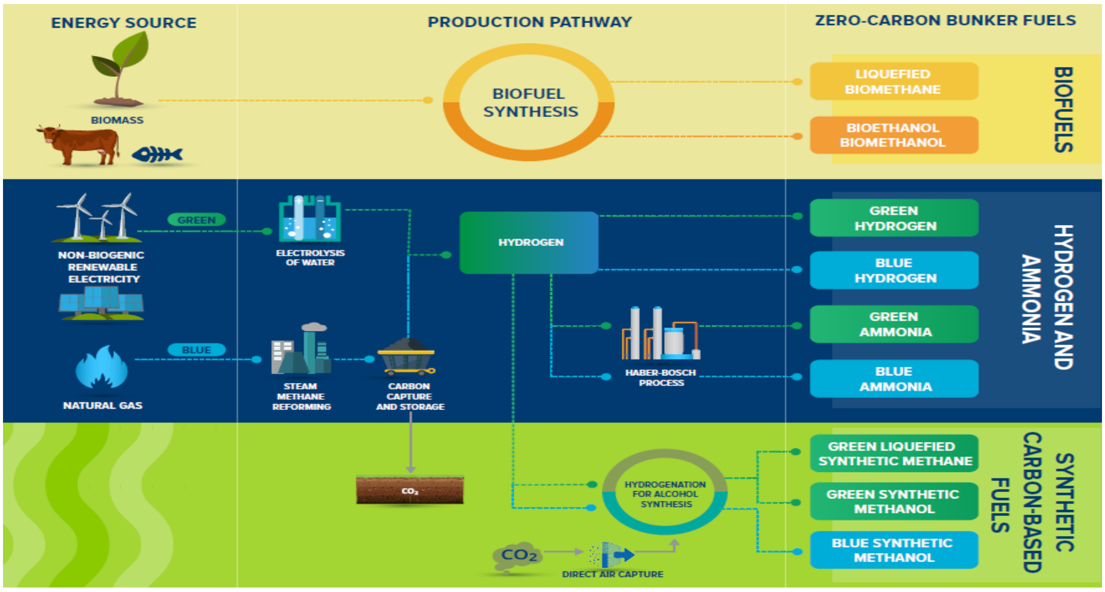

Figure 18-ZERO-CARBON BUNKER FUEL OPTIONS FOR SHIPPING(Source: The Potential of Zero-Carbon Bunker Fuels in Developing Countries)

From the perspective of hydrogen compatibility and technology, the commercialization of hydrogen fuel in the production route is mature, but it has not yet been widely used on ships. Some small hydrogen fuel demonstration ships, such as the Norwegian Maritime Administration HYBRID project, are still being started. Second, hydrogen is suitable for engines and fuel cells. Wärtsilä announced in 2021 that it will develop an engine and power plant concept that will be able to use 100 percent hydrogen by 2025. In 2021, Japan's Kawasaki Heavy Industries, Yanmar, and J-Eng engine companies jointly established a new company dedicated to two-stroke hydrogen fuel engines. The Norwegian shipowner has also recently obtained the certificate of approval in principle for the world's first zero-emission self-unloading hydrogen fuel bulk carrier. The ship will be powered by hydrogen, which is compressed for use by the hydrogen-fueled main engine. Delivery is scheduled for 2024.

In terms of infrastructure, there is currently no infrastructure for hydrogen fuel, and dedicated infrastructure is required. Green hydrogen is not now produced on a large scale, and it is essential to note here that the supply of hydrogen depends on the current power generation system's ability to support hydrogen production from renewable energy sources. However, a series of "big moves" indicate that the supply and deployment of hydrogen are underway worldwide. For example, the hydrogen-to-ammonia production plant in Saudi Arabia recently announced that it could produce green hydrogen. Spain's largest shipyard and energy company plan to invest nearly 3 billion US dollars to "build" the hydrogen industry chain. Over time, hydrogen production plants' capital costs will decrease, reducing hydrogen fuel costs (Calado &

Castro, 2021). However, as shown in Table 1 below, the low energy density per unit volume of hydrogen remains a limiting factor for marine applications.

Table 1-Comparison between ammonia and other internal combustion engine fuels(Cardoso et al., 2021)

Parameters	Fuel				
	Ammonia	Hydrogen	Gasoline	Diesel	LPG (Propane)
Density (kg/m^3)	0.73	0.08	720–780	850	495
Boiling point (K)	239.80	20.28	310–477	455–633	231
Freezing point (K)	195.50	13.99	215	219	85
Energy content, LHV (MJ/kg)	18.80	120	43.50	45	45.50
Octane number	130	130	86–94	8–15	120
Auto-ignition temperature (K)	930	773	643	527	728
Latent heat of vaporization (kJ/kg)	1371	461	380	375	428
Autonomy - 500 km range (litres)[a]	107.30	279.50	39.20	34.50	53.10

From the whole life cycle perspective, ammonia fuels produced by different routes have different emission reduction effects. The emission reduction potential of gray ammonia produced from natural gas is zero, and the emission reduction potential of blue ammonia produced by combining carbon capture and storage technology is 85%. The technological maturity and economy still need to be improved. The emission reduction potential of green renewable electrolytic ammonia production is 75% (if the electricity is 100% renewable, then its emissions are zero) (Al-Aboosi, El-Halwagi, Moore, & Nielsen, 2021).

There are greenhouse gas emissions in the path of ammonia production from natural gas. Therefore, it is necessary to combine CCS to produce blue ammonia. Ammonia production by electrolysis can be achieved with commercially mature facilities, but these production routes are not yet widely used due to the cost of electricity from renewable sources(Chen, Xia, Feng, & Liu, 2021; Klaas, Guban, Roeb, & Sattler, 2021). As shown in Figure 19 below, high-temperature electrolytic ammonia production will not be realized until 2030 or later (forecast performed at 2% growth)(Chehade & Dincer, 2021). There are also many cases in the research industry of green ammonia, but there are mainly two ways of using wind and solar energy. Figures 20, 21, and 22 below show different principles, but there is no definite timetable for its commercial use.

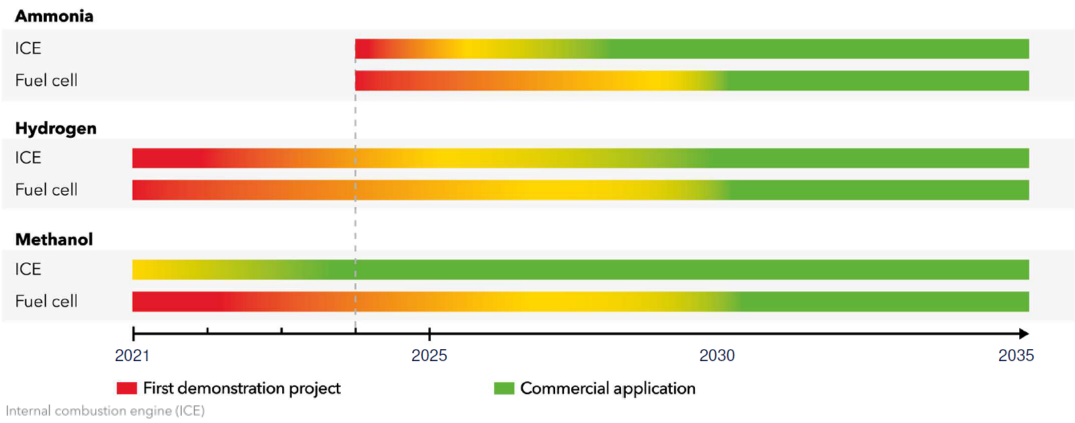

Figure 19-Timeline for expected availability of alternative fuel technologies (Source: Maritime Forecast to 2050-DNV)

