8-30-2023

Onboard Carbon Capture and Storage (OCCS): Feasibility Analysis and Policy Measures

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ONBOARD CARBON CAPTURE AND STORAGE (OCCS)

FEASIBILITY ANALYSIS AND POLICY MEASURES

WEIXUAN WANG

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the award of the degree of Master of Science in Maritime Affairs

2023

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.

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Date: May 30th 2023

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Supervisor's affiliation: Dalian Maritime University

Acknowledgement

This thesis has been my interest since I was honored to participate in the MSEM program in 2022. I am very grateful to the professors at World Maritime University (WMU) and Dalian Maritime University (DMU) for inspiring me with rich knowledge and experience. In particular, the course of TEC (Impact of Maritime Innovation and Technology), ENG (Applied Marine Engineering), and MAP (Maritime Policy Design, Implementation, and Evaluation) have provided me with a deeper understanding of shipping emission reduction technologies, the details of ship exhaust treatment, and shipping policy design and evaluation, which have inspired me to explore the development of OCCS technology from the policy aspect. I would like to show my appreciation to them.

I would like to express my most sincere gratitude to Professor HUI XING, who has fully respected my research ideas, and led me to conduct deeper research and analysis with profound knowledge, rigorous academic attitude, expertise and patience.

I am also grateful to China MSA for offering me an opportunity to join the program and know more about international maritime affairs. Thanks to my superior leaders for releasing me from the daily working affairs so that I can further my study and finish the thesis writing.

I would like to thank my dear family members who have been giving me full support and encouragement, always sharing happiness with me, and taking care of my kitty.

Abstract

Title of Dissertation: **Onboard Carbon Capture and Storage (OCCS): Feasibility Analysis and Policy Measures**

Degree: **Master of Science**

This paper conducts research on the policy measures for onboard carbon capture and storage (OCCS) applications. A brief introduction has been taken to the decarbonization goals and the initiatives for the shipping industry, showing that OCCS has been studied as a possible transitional measure. After reviewing the focus of academic research on OCCS technology and the results of OCCS pilot projects around the world, it is recognized that the current development of OCCS technology development still suffers from low technology maturity and high construction and operating costs.

The Formal Safety Assessment (FSA) method is taken to evaluate the possible risks in the operation and management of OCCS technology. It is recognized that filling the legal or supervision gap, and standardizing management are the methods to deal with the main risks. Through economic analysis, it is believed that the application of OCCS technology may effectively reduce the cost of ship carbon emissions, and it may be commercialized in the industry. Therefore, it is necessary to formulate a legal framework for OCCS technology to regulate ship operations and ensure the legal disposal of captured products.

Policy reviews are carried out to analyze the status quo and possible developments of regulations in the OCCS field, and a proposed legal framework and revision opinions are raised.

The concluding chapter summarizes the necessity and development proposals on the OCCS legal aspect and calls for the follow-up revision and development of the legal framework to be matched with the maturity of OCCS technology.

KEYWORDS: Feasibility, Economic analysis, Policy measures, Formal Safety Assessment (FSA), Onboard carbon capture and storage (OCCS)

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List of Abbreviations

ABS	American Bureau of Shipping
AIP	Approval in Principle
$CaCO_3$	Calcium Carbonate
CAPEX	Capital Expenditures
CII	Carbon Intensity Indicator
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CO_2ASTS	CO_2 Capture, Storage and Transfer in Shipping
CRF	Capital Recovery Factor
CS-SSGS	CO_2 Sequestration in Sub-Seabed Geological Structures
DNV	Det Norske Veritas
RINA	Royal Institution of Naval Architects
EEA	Exhaust Emission Abatement
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicators
EEXI	Energy Efficiency Existing Ship Index
EGCS	Exhaust Gas Cleaning System
FOPEX	Fixed Operating Expenditure
FSA	Formal Safety Assessment
GHG	Greenhouse Gas
IEA	International Energy Agency
IGC Code	International Code for the Construction and Equipment of ships Carrying Liquefied Gases in Bulk
IPCC	Intergovernmental Panel on Climate Change
LCC	Life Cycle Cost
LR	’Lloyd’s Register
NaOH	Sodium Hydroxide
MARPOL	International Convention for the Prevention of Pollution from Ships
MEA	Mono-ethanolamine
MDEA	N-methyl-diethanolamine
MBM	Market-based Measures
OCCS	Onboard Carbon Capture and Storage
OPEX	Operating Expenses
PZ	Piperazine
SEEMP	Ship Energy Efficiency Management Plan
SMDERI	Shanghai Marine Diesel Engine Research Institute

TtW	Tank-to-Wake
UN	United Nations
VOPEX	Variable Operating Expenditure

Chapter 1 Introduction

1.1 Background and significance

Climate change has become a popular issue in global development, and the increase of carbon emissions from industrial activities is considered to be an important cause of global warming. Article 2 of the Paris Agreement sets the goal of “Holding the increase in the global average temperature to well below 2℃ above preindustrial levels” (UN, 2016). This inter-country consensus on global average temperature control, though excluding the shipping and aviation industries, sets the stage for further environmental impact control across industries. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Mitigation of Climate Change, states that global greenhouse gas (GHG) emissions continued to rise to 2019 and that only urgent and ambitious action is likely to achieve the goal of limiting warming to below 2 ℃ (IPCC, 2022). With the maritime sector’s share of global anthropogenic carbon emissions increasing from 2.76% in 2012 to 2.89% in 2018 (IMO, 2020), as shown in Table 1. By 2050, IMO estimates that carbon emissions from shipping could reach 90-130% of 2008 emissions, depending on socio-economic scenarios (IMO, 2020). The projections of maritime ship emissions under different scenarios are shown in Figure 1. Therefore, to set a pathway to the emission reduction trend, effective mitigation measures within the shipping industry shall be carefully and comprehensively considered.

Year	Global anthropogenic CO_2 emissions	Total shipping CO_2	Total shipping as a percentage of global	Voyage-based International shipping CO_2	Voyage-based International shipping as a percentage of global	Vessel-based International shipping CO_2	Vessel-based International shipping as a percentage of global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1,026	2.90%	727	2.05%	894	2.53%
2017	35,810	1,064	2.97%	746	2.08%	929	2.59%
2018	36,573	1,056	2.89%	740	2.02%	919	2.51%

Table 1: Total shipping, voyage-based and vessel-based international shipping CO2 emissions 2012-2018 (million tons)

Source: IMO, (2020), *Fourth IMO Greenhouse Gas Study*, p.2, London: Author.

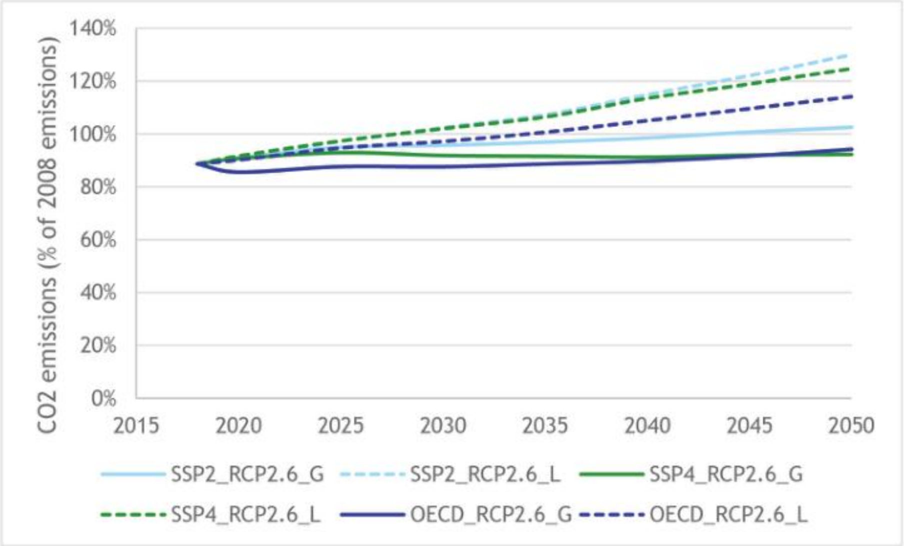
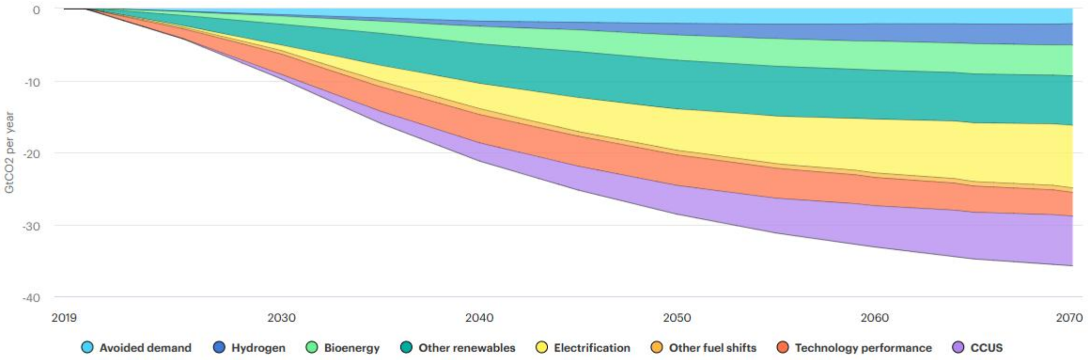