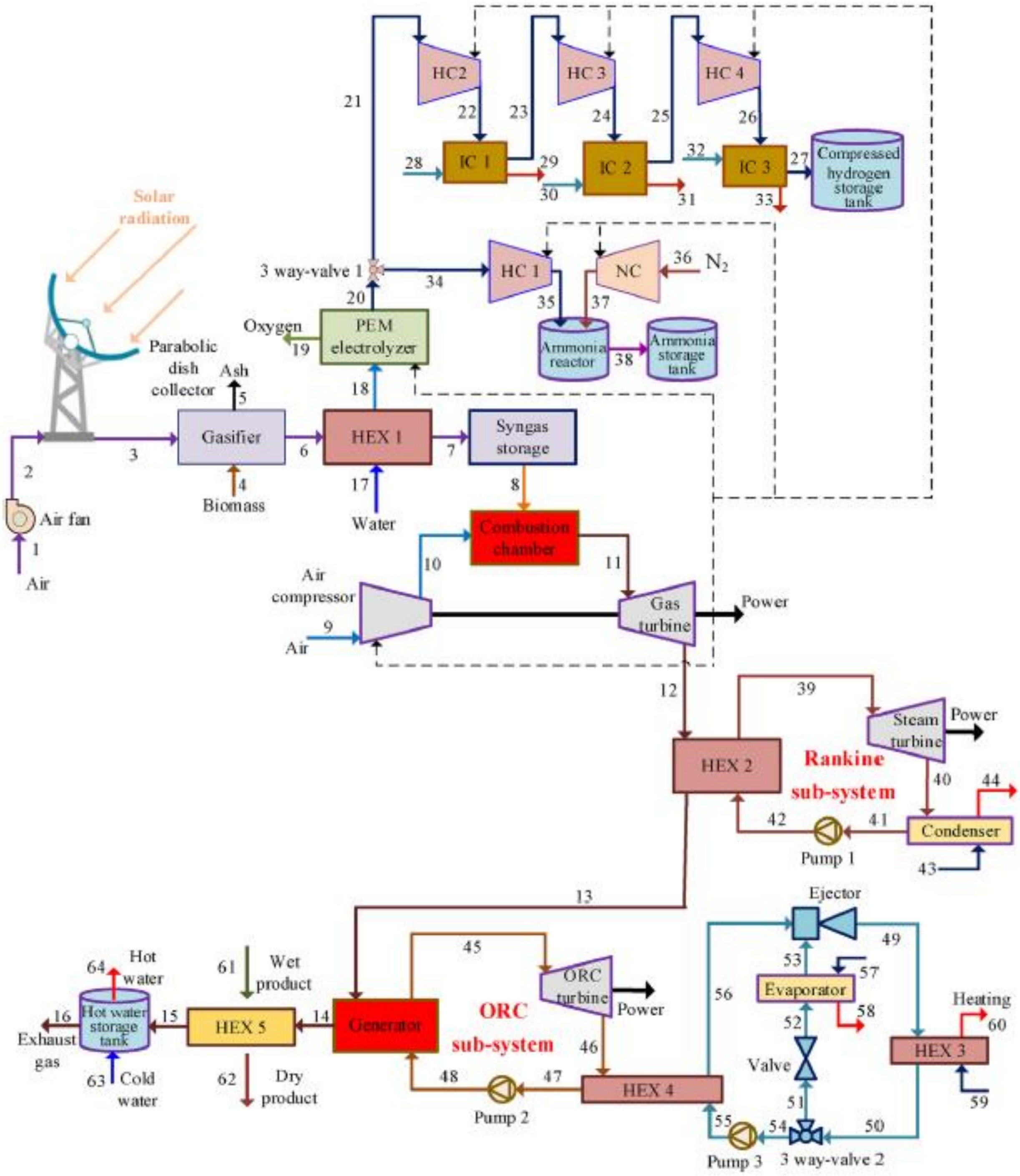

Figure 20-The outline of the solar and biomass energy (Ishaq & Dincer, 2021; Tukenmez, Koc, & Ozturk, 2021)

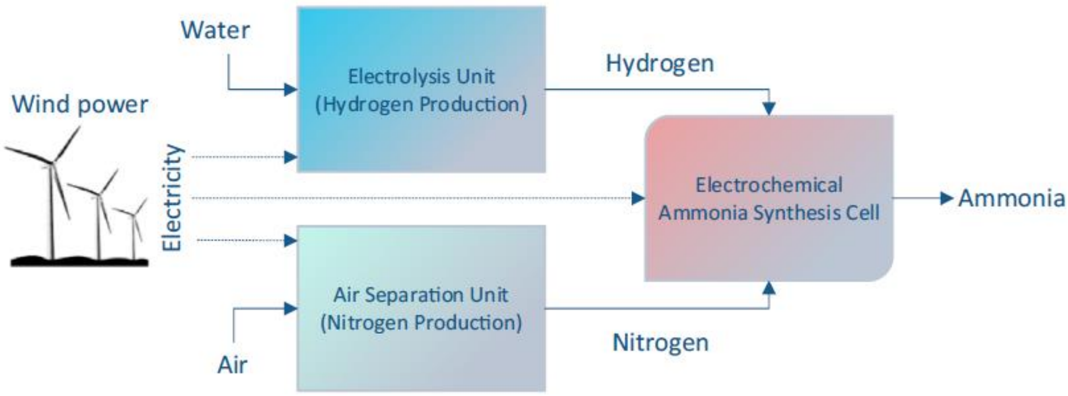

Figure 21-Schematic diagram of the wind-powered electrochemical ammonia synthesis(Bicer, Khalid, Mohamed, Al-Breiki, & Ali, 2020))

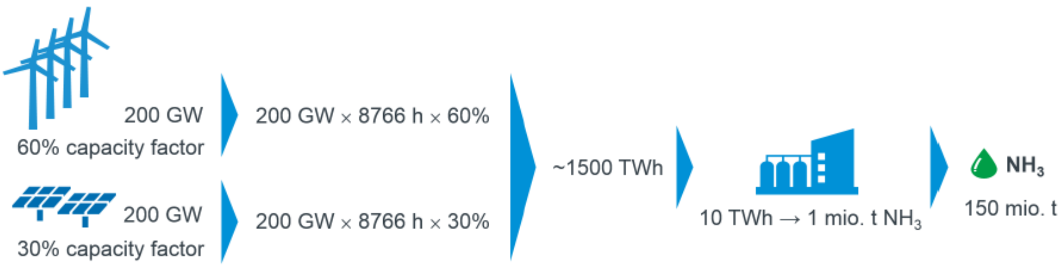

Figure 22-200 GW of wind and 200 GW of photovoltaics (Source: Ammonfuel – an industrial view of ammonia as a marine fuel-2021)

The following options are available for ammonia compatibility and technology. First, ammonia can be compatible with improved engines. We see that European engine plants are currently making efforts in this regard. As shown in Figure 23 below, MAN is developing ammonia-fueled low-speed engines to design and develop large-scale marine two-stroke engines. Ammonia engines and associated fuel supply systems are planned to be launched by 2024. Wärtsilä launches an ammonia fuel test and ammonia storage and supply system in 2020(Kim, Roh, Kim, & Chun, 2020). Second, in terms of ship type research and development, DSIC launched the ammonia-fueled 23,000TEI container ship design in 2019, and Jiangnan Shipbuilding launched the ammonia-fueled 40,000-m3 medium-sized liquefaction ship design in 2021. Nippon Yusen (NYK) and Japan Shipbuilding Union (JMU) have launched the research and development of ammonia-fueled ships. Samsung Heavy Industries also found the research and development of ammonia-fueled Suezmax tankers. Third, although ammonia has not yet been used as a marine fuel, the port already has relevant experience handling ammonia cargoes, has loading and unloading facilities, and has developed safety procedures for handling this substance, etc. (Schönborn, 2020). As far as the two most competitive zero-carbon fuels are concerned, ammonia is in many ways due to hydrogen. However, due to its toxicity, low burning velocity and high fuel NOx emissions, and lack of corresponding legal regulations as a marine fuel, etc. It still needs to be solved and perfected. The related research on adding hydrogen to ammonia and other guiding fuels also considers the possibility of solving the problem(Chai, Bao, Jin, Tang, & Zhou, 2021).

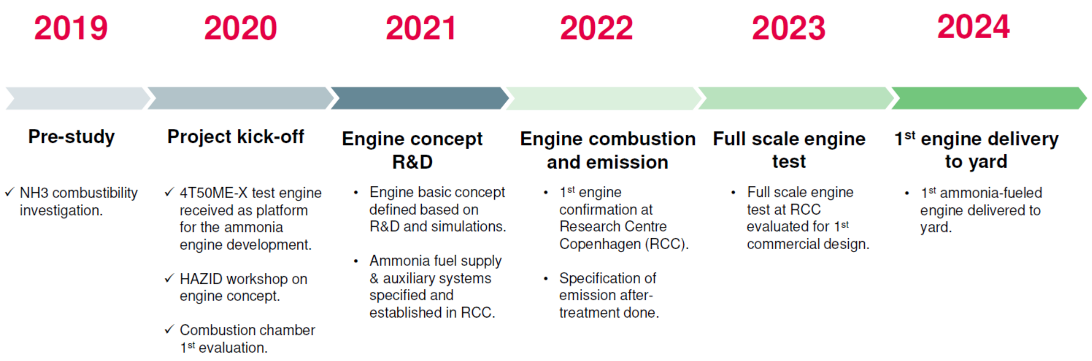

Figure 23-Two-stroke ammonia engine development schedule (Source: MAN Engines for alternative fuels-2021)

3.4.3 Prospects of Marine Batteries and Fuel Cells

Marine propulsion powered by batteries can be divided into diesel-electric propulsion, hybrid propulsion, or total battery power propulsion. All-battery-electric propulsion is only technically feasible for short-haul shipping or small ships with little power demand. This limitation will not disappear for a long time. Hybrid or battery-electric assisted power usage seems more likely for ocean-going shipping, given that the weight of batteries that provide the energy needed for ocean-going voyages could sink a ship if measured using current and anticipated battery technology. However, the cost of batteries is a major obstacle to electric propulsion ships. With current technology, the cost of batteries alone may exceed the sum of the costs of other parts for an ocean-going pure battery ship. In addition to the battery itself, large-scale batteries on board also require battery control hardware and software, such as system integration, thermal management, and corresponding electronics. The sum of these costs may also exceed the price of the battery itself.