Figure 1: Projections of maritime ship emissions as a percentage of 2008 emissions under six kinds of scenarios

Source: IMO, (2020), *Fourth IMO Greenhouse Gas Study*, p.3, London: Author.

In 2018, the IMO adopted the Initial IMO Strategy on Reduction of GHG Emissions from Ships (RESOLUTION MEPC.304(72)), which sets the goal of "to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008", and lists the candidate short-term, mid-term and long-term measures. The IMO has also introduced the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII) and the Ship Energy Efficiency Management Plan (SEEMP), which provide strong measures to control carbon emissions from ships in the short-term. In order to achieve the emission reduction target, the mid-term and long-term take the market-based measures (MBM) into consideration, and rely more on ship CO_2 reduction technology and the development of zero-carbon powered ships. In the long term, complete decarbonization of shipping depend on the development of zero-carbon energy sources and supporting technologies, such as green ammonia, methanol and hydrogen. However, such innovations imply an overall iteration of ship structure, requiring more time and effort. Onboard carbon capture and storage (OCCS) technology offers a possible transitional measure. With limited modifications to the conventional ship structure, net zero emissions may be achieved by offsetting the CO_2 emitted with the CO_2 captured to achieve net zero emissions. In the OCCS system, carbon could be captured from the energy supply process of conventional carbon-containing fuels (e.g., LNG, heavy fuel oil, diesel), and stored on ships for transporting ashore for sequestration or reuse.

One reason to increase confidence in the adoption of OCCS technology is the relevantly mature development of land-based carbon capture, utilization and storage (CCUS) technology. It explores the capture and purification of CO_2 emissions from large industrial sites, and explore the possibility of permanent storage or reuse of CO_2 for industrial purposes. The International Energy Agency (IEA) believes that CCUS must be one of the four key pillars of the global energy sector transition, along with technologies to widely electrify end-use sectors, bioenergy, and hydrogen related technology (IEA, 2021). The IEA also predicts that CCUS will provide a cumulative 15% reduction contribution to the decarbonization of the global energy sector by 2070, and that the contribution of CCUS will grow over time with the improve of technology. The predicted CO_2 emission reductions in the context of sustainable development are shown in Figure 2. The working principle and system structure of land-based CCUS technology, facility layout and legal system provide the basis for the development of OCCS technology (Ros, *et al.*, 2022). Undeniably, carbon capture is one of the few options available to help abate caron emission in long-haul transport such as shipping. While it should also be noted that OCCS technology is faced with challenges such as the working environment of mobile carriers, limited equipment space and high dependence on reception facilities. These are the important factors for the high cost and difficulty of commercialization of OCCS technology.



IEA. All rights reserved.

Figure 2: Predicted CO2 emission reductions in the context of sustainable development

Source: IEA, (2021), CCUS in the transition to net-zero emissions – CCUS in Clean Energy Transitions – Analysis - IEA

OCCS technology is a considerable research field for carbon reduction in shipping, and it is worth exploring its practical role in carbon reduction in shipping. Optimistically, the development of OCCS in the shipping sector may of the following roles. First, it may extend the use of fossil-fueled ships and ease the pressure on the global shipping industry to reduce carbon emissions and transit to the clean energy era. Second, compared with giving up traditional vessels directly for the use of clean energy vessels, OCCS systems are more economical, and can be more profitable for ship owners under the general trend of low carbon. Third, the idea of producing methane with captured CO_2 from the exhaust gas for LNG fuel recycling provides some reference for the trial application of zero-carbon energy ship technology in the future. Fourth, OCCS technology can also be used as the "last mile" of carbon neutralization. That's to say, after all the carbon reduction measures have worked, the CO_2 that has to be produced unavoidably could be absorbed and offset by OCCS technology. Therefore, this dissertation attempts to collate current OCCS research and experiments, explores the need for policy regulation and raises possible regulatory initiatives, which are of some value to make up for the gaps in international legal norms in this field.