As for fuel cells, the fuel cells are usually powered by hydrogen (but also others such as natural gas, methanol, and ammonia). Compared with 50% of traditional diesel engines, fuel cells' energy efficiency can reach almost 100%(Herdzik, 2021). However, the disadvantages of fuel cells are also prominent. Using battery fuel requires adequate training and safety precautions; fuel cells' combined size, weight, related support systems, and fuel reserves are larger than engines(Cheliotis et al., 2021). And its service life is shorter than that of diesel engines, especially in harsh marine environments, the expected service life may be more straightforward(Ammar, 2019). Some technical issues may change with the development of fuel cell technology in the future, but the cost involved is still an issue(Mukelabai, Gillard, & Patchigolla, 2021). Cost is the main obstacle to the promotion of fuel cells, and the stability and scale of fuel cells in harsh environments are also challenged(Zhijian Wan, Tao, Shao, Zhang, & You, 2021).

3.5 Market-based measures to decarbonize

The traditional economic theory believes that human economic activities will bring external economics and external diseconomies (External Diseconomies); typical external diseconomies include environmental pollution and climate warming (Lagouvardou et al., 2020). To explain and reduce the adverse effects of external diseconomies, many scholars try to make breakthroughs from the perspective of property rights, the most famous of which are Harding's "Tragedy of the Commons" theory and Coase's theory of property rights economics. The tragedy of the Commons thought that the unrestricted use of public environmental resources would prompt people to turn public resources into the wealth of private individuals or groups based on economic considerations so that the long-term interests of all members would be damaged or even destroyed. For example: when the atmospheric environment is open to all enterprises that emit air pollutants, from the standpoint of individual or group interests, each enterprise strives to maximize its immediate interests and increase its production as much as possible. The amount is the amount of sewage and all the income it brings. However, from a public standpoint, every increase in emissions will damage the environment, and all the general living shares this damage in the atmospheric environment. That is to say, and companies gain personal benefits by increasing their emissions while leaving the external diseconomies brought about by their more significant emissions to the public. As a result, there are more and more pollutants in the atmospheric environment. The pollution and degradation of the atmospheric environment are becoming more serious, eventually worsening its quality, making it impossible for people to live and produce. All residents have to leave the area. Withdrawing or investing funds to deal with air pollution has led to the "tragedy of public environmental pollution."

Coase's theory of property rights economics points out that the ambiguity of ownership and property rights is a source of market failure, and the "tragedy of the commons" is a good example. The externality of resource allocation is caused by the asymmetry of rights and obligations of resource subjects, and the unclear definition of property rights causes market failure. As long as ownership is clearly defined, transactions or economic activities between market entities or actors can effectively solve the problem of external diseconomy. That is, external costs can be internalized through the precise definition of property rights. Strictly defining private property rights not only does not exclude cooperation but is conducive to cooperation and organization. Through internalizing external costs, the main body of property rights will be based on economic considerations, reducing the charges that have been internalized by utilizing market-oriented transactions and improved technology to play a positive role in protecting the environment and reducing pollution emissions. Under the guidance of Coase theory, the emission trading system implemented in the United States to control acid rain has achieved good results. The accumulated experience has directly promoted the theoretical accumulation and institutional practice of carbon emission trading(Psaraftis et al., 2021).

Since the "Kyoto Protocol" formally established the carbon emission trading system in 1997, there have been mainly two legislative models of carbon emission trading in the world: one is a comprehensive legislative model represented by the European

Union, and the other is the United States. Representative of the discrete legislative model. Based on the fragile natural environment, import-dominated energy structure, and seizing opportunities for low-carbon economic development, Europe has become the first economy in the world to start carbon neutrality and the most active in promoting carbon emission reduction. It has a global top-level design. A sound carbon-neutral planning system, a proper legal carbon tax, and other institutional systems are planned to achieve carbon neutrality goals by 2050. Compared with the European Union, as the world's second-largest emitter of greenhouse gases, the United States' carbon emission reduction system highlights the constraints imposed by the Energy Act on energy structure, energy utilization technology, and efficiency. Still, it lags significantly in the setting of emission reduction targets. There are also apparent differences in the application of emission reduction means(Psaraftis, 2021).

The following model explains the difference between technical and operational emission reduction and market-based means in the allocation of ship emission reduction resources. Assuming that there are two ships, Ship1 and Ship2, in the market, the functions of the relationship between the emission reduction and the average emission reduction cost are MCC_1 and MCC_2, respectively, and the emission reduction function of the entire market is C(total)=MCC_1+MCC_2. With the increase in emission reduction, the cost of emission reduction per unit amount of CO_2 increases, and both MCC_1 and MCC_2 are monotonically increasing functions. Assume that the relationship between the average emission reduction cost and emission reduction function of Ship1 and Ship2 is shown in Figure 24 below. In the figure, the emission reduction efficiency of Ship2 is lower than that of Ship1, and the emission reduction cost of Ship1 is lower under the same emission reduction. When adopting technical/operational means to control carbon emissions, two ships, Ship1 and Ship2, are required to meet the same emission reduction standard T, and the cost paid by Ship1 is P1, and the price paid by Ship2 is P2. At this time, the Pareto optimality is not reached. That is, Ship2 is willing to pay to make Ship1 reduce emissions more, and the market loses some economic efficiency.

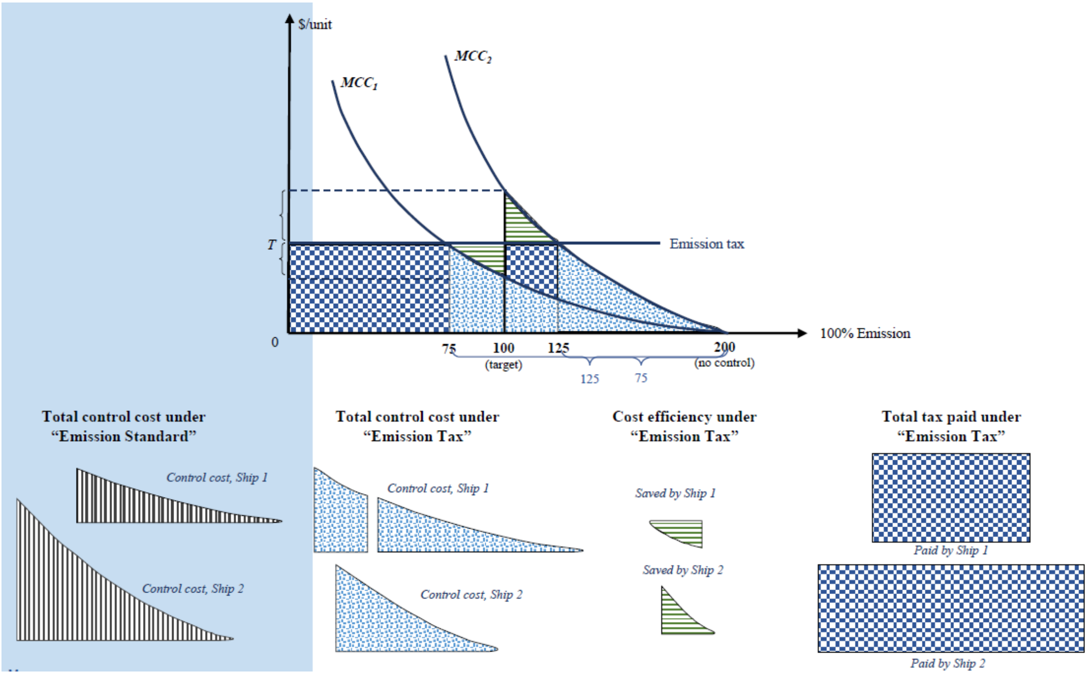

Figure 24-Emission tax scheme(Source: Economics of Maritime Business -Suo Ma-2022)

After adopting the market-oriented measures ETS, the government set a total emission reduction Cap. As shown in Figure 25 below, the total amount of emission reduction required by the market is Q Total=Q Ship1+Q Ship2, and carbon emission trading can be conducted between Ship1 and Ship2. Finally, the market reaches the equilibrium price Market price. At this time, the emission reduction of Ship1 is Q'Ship1, Ship2 emission reduction is Q'Ship2, QTotal= Q Ship1+Q Ship2= Q'Ship1+Q'Ship2.

Although ETS is not a means of direct emission reduction, it can allow emission reduction resources to be allocated more economically among units. The carbon tax also has the same function. The carbon tax price is set to P. If the emission reduction cost of the enterprise is greater than P, the enterprise chooses to pay the carbon tax and does not implement emission reduction. Otherwise, the emission reduction cost is less than P, the enterprise decides to reduce emissions, not pay the carbon tax, and finally reach market equilibrium. The difference is that carbon tax is price control, and ETS is a total emission reduction control. Adopting a carbon tax method requires collecting more information on carbon emission prices. This mechanism provides an option for older ships with higher abatement costs navigating the ETS region (Y. Xing, Yang, Ma, & Zhang, 2019). However, as shown in Figure 26 below, as the price of carbon increases, there will also be incentives for ships that are actively adopting new technologies to decarbonize (Dirzka & Acciaro, 2021; T.-C. Lee, Chang, & Lee, 2013).

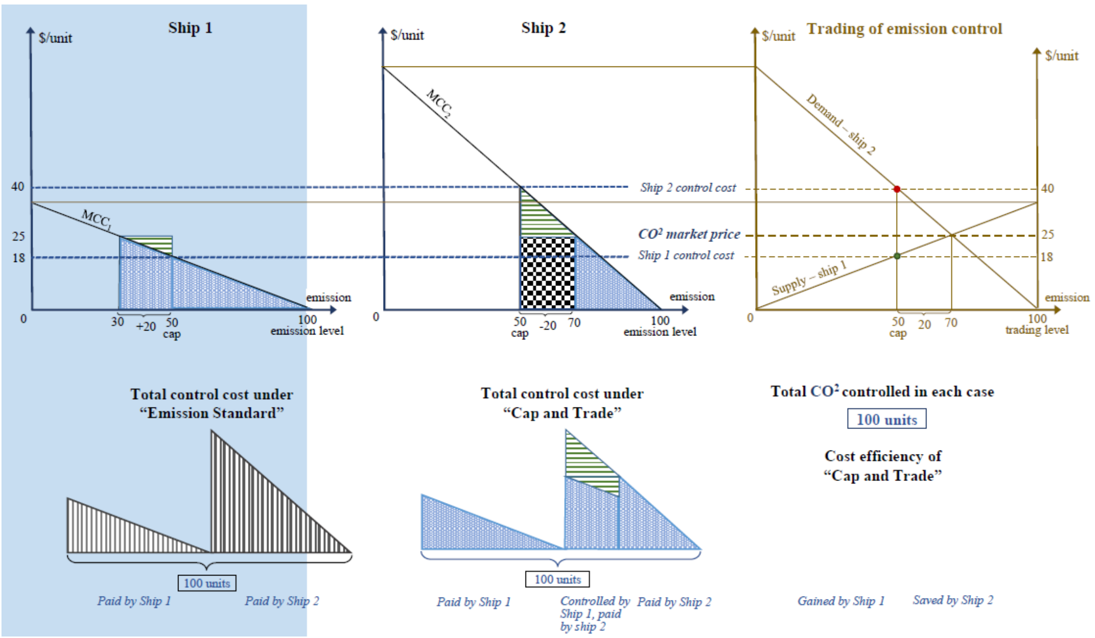

Figure 25-Cap and trade scheme(Source: Economics of Maritime Business -Suo Ma-2022)

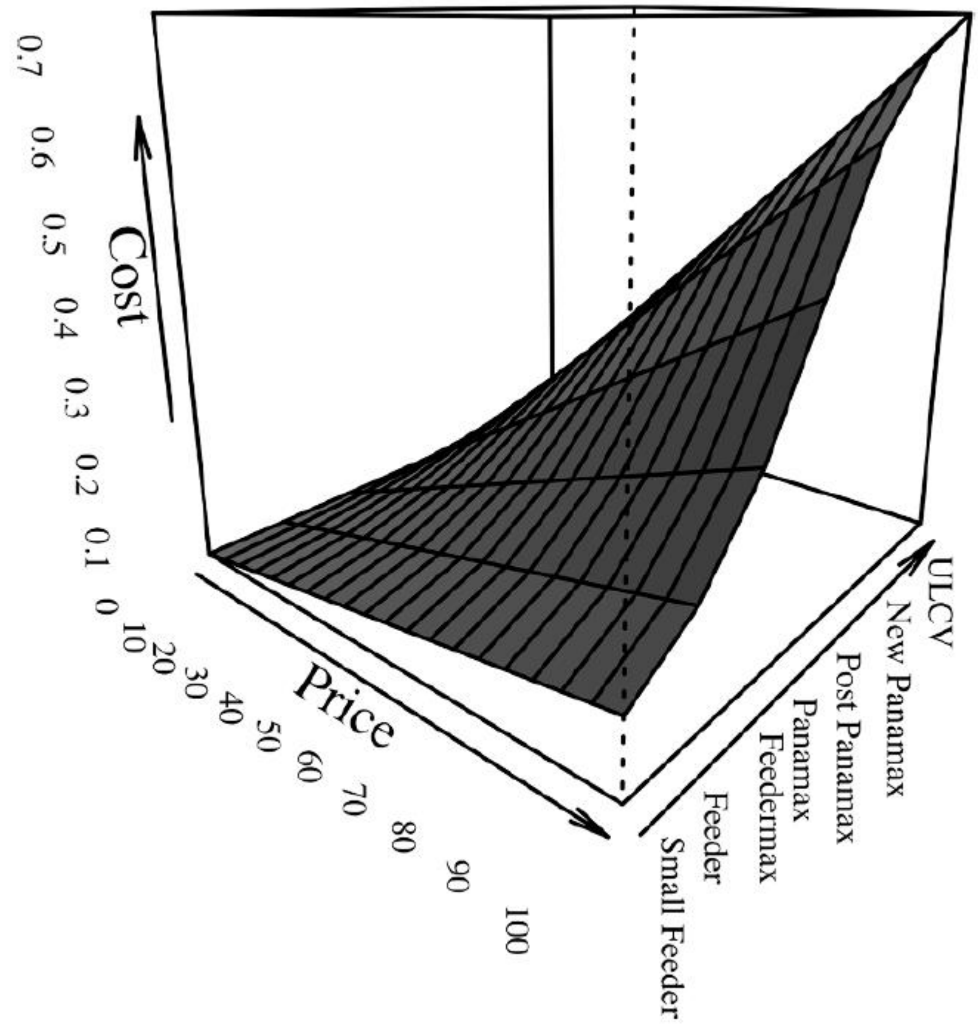

Figure 26-The dynamic relationship between the carbon price and cost with different container ship sizes.(Dirzka & Acciaro, 2021))

CHAPTER 4 - INTRODUCTION OF SAMPLE CONTAINER COMPANY

4.1 Company Profile

The sample container company selected in this article is OOCL. All data cited in this article are obtained from its official website and public channels such as the Hong Kong Stock Exchange. This company has been chosen because I am a captain of this company and hope to contribute to the company's decarbonization process. Second, it has a specific representation because OOCL is a leading liner company with a complete fleet and rich routes.

OOCL is a wholly-owned subsidiary of Orient Overseas (International) Limited, a company listed on the Hong Kong Stock Exchange. It is one of the world's most extensive integrated international container transportation, logistics, and terminal companies with routes throughout Asia, Europe and North America, the Mediterranean, the Indian subcontinent, the Middle East, and Australia/New Zealand. Before being acquired by COSCO Shipping in 2018, it ranked eighth in the global container capacity ranking. As shown in Figure 27 below, when OOCL HONGKONG was launched in 2017, it was the largest container ship in the world at that time.

Figure 27-Container ship OOCL HONG KONG (Source: OOCL official website-2021)

According to its 2021 Annual Report and Sustainability Report, OOCL believes that in addition to adopting clean technology in operations, the best way to reduce emissions in the shipping industry is to save fuel. This company has been focusing on bunker-saving programs and helping customers achieve a lower carbon footprint in their supply chains for many years. By taking these initiatives, As shown in Figure 28 below, OOCL has cut carbon dioxide emissions by nearly 55% since 2004.

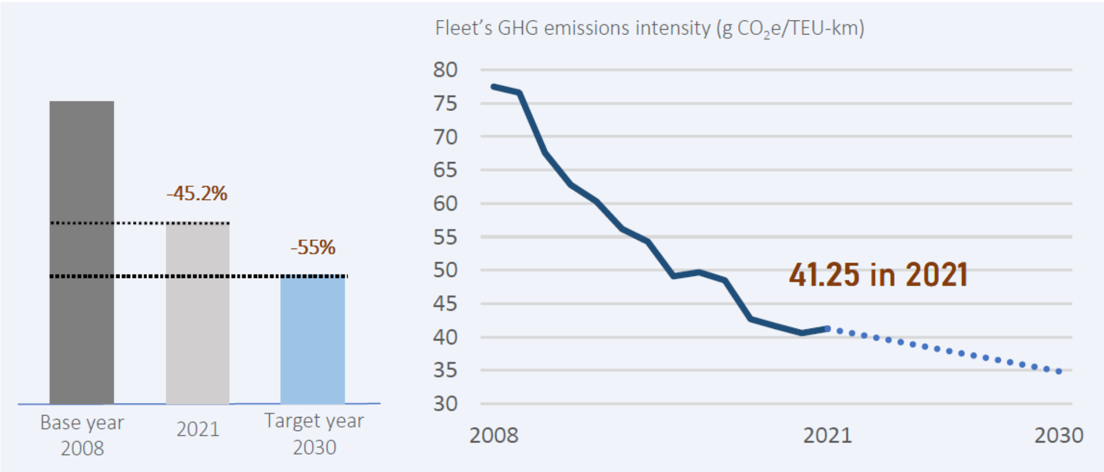

Figure 28-Direct GHG emissions intensity & Marine fuel consumption intensity reduction(2008-2021).（Source: OOIL Sustainability Report 2021）

4.2 Fleet composition

The ships in this analysis are only their own and operated vessels, as owners of such fleet have full autonomy to implement various decarbonization measures. As shown in Figures 4, 5, and 6 below, its fleet composition has the following characteristics:

1. In terms of TEU capacity, trans-oceanic vessels with more than 5,000 TEUs account for 83% of the total, and ships on the Asia-Europe route with over 10,000 TEUs account for 47% of the total capacity.

2. The shipping capacity of its ships within ten years accounted for 57%, mainly concentrated on vessels with more than 10,000 containers. More than 20 years of transportation capacity accounted for 7%, mainly for feeder ships.
3. The capacity built after the EEDI rules came into effect accounted for 57%, and the capacity built before 2013 accounted for 43%.