1.2 Literature review

The current development of OCCS technology is based on outcomes of proven onshore CCUS technologies, concentrating on technical feasibility studies while considering safety and cost savings issues. At the level of international regulations, some studies have considered the CO_2 reduction obtained from OCCS technology to be regulated in the EEDI framework.

1.2.1 Pre-combustion carbon capture technology

The research on CO_2 absorption onboard is mainly divided into pre-combustion and post-combustion method. Pre-combustion capture technology is more costly compared to the other method, but the captured CO_2 can be used as a synthetic material for renewable methanol, potentially enabling carbon recycling. Malmgren *et al*. (Malmgren, Brynolf, Fridell, Grahn, & Andersson, 2021) and Thaler *et al*. (Thaler, *et al*., 2022) have studied pre-combustion capture systems using renewable methanol as fuel, with the former assessing the overall environmental impact of the technology and the latter exploring the design with optimal costs of combining pre-combustion and post-combustion technology together. The concept of carbon cycle in the reproduction of fuel is attractive, but the maturity of renewable energy technology industry and equipment development is in the shipping still far from enough, and the commercialization of the concept would take a long period of time.

1.2.2 Post-combustion carbon capture technology

Post-combustion capture technology is relatively mature and universally adapted to most ship types and is the focus of current researches related to OCCS technology, mainly using solvent-based chemical absorption and membrane-based physical absorption methods onboard ships.

1.2.2.1 Solvent-based chemical absorption

Zhou and Wang (Zhou & Wang, 2014) proposed a solidification method of turning CO_2 to calcium carbonate (CaCO3) using alkaline absorbers such as sodium hydroxide (NaOH). Besides, applied technologies mostly use chemical solvents such as MEA, N-methyl- diethanolamine (MDEA), ammonia, piperazine (PZ), etc. Luo and wang (Luo & Wang, 2017), Van den Akker (Van den Akker, 2017), Feenstra *et al*. (Feenstra, *et al*., 2019), and Ros *et al*. (Ros, *et al*., 2022) used Mono-ethanolamine (MEA) as solvent to study the capture effect, which could reach a rate of 73%、90%、90%、72.5%. Feenstra *et al*. (Feenstra, *et al*., 2019) and Long *et al*. (Long, *et al*., 2021) also studied the effect of using the PZ solvent. Feenstra *et al*. (Feenstra, *et al*., 2019) concluded that the system applying PZ-based chemical absorption can save more space and control cost than systems using MEA; Long concluded that when advanced solvents (MEA+PZ and MDEA+PZ) are used under the same external conditions, the absorption is more efficient is better than that of MEA. In the study case of Lee (Lee, Yoo, Park, Ahn, & Chang, 2021), the capture effect of MDEA solvent could reach 94.7%. Awoyomi *et al*. (Awoyomi, Patchigolla, & Anthony, 2020) compared the capture effect of ammonia with MEA and estimated that the capture rate could reach 90%. The improvement of capture rate and cost control by waste heat recovery and heat integration are also studied (Awoyomi *et al*., 2020; Ros, *et al*., 2022). Capital Expenditures (CAPEX) and Operating Expenses (OPEX) analysis based on the life cycle cost (LCC) are introduced to estimate the installation and management cost (Feenstra, *et al*., 2019; Einbu, *et al*., 2022).

1.2.2.2 Membrane-based physical absorption

Unlike solvent-based chemical absorption methods, membrane-based physical absorption methods often occupy less space and may serve as an alternative to OCCS for applications in space-limited shipboard environments. Studies on membrane absorption have been mainly based on onshore CCUS technology, while the CO_2 mole fraction in ship exhaust gas (e.g. in the case of LNG vessels) is very low compared to land-based flue gases (Lee, Yoo, Park, Ahn, & Chang, 2021). Therefore, the characteristics of the membranes used in OCCS technology are different from those in shore-based CCUS technology. Oh *et al.* (Oh, Anantharama, Zahid, Lee, & Lim, 2022) compared the performance of energy consumption and capture effect of an amine-based onboard system with a membrane carbon capture and liquefaction system, and verified the feasibility of membrane capture in shipboard application.