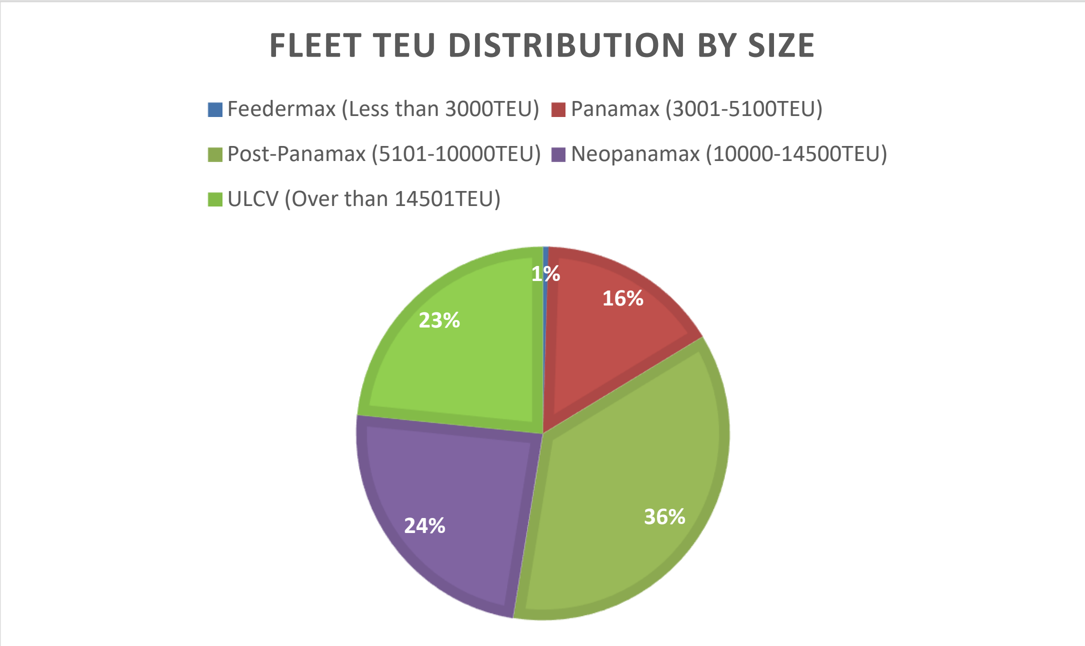

Figure 29-OOCL Fleet TEU distribution by size (Source: made by the author based on relevant data,2022)

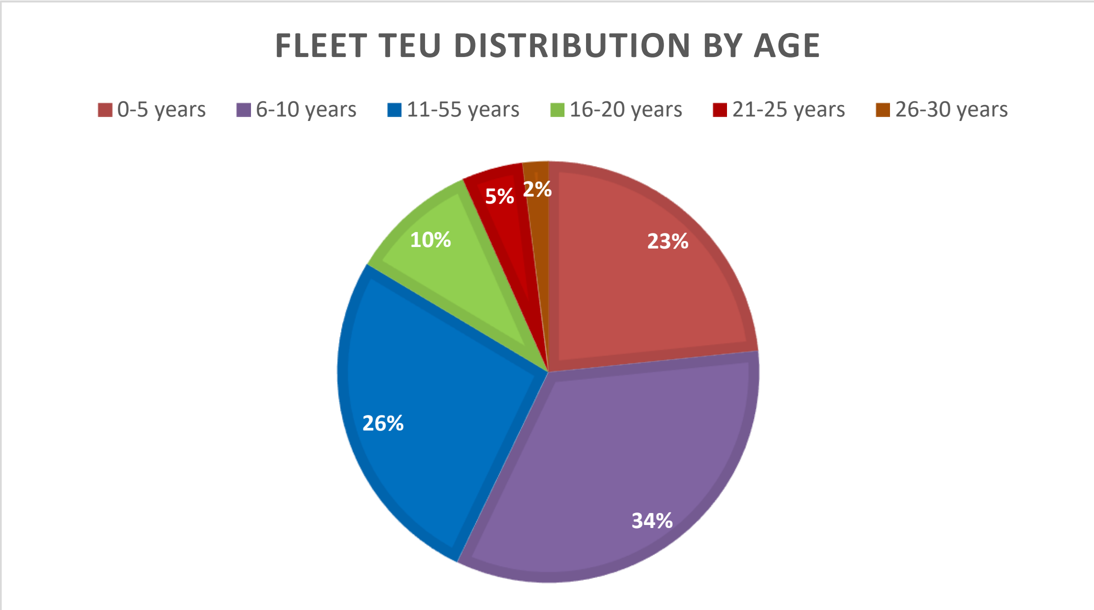

Figure 30-OOCL Fleet TEU distribution by age (Source: made by the author based on relevant data,2022)

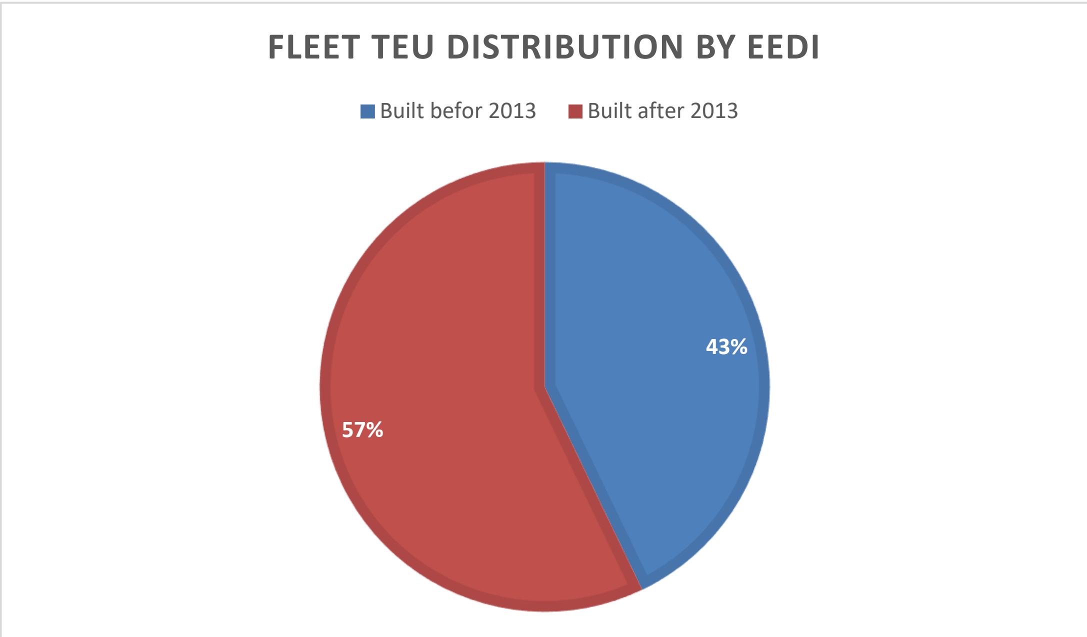

Figure 31-OOCL Fleet TEU distribution by EEDI (Source: made by the author based on relevant data,2022)

On 30 October 2020, Orient Overseas (International) Limited (OOIL), the parent company of OOCL, entered into shipbuilding contracts with Dalian COSCO KHI Ship Engineering Co., Ltd. (DACKS) and Nantong COSCO KHI Ship Engineering Co., Ltd. (NACKS) ordered 12 23,000 TEU container vessels, the contracts are valued at HK$ 8.6 billion. The ships are expected to be delivered between the third quarter of 2023 and the third quarter of 2024. On 2 September 2021, OOCL ordered another ten 16000TEU environmentally friendly containerships with a total price of US$1.58 billion. The new vessel order, also built by the shipyards affiliated with COSCO Group, is expected to be delivered between the fourth quarter of 2024 and the fourth quarter of 2025. OOIL revealed that new container ships would be equipped with energy-saving and emission reduction technologies, which will generate cost advantages and help environmental protection. However, OOCL did not mention whether the new buildings were dual-fuel or other fuel-reserved ships. But according to media reports, the new building mainframe LNG-Ready type。 In addition, OOCL claims that upon delivery of the new vessels, it plans to return or dispose of 13 vessels in its fleet that have completed long-term service, totaling approximately 76,000 TEU. It is foreseeable that after all 22 ULCVs are delivered and all 13 old ships are disposed of, more than 70% of its vessels with a capacity of more than 10,000 TEUs will be accounted for, and the age of these ships will not exceed 12 years.

In terms of operating costs, as can be seen in Figure 32 below, although fuel costs have risen from an average of US$378 per ton in 2020 to an average of US$495 per ton in 2021, increasing the overall annual fuel cost by 38%, the proportion of fuel costs in the overall operating expenses has not changed. They indicated that the epidemic increased by about 38% of other operating expenses.