1.2.3 Regulatory aspects

Some studies found that the installation of OCCS devices may have an impact on the calculation of indicators such as EEDI. These studies estimated the changes brought by OCCS to the calculation of the formular. Based on the calculation of Energy Efficiency Operational Indicators (EEOI), Fang *et al.* (Fang S. , *et al.*, 2019) studied the optimal capacity of the OCCS system for application on pure electric ships, with concerns on the methods to relieve the power shortage issue of shipboard CCS. Stec *et al.* (Stec, Tatarczuk, Iluk, & Szul , 2021) concluded that OCCS technology should be considered in the in reasonable correction of the EEDI calculation factor and estimated that the EEDI value with OCCS systems could be twice smaller than tankers without the systems. Lee *et al.* (Lee, Yoo, Park, Ahn, & Chang, 2021) proposed a new method for calculating EEDI, and they predicted that EEDI could be reduced by nearly 50% at capture rates close to 70%.

In conclusion, the research and study on OCCS is focused on the technical improvement of shipboard installations to enhance safety and reduce costs, and most of them take LNG ships as case targets for analysis. OCCS technology research has gradually reflected the difference from onshore CCUS technology, but a relatively mature technology model has not yet been formed. The overall collaboration of the cross-industry carbon capture supply chain on which OCCS technology relies is not yet formed, and the prospects for commercialization are not yet clear (Ricardo and DNV, 2023). However, studies have noted that OCCS technology could make effects on IMO GHG policy tools, such as its representation in EEDI and EEOI.

1.3 Objectives and methodology

The aim of this dissertation is to analyze the current development stage of OCCS technology and try to answer whether it is necessary to make international regulations, and to raises possible regulatory initiatives to facilitate the change to zero carbon emissions in shipping through the application of OCCS technology. The thesis pursues the following objectives:

Objective 1: Determine the extent of development of existing research and testing on OCCS technologies.

Objective 2: Assess the necessity and feasibility of regulatory development.

Objective 3: Develop a regulatory framework for OCCS and make regulatory recommendations for this phase.

To achieve the above objectives, the research methods include analysis based on literature review, FSA-based risk assessment methods, cost analysis methods, etc. The literature review will be used to evaluate the level of development of OCCS technology in general and the degree of development of international regulations involved in OCCS, and for qualitative studies of different risk points in terms of frequency and severity in the FSA and the presentation of cost estimates in the economic analysis.

1.4 Structure of dissertation

Based on the above research objectives, the dissertation is structured as follows:

In the first part, it outlines the global policy trend of carbon emission reduction and the determination of the shipping industry to decarbonize, describes the necessity of OCCS technology development and the significance of this paper's research, and analyzes the overall research status.

Chapter 2 clarifies the concept and principle of OCCS technology, and lists the progress of pilot projects worldwide in recent years to present the general situation of technology application.

Chapter 3 argues for the necessity and feasibility of international regulations based on the economic analysis and safety analysis.

Chapter 4 presents the IMO legal framework and conference concerns related to OCCS technology, develops the rule framework and suggestions on policy directions.

Chapter 5 summarizes the role of adopting policy measures under the current OCCS technical and regulatory developments, and points out the limitations of this paper's research as a concluding remark.

Chapter 2 Overview of OCCS

2.1 Concept and characteristic of OCCS

OCCS technology originates from onshore CCUS technology, the concept of which is to collect and separate CO_2 from combustion sources, initially purify it and store it onboard for reuse or transfer it to shore for treatment. The supply chain of OCCS is displayed in Figure 3. Onboard the ship, CO_2 or solid carbon is collected by pre- or post-combustion capture methods and then stored onboard in the form of solid, liquid or gas. Because CO_2 gas is larger in size and less easily stored compared to the other two states, research on carbon storage onboard is dominated by liquid or solid methods. Liquid storage methods typically pressurize or cool CO_2 to keep it in liquid form. Solid storage methods include the conversion of CO_2 into stable compounds (e.g., limestone) through chemical reactions, and the use of solid sorbent materials that can be easily transported and stored (The Lloyd's Register Maritime Decarbonisation Hub, 2023) . CO_2 stored onboard ships needs to be unloaded at a port or transport vessel for transfer to a CO_2 disposal or sequestration site via pipelines or other transport facilities such as vehicles. The offloaded CO_2 can be used as industrial feedstock, or for geological and biological purposes, or it can be put into the deep ocean for geological sequestration, depending on the extent of onshore CCUS technology development. The current technological maturity of CCUS technology for transportation, storage and utilization is shown in Figure 4.