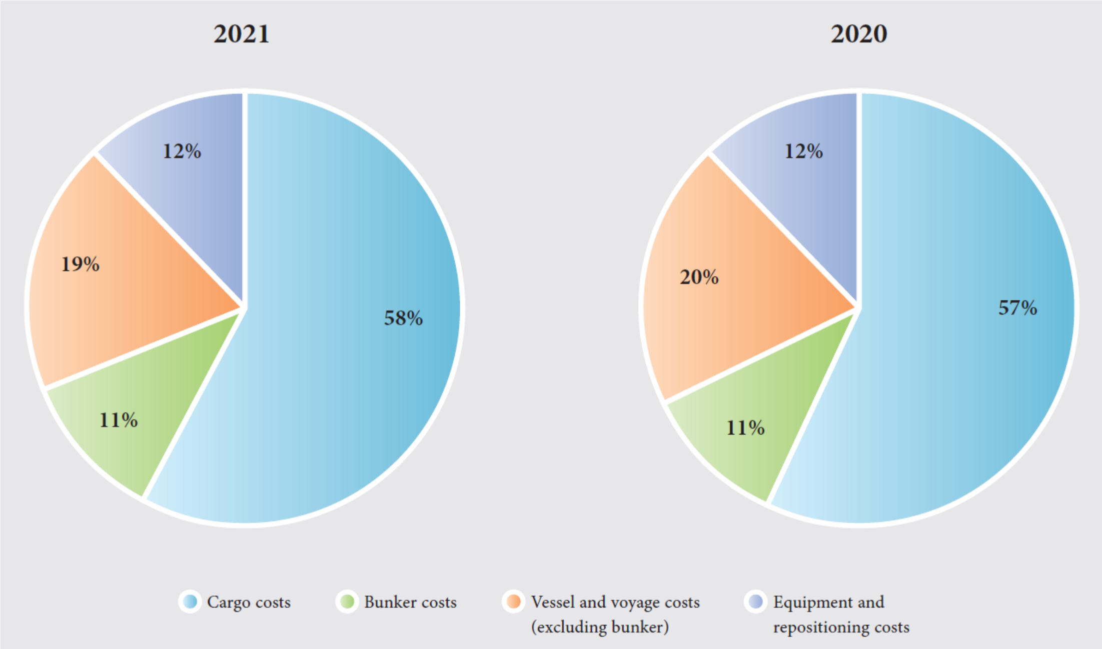

Figure 32-OOCL Fleet operating costs (Source: OOCL Annual Report 2021)

4.3 Existing decarbonization measures and targets

Figure 33 below lists the various decarbonization measures the OOCL fleet took in its sustainability report. Most measures are mainly to optimize energy efficiency management and minimize fuel consumption. The use of new decarbonization technologies is concentrated primarily on new buildings. OOCL has always been strictly following and abiding by the IMO goals. Still, at the same time, it urges regulatory bodies to lay out decarbonization roadmaps and support the maritime shipping industry in the journey to net-zero carbon emissions by 2050. It shows that OOCL is also ready to achieve zero footprints by the middle of this century.

Measure	Mitigation	Adaptation
Invest in weather-routing systems for safer and shorter routes.		✓
Enhance Global Vessel Voyage Monitoring Centre (GVVMC) and Robo-advisor Solution to optimise berth visibility and minimise bunker consumption.	✓	✓
Order and launch containership newbuilds with energy-efficiency higher than the current requirements.	✓	
Conduct equipment retrofit in existing owned vessels.	✓	
Regular vessel maintenance and cleaning.	✓	✓
Engage with employees from diverse expertise, customers, industry peers and other stakeholders regarding decarbonisation roadmap and strategies, including the development of cleaner alternative fuel.	✓	
Strive for transparency of sustainability and climate disclosure.	✓	
Ensure the maturity of remote 'in-office' operations to prepare for disrupted office operations by extreme weather events.		✓

Figure 33-The details of the mitigation and adaptation measures taken by OOCL (Source: OOIL Sustainability Report 2021)

CHAPTER 5 - DECARBONIZATION PATH CHOSEN BY OTHER CONTAINER COMPANIES

With the increasing voice of international decarbonization, the IMO and regional decarbonization requirements are becoming more and more stringent. As the liner company with the highest proportion of carbon emissions in the shipping industry, the leading companies have dealt with stricter regulations and meet the low-carbon supply chain preferences of shippers and the expectations of the capital market.

However, because many decarbonization options are mentioned above, and different options are different in terms of economy, technology, and emission reduction effects, major shipping companies weigh the pros and cons and combine their development strategies. It varies, which also shows from the side that there is no clear answer on how to reduce the carbon footprint of shipping.

Because short-term energy efficiency management measures have matured, and long-term net-zero carbon fuels remain to be seen, the different choices of major container companies now mainly focus on which alternative fuels to use to achieve medium-term decarbonization goals. This point can be roughly divided into LNG, methanol, and other camps.

According to Clarksons Research data, 32.7% of the tonnage of new building orders in 2021 was powered by alternative fuels (449), compared to 209 in 2020 and 46 in 2016. It is not difficult to see that the application of alternative fuels has been on the rise in recent years, as shown in Figure 34 below. Although the results are different due to different data collection time points and paths, it also reveals the growing trend of alternative fuels.

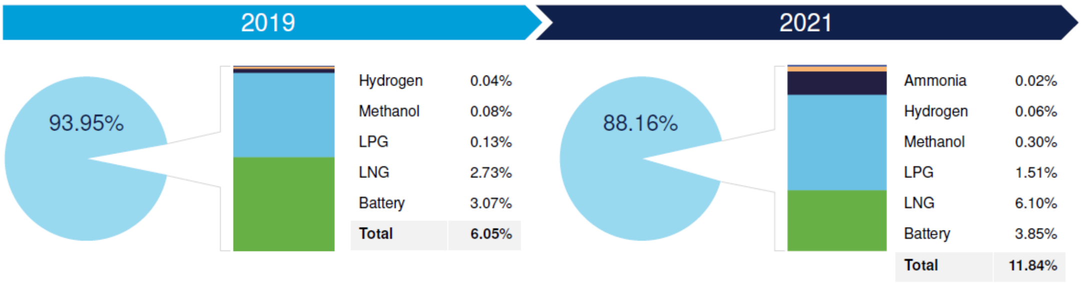

Figure 34-Uptake of alternative fuels for the world fleet as of June 2021(Source: Maritime Forecast to 2050-DNV)

In new orders, shipowners tend to choose designs that can use multiple alternative fuels or reserve alternative fuels (10% of orders in the first quarter reserved LNG power for ammonia fuel) to have more options in the future uncertainty.

Judging from the orders in hand until the middle of 2022, the proportion of ships using alternative fuels reached 37.8%, and the growth rate exceeded the total of the previous four years. Among them, 33.3% of the orders will use LNG fuel (647 ships), 2.3% of the orders will be Using LPG fuel (88 vessels), 3.2% of the orders will use other alternative fuels (about 200 vessels), including methanol (24 vessels), ethane (11 vessels), biofuels (5 vessels), hydrogen (6 vessels) and Battery/hybrid propulsion (about 150 ships). At the same time, there are more than 270 ships in the existing fleet, 94 ships in the order can be converted to LNG power in the future, another 74 ships can be converted to ammonia power, and 9 ships can be converted to hydrogen power.

5.1 LNG

As the first container shipping giant to invest in LNG power, CMA CGM currently has 29 LNG-powered container ships in operation, and this number will increase to 77 by

2026. In 2017, CMA CGM Group first announced the order for nine LNG-fueled 22,000 TEU ultra-large container ships, the first order of this size in the history of the shipping industry. CMA CGM once said that LNG is currently the most advanced solution in terms of protecting air quality. Compared with traditional fuels, it can reduce sulfur dioxide by 99%, particulate matter by 91%, and nitrogen oxide by 92%, far exceeding the requirements of current regulations. LNG-powered ships can reduce CO_2 emissions by up to 20%. CMA CGM has always been the world's largest shipping company investing in LNG fuel. CMA CGM 2020 announced plans to achieve net-zero emissions by 2050. The company's low-carbon solutions mainly use cleaner alternative energy LNG and biofuels, as well as carbon trading.

Rudolf Sade, Chairman and CEO of CMA CGM Group said: "With the launch of the first low-carbon shipping service powered by biomethane, we have taken a new step. We are well aware that achieving the Paris Agreement Commitments goals still has a long way to go. Achieving these goals cannot rely on a single solution but requires a series of complementary initiatives and new technologies." After that, CMA CGM Group will achieve a further 4% emission reduction in 2020. Currently, the group's CO_2 emissions per unit of container transport volume have been reduced by 49% compared to 2008.

On June 3, 2022, CMA CGM revealed in its latest 2022 first-quarter performance report that the company ordered 16 container ships in the first quarter of this year, including four 23000TEU and six 7900TEU total. The 10 LNG dual-fuel vessels increased the size of the order book to 69, with a total of 657,400 TEU, equivalent to 20% of the current fleet capacity. Among them, 48 new ships under construction are LNG dual-fuel.

The choice of low-carbon fuels for MSC is unclear. The company took the lead in using bio-blended fuels as ship power in 2019. The current fleet uses up to 47% bio-blended fuels on a large scale while researching technologies such as hydrogen-derived fuels, methanol fuels, and bio-liquefied natural gas. MSC said in 2020 that it would not invest in any new LNG-powered ships, saying it was "not a viable option." However, the company leased 11 LNG-powered newbuildings in May this year, claiming that the colossal fleet requires more diversified green solutions and will continue to explore a range of fuel solutions to achieve a zero-carbon future.