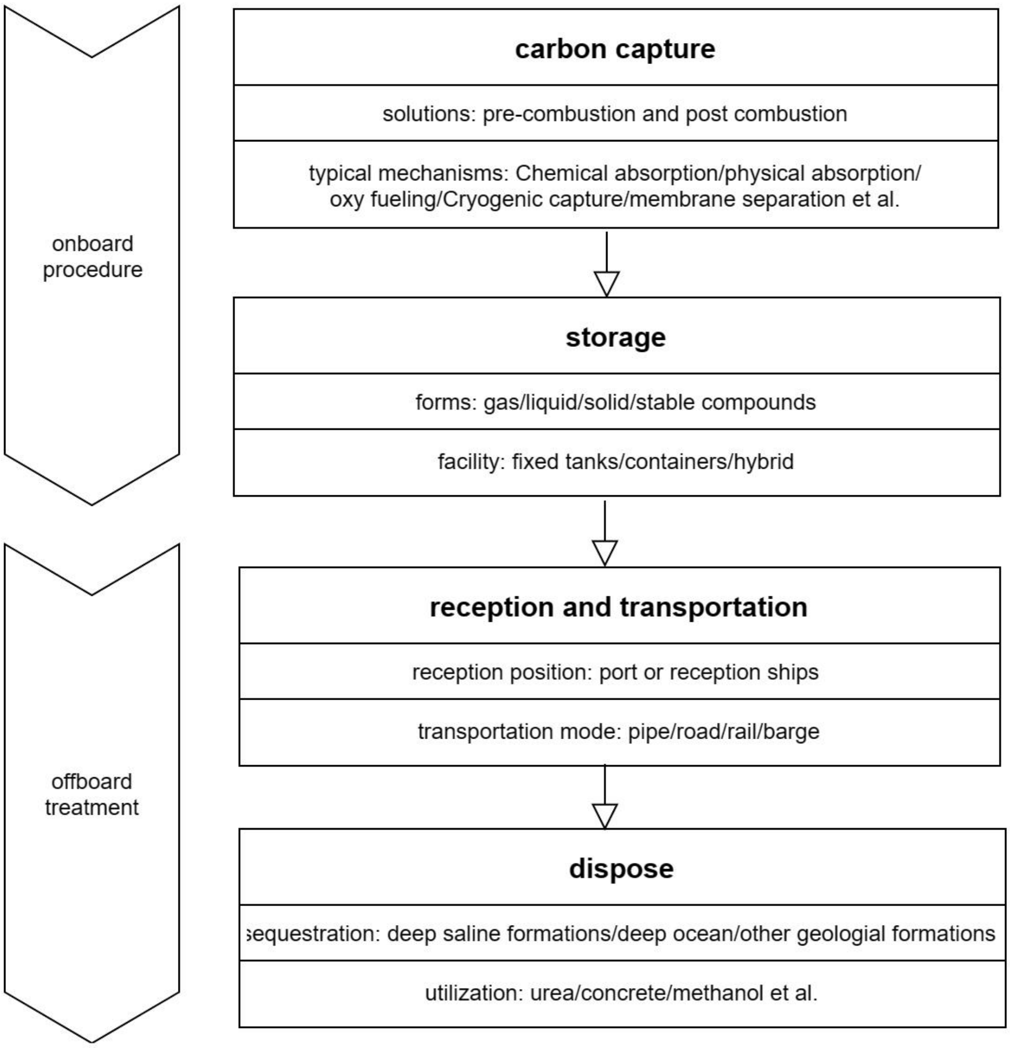


Figure 3: The supply chain of OCCS from ship to shore

Source: Compiled by the author based on the supply chain of shore-based CCUS in IEA's report (IEA, 2021) and the introduction on OCCS technology in The Lloyd's Register's report (The Lloyd's Register Maritime Decarbonisation Hub, 2023)

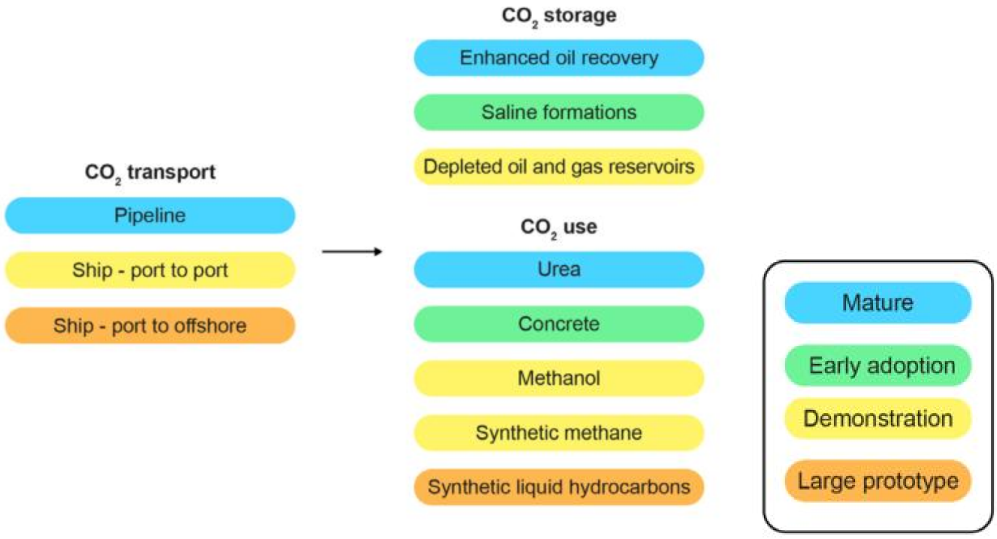


Figure 4: Readiness level of CO2 transport, storage technologies along the CO2 value chain

Source: IEA, (2020), Energy Technology Perspectives,110.

The amount of CO_2 that can theoretically be captured by the OCCS system depends on the facility structure, working principle and operating conditions, such as the choice of CO_2 absorption medium, the size and power of the system, and the flow rate of the ship's exhaust gas. The capture rate reflects the effectiveness of the OCCS system, and is typically the ratio of CO_2 captured to the CO_2 that would have been emitted from the ship's exhaust if the OCCS system had not been used. Based on the results of current studies and trials, it is estimated that 80% to 90% capture rates could be achieved if cost control is not the first to be considered. (Buirma, Vleugel, Pruyn , Doedée, & Schott, 2022).

2.2 Typical structure of current OCCS technology

As displayed in the literature review, OCCS technologies often apply pre-combustion capture and post-combustion capture methods. In addition to these two types of onshore CCUS technologies, oxy-fuel capture methods are also researched as one of the CCUS technologies on land. Oxygen capture requires the combustion of fossil fuels in pure oxygen to obtain a high concentration of CO_2 gas (Wang, Zhou, & Wang, 2017). Considering the cost of prefabricated oxygen and the environmental requirements of pure oxy-combustion equipment, the research and development of oxyfuel capture in OCCS is still very limited (ABS, 2021). Therefore, this section focuses on the system structures of pre- and post-combustion capture methods, with examples of typical ongoing projects.

2.2.1 Pre-combustion systems

Pre-combustion capture technology is a technology that separates CO_2 before the fuel is burned. The ships that apply this system are mainly those that propelled by hydrogen combustion. The HyMethShip concept is an example to display the structure of this system, as shown in figure 5 (Malmgren, Brynolf, Fridell, Grahn, & Andersson, 2021). Clean energy supplies the electrolyzer to produces hydrogen from water. The hydrogen reacts with CO_2 to produce methanol, which is stored on board as a carrier of hydrogen. When required, the reformer decomposes methanol into hydrogen and CO_2, where hydrogen is burned for ship propulsion; while the CO_2 produced is captured and stored on board, for unloading in ports. The CO_2 unloaded could be used in the electro-methanol production. The orange border in the figure shows the workflow of the system onboard, while the CO_2 recycling process is shown in the gray border. Since CO_2 capture process is performed before fuel combustion, the collected gas is not yet diluted by N_2, and the CO_2 concentration in the fuel gas is high, the capture efficiency is high and the cost is low. However, since the pre-combustion concept is only applicable to specific energy-powered ships, the prospect of promoting it is still unknown.