5.2 Methanol

As early as 2018, container shipping giant Maersk announced a goal of achieving net-zero emissions by 2050, and this goal has been advanced to 2040. Following an announcement in early 2021 that methanol was selected as one of the four future marine fuels, shipping giant Maersk announced in May that it had joined the global methanol industry association (The Methanol Institute) and officially finalized the first methanol dual-fuel container ship order in July, The 2100TEU dual-fuel feeder container ship will be built by Hyundai Mipo Shipbuilding in South Korea and is expected to be delivered in 2023. After completion, it will become the world's first methanol-powered ship not used for methanol cargo transportation. Subsequently, Maersk signed an agreement with South Korea's Hyundai Heavy Industries in August to order 8+4 16,000TEU large carbon-neutral methanol dual-fuel container ships, the first of which will be put into operation in the first quarter of 2024. These ships can run on carbon-neutral methanol or conventional ultra-low sulfur oil. The emergence of the order for these nine container ships has broken the traditional form of methanol fuel application in the shipping industry.

Maersk said it was a clear target for future new ships to run entirely on green methanol and that using hybrid technology is a risk mitigation strategy for now, as the life cycle of ships is 20 to 25 years. It is not yet known which fuel technology will ultimately win. Maersk has made it clear that it will not choose LNG power as a transition fuel and has decided to stop buying ships without zero-carbon emissions capabilities. The company believes that LNG fuel is not a long-term solution to reducing emissions. In addition, Maersk has dabbled in hydrogen and ammonia investments, seeing green ammonia as a promising marine fuel option, saying a dual-fuel engine for ammonia is under development.

In addition to building methanol-powered ships, Maersk is also actively purchasing green methanol and making related investments. The company has invested in WasteFuel Marine, the latest renewable fuel solution for the shipping industry, from US-based low-carbon fuel developer WasteFuel, whose initial product will be biomethanol for container ships. Waste Fuel uses proven technologies to convert waste into renewable fuels, including sustainable aviation fuel, green bioethanol, and renewable natural gas. In addition, Maersk has partnered with Thailand's PTT Exploration & Production Public Co, France's Air Liquide, Singapore's YTL PowerSeraya, Oiltanking Asia Pacific, and Kenoil Marine Services to sign the Green Methanol Value Chain Partnership jointly. Value Chain Collaboration to explore the feasibility of establishing a green electricity-to-methanol pilot plant with an annual production capacity of more than 50,000 tons, which will be the first green electricity-to-methanol plant in Asia, and methanol fueling is expected soon be achieved in

Singapore. The plant converts captured biogenic carbon dioxide into green electricity to methanol.

It is worth mentioning that in November 2021, Farid Trad, vice president of fuel and energy transition at CMA CGM, publicly stated that methanol fuel has "some flaws." These include volume loss due to lower energy efficiency, the absence of a large-scale distribution network at present, and toxicity. And half a year later, CMA CGM decided to order the first batch of methanol-powered ships. CMA CGM said in its first-quarter report that the first methanol-powered vessel order is in line with the company's strategy to expand its energy mix to achieve net-zero emissions by 2050; CMA CGM is investing in LNG and methanol fuels through large-scale investments. To accelerate the decarbonization trajectory, the two sectors will complement each other and drive the decarbonization of the shipping industry in the coming years.

Methanol fuel has been hotly debated. Methanol fuel produces 15% less carbon dioxide during combustion than conventional fuels. While not as good as LNG in this number (LNG is 25% less than traditional fuels), methanol is easier to handle than LNG. In addition to Maersk and CMA CGM, Japan Ocean Network (ONE) is also considering using methanol fuel. In May 2022, ONE announced the order to build 10 13,700TEU Neo-Panamax container ships. These new ships are designed with ammonia or methanol fuel reserves.

5.3 Other option

While CMA CGM has placed the bulk of its decarbonization efforts on LNG, it has also continued experimenting with alternative fuels. CMA CGM has said that investment in biofuels and biomethane fuels is also significant in addition to LNG. CMA CGM is the first shipping group to use biofuels on container ships successfully. Using biofuels made from waste cooking oil can reduce greenhouse gas emissions by 15% to 85%, thus providing customers with better decarbonization of cargo—a comprehensive solution. In May 2021, the CMA CGM Group put into operation the ships fueled by biomethane, and the current annual output of biomethane fuel is 12,000 tons. In addition, the company is also beginning to explore the large-scale use of hydrogen as a fuel in the shipping industry.

China's largest container company, COSCO SHIPPING Holdings, has been reluctant to use LNG on its new ships due to concerns about a lack of LNG fueling infrastructure. But the company appears to have changed its mind for now, as it needs to coordinate with the deployment of ships from its Ocean Alliance partner CMA CGM and the Chinese government's mandate to decarbonize China's economy (Shipping emission inventories in China's Bohai Bay, Yangtze River Delta, and Pearl River Delta in 2018). Its 2021 annual report claims that the large container ships contracted and built in 2020 and 2021 can meet the IMO's limit standards for sulfur oxides (SOx) and nitrogen oxides (NOx) emissions and can also meet the 2030 "carbon emissions." emission reduction" medium-term target requirements.

CHAPTER 6 - ANALYZE THE BEST PATH FOR THE SAMPLE CONTAINER COMPANIES

This chapter will analyze and recommend short-, medium- and long-term decarbonization paths for sample container companies under the following conditions:

1, Aim to achieve net-zero emissions by 2050. Based on the pressure of the United Nations Climate Conference, the EU ETS system, and the major shipping companies to fully decarbonize by 2050 and the expectations of major shipping organizations, the possibility of IMO changing the target in 2023 is increasing. At the same time, sample container companies are also determined to achieve net-zero emissions by 2050.

2, Use a well-to-wake approach instead of tank-to-wake. Because Using a tank-to-wake system could misrepresent the total climate and health impacts of marine fuels. At ISWG-GHG 11, the working group reported on developing the draft Life Cycle Greenhouse Gas Assessment Guidelines (LCA Guidelines) that will allow the calculation of well-to-wake emission factors related to total GHG emissions, including well-to-tank and tank-to-wake emission factors for alternative marine fuel production and use. Coping with climate change requires a global effort, and it has gradually become a trend to calculate the carbon emissions of fuels in the whole life cycle.

3, EU-ETS will incorporate shipping in 2024 and entirely in 2026. On 22 June 2022, the Plenary Assembly of the European Parliament voted to adopt positions on three critical drafts of the draft package of climate legislation (Fit for 55) presented by the European Commission on 14 July last year, which decided to start from January 2024. The maritime industry will be included in the EU ETS from January 1, with no transition period. Until December 31, 2026, the EU ETS covers only 50% of the emissions of flights outside the EU. From January 1, 2027, 100% of emissions from all flight sectors within and outside the EU will be included. In addition, the draft also mentioned that if the IMO adopts global market measures, the European Commission will consider the possibility of coordination with it.

4, The short-term goal is to reduce absolute carbon dioxide emissions by 20% by 2026, the medium-term goal is to reduce carbon dioxide emissions by 60% by 2040, and the long-term goal is to achieve net-zero emissions by 2050. Emissions here are carbon emissions per freight ton.

5, The evaluation will mainly refer to the technology readiness level criteria. Carbon dioxide emission reduction potential, Likely adoption rate, Cost-effectiveness.

6.1 Recommended measures to achieve short-term goals

1. Eliminate ships with CII energy efficiency classes D and E from the fleet by 2026. From a regulatory point of view, 2026 is a time node. First, shipping will be fully incorporated into EU-ETS in 2026, as shown in Table 3 below. At that time, the emission reduction cost of high-energy-consuming ships will increase significantly(Cariou et al., 2019). The second is that the annual reduction rate of CII is only 2% before 2026, and there are no corresponding penalties. From an economic perspective, container ship owners have made huge profits in 2020 and 2021 due to the strain on the global supply chain caused by the COVID-19 pandemic (Notteboom, Pallis, & Rodrigue, 2021), and also ordered a large number of new ships, most of which will be delivered before 2025. According to Clarkson's forecast, as the epidemic improves and the supply chain returns to normal, plus a large number of new ships put into operation, the container shipping industry will be in 2024. There will be excess capacity around the year, and the freight rate will undoubtedly drop. It will be a wise

move to choose to eliminate high-energy-consuming ships at this time. After the high energy consumption ships are eliminated, 70% of the sample companies' fleet will be A and B class ships.

Table 2-Optimal behavior for selected vessels(Goicoechea & Abadie, 2021).

Results	Minimum	Panamax	Post-Panamax	New Panamax	ULSC	VLC
	2000	4500	8500	13,000	14,800	20,000
With 100% emission price						
Optimal Speed (knots)	15.9	17.4	18.0	17.9	17.8	17.4
Variable Margin ($)	5,435,876	16,617,004	32,760,526	50,167,756	56,324,548	67,571,408
Cost of Emissions ($)	810,712	1,315,773	2,438,432	3,645,283	4,006,049	4,446,637
Emissions (tonnes)	30,377	49,302	91,368	136,589	150,107	166,616
Variable Margin ($/TEUs)	2717.94	3692.67	3854.18	3859.06	3805.71	3378.57
Cost of Emissions ($/TEUs)	405.36	292.39	286.87	280.41	270.68	222.33
Emissions (tonnes/TEUs)	15.19	10.96	10.75	10.51	10.14	8.33
With 50% emission price						
Optimal Speed (knots)	16.1	18.0	18.7	18.7	18.5	17.8
Variable Margin ($)	5,847,938	17,306,443	34,056,482	52,120,091	58,459,748	69,874,931
Cost of Emissions ($)	416,965	732,825	1,377,294	2,096,556	2,266,558	2,383,289
Emissions (tonnes)	31,247	54,918	103,214	157,116	169,856	178,604
Variable Margin ($/TEUs)	2923.97	3845.88	4006.64	4009.24	3949.98	3493.75
Cost of Emissions ($/TEUs)	208.48	162.85	162.03	161.27	153.15	119.16
Emissions (tonnes/TEUs)	15.62	12.20	12.14	12.09	11.48	8.93
With 0% emission price						
Optimal Speed (knots)	16.4	18.8	19.6	19.6	19.3	18.3
Variable Margin ($)	6,276,801	18,091,454	35,552,756	54,375,926	60,901,254	72,368,127
Cost of Emissions ($)	0	0	0	0	0	0
Emissions (tonnes)	32,688	63,144	119,897	182,526	194,593	195,067
Variable Margin ($/TEUs)	3138.40	4020.32	4182.68	4182.76	4114.95	3618.41
Cost of Emissions ($/TEUs)	0.00	0.00	0.00	0.00	0.00	0.00
Emissions (tonnes/TEUs)	16.34	14.03	14.11	14.04	13.15	9.75

2. For transoceanic ships with low energy efficiency, reducing ports of call is adopted to reduce ship speed and carbon emissions. According to the research of (Yu et al., 2021), the profit will be maximized if the ships sailing across the ocean reduce the number of calls to a single port, while the sailing speed will be slowed down. A system consisting of ocean-going sets and short-term container liners can increase the 4.05% profit, reducing carbon emissions by 19.70%.

3. Continuously deepen energy efficiency management measures. The first is to strengthen the relevant training of shore-based and crew members, set assessment and incentive standards, and implement various energy-saving measures. The second is to

purchase more advanced fleet network adjustment algorithms to reduce fuel consumption by dynamically adjusting ports of call and refueling ports. The above measures can reduce carbon emissions by 10-20% if implemented through the assessment.

6.2 Achieving medium-term goals requires technology and alternative fuels to assist

1. From 2026, LNG-ready ships calling at EU ports will start to use LNG fuel. After the shipping industry is fully incorporated into ETS in 2026, the top three container companies, MSC, Maersk, and CMA CGM will already have a considerable number of dual-fuel ships, mainly LNG and methanol. These ships will undoubtedly be put into Asia-Europe or America-Europe routes to reduce the operating costs caused by MBM. OOCL can only compete with it if it takes corresponding measures. In addition, according to Clarkson's research data, fuel prices and guaranteed refueling infrastructure are very mature in terms of Technology readiness level, Likely adoption rate, and Cost-effectiveness after more than ten years of development. Through this measure, carbon emissions can be reduced by about 20%.

2. For the main engine without LNG-Ready installed, new decarbonization technology will be gradually installed from 2026 to dock for ship repair. These decarbonization technologies applicable to container ships are comprehensively ranked in terms of Technology readiness level, CO_2 emission reduction potential, Likely adoption rate, Cost-effectiveness, etc. Bulbous bow retrofit, Air lubrication, new high-efficiency hull coatings, Waste heat recovery. The combined use of these technologies will result in a carbon footprint reduction of approximately 15-25%. In addition, such ships can also

use drop-in biofuels, such as FAME and HVO, in 2030, reducing carbon emissions by about 50%.

3. Newbuildings after 2026 must be installed with alternative fuels engine

4. Start trying to use CCS technology after 2030. Although currently, onboard CCS faces many challenges associated with it. These include the capital and operational costs, space and energy requirements (increases in fuel consumption of up to 20% can be expected), and the effectiveness in capturing CO_2 (can potentially reach 100%, but this is untested; 80% is a more realistic expectation). However, as shown in Figure 35 below, according to the predictions of Willson et al., with the constant maturity of technology and the improvement of relevant laws and regulations, marine CCS will be a very competitive decarbonization option after 2030.

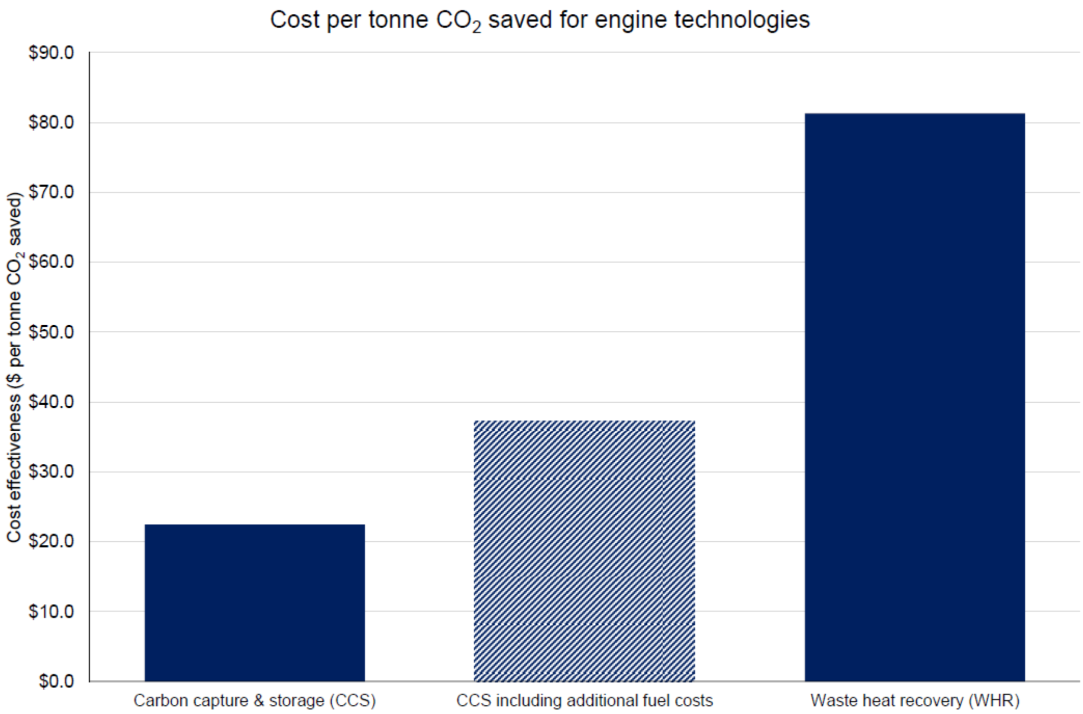

Figure 35-Cost-effectiveness ranking for engine technologies in 2030 (Willson et al., 2019)

6.3 Green zero-carbon fuels and CCS are key to achieving net-zero carbon emissions by 2050

1. Starting from 2040, all new ships must be able to use green zero-carbon fuel. From the current research(MacFarlane et al., 2020), according to Technology readiness level, Likely According to adoption rate and cost-effectiveness criteria, green methanol has a relatively high chance of standing out, followed by green ammonia, and finally green hydrogen.

2. To gradually install CCS on existing ships that have not been dismantled or sold before 2050 to eliminate the carbon footprint of all vessels in the fleet.

CHAPTER 7 - CONCLUSION

Although, until now, there are still voices questioning whether global warming will bring disaster to humankind, most of these voices are funded by fossil energy companies. But it is undeniable that more and more countries and more and more industries around the world are constantly taking action to curb climate change, aiming to achieve carbon neutrality by the middle of this century to avoid the catastrophic consequences of climate change across the globe.

As an essential pillar of global trade and the largest source of carbon emissions from the shipping industry, container shipping will play a key role in IMO's ambition to decarbonize shipping. At the same time, it is also the most deeply affected by the carbon footprint reduction by IMO and various regions. Moreover, To meet the expectations of shippers' supply chain decarbonization and green capital, the decarbonization process of container shipping is faster than that of other ship types, and almost all leading companies have announced their ambition to achieve net-zero carbon emissions by 2050.

As a well-known brand among liner companies, the sample container company OOCL analyzed in this paper also demonstrates its determination to achieve green shipping before 2050. But unlike industry giants such as CMA CGM and Maersk, which have aggressive decarbonization paths, OOCL has adopted a more robust and economic strategy. Among the many decarbonization options, this paper uses Technology readiness level, CO_2 emission reduction potential, and Cost-effectiveness as indicators to formulate an economical and practical short, medium, and long-term decarbonization plan according to its fleet composition.

The analysis results show that, according to the fleet structure of the sample companies, the existing EEXI and CII requirements can be met in the short term by eliminating old ships with high energy consumption and strengthening energy efficiency management. The medium-term goal needs to be achieved by using LNG and adding decarbonization technologies such as air lubrication. To fully meet the requirements of net zero emissions before 2050, we must rely on zero-carbon fuels such as green ammonia and marine CCS technology that has been perfected by then.

In addition, as time goes on, it is believed that there will be more new decarbonization technologies or fuels that are not discussed in this article. All shipping companies should keep an open mind and pay close attention to the progress of new technologies. Invest in new technologies or fuels to reduce decarbonization costs and lock supply.

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