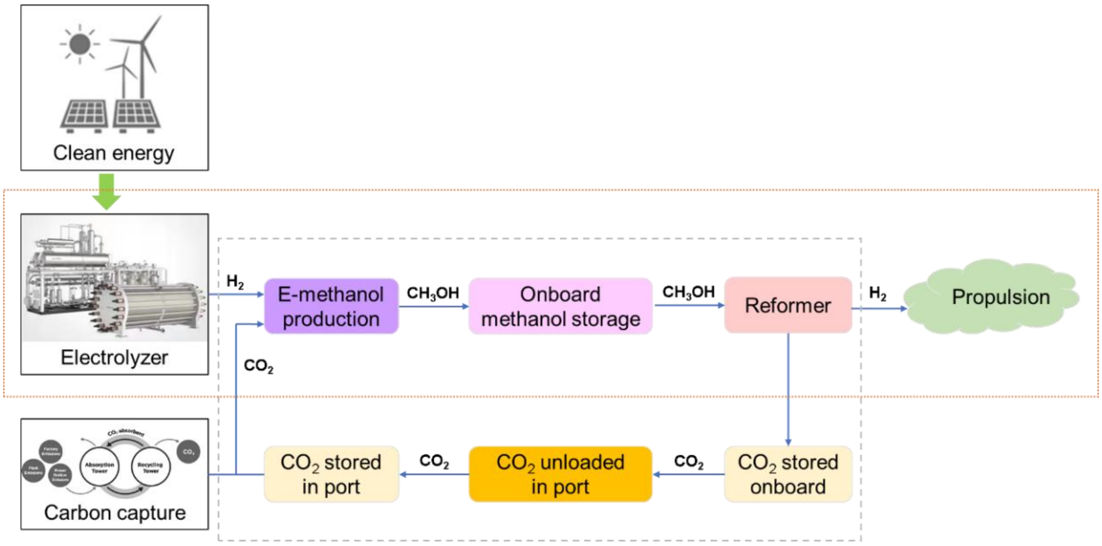


Figure 5: Structure of the pre-combustion capture system in the HyMethShip concept

Source: Malmgren, (2021), The environmental performance of a fossil-free ship propulsion system with onboard carbon capture – a life cycle assessment of the HyMethShip concept, *Sustainable Energy & Fuels*, (5), p.2755. DOI: 10.1039/d1se00105a

2.2.2 Post-combustion systems

Post-combustion capture technology is relevantly mature and is a heated direction for carbon capture technology research onboard. Post-combustion capture technologies may involve chemical adsorption, cryogenic carbon capture, physical absorption and membrane-based technologies (Ji, Yuan, Huffman, El-Halwagi, & Wang, 2021) . This capture method is structurally similar to exhaust emission abatement (EEA) equipment and can be retrofitted on existing ships, or incorporated into new ship designs. However, due to the storage characteristics of CO$_2$, OCCS equipment faces challenges such as more complex structures, larger equipment volumes, changes to ship structure and energy consumption, and safety issues.

When the post-combustion method is applied, CO_2 is removed from ship exhaust, and then liquified and stored centrally onboard. Taking the technology used in the CC-OCEAN project launched in Japan in 2021 as an example, the structure of the post-combustion capture system based on chemical absorption is researched. The method of chemical absorption has not only been well developed on land, but also applicable to ship exhaust gas with low partial pressure of CO_2 (ClassNK, 2023) and is the OCCS structure with the most market potential. In the CC-OCEAN project, a post-combustion system was designed with liquid amine as the absorbent, the structure of which is illustrated in the Figure 6. The installation was designed with a shipboard structure that includes a capture unit, a liquefaction unit, and a storage unit. The exhaust gas is first cooled by the quencher and then enters the absorption tower, which captures CO_2 from the exhaust gas into a solution. The absorption tower releases the remaining exhaust gas, which is further treated by the cleaning device and then discharged to the air. While the solution rich in CO_2 is sent to the regeneration tower, where the dissolved CO_2 is released by heating, and the separated solvent can be recycled into the absorption tower. The high-concentration CO_2 released from the tower is then precipitated through the reflux drum and enters the liquefaction unit. The captured CO_2 is compressed and condensed at the liquefaction unit and finally enters a storage tank for transfer and disposal.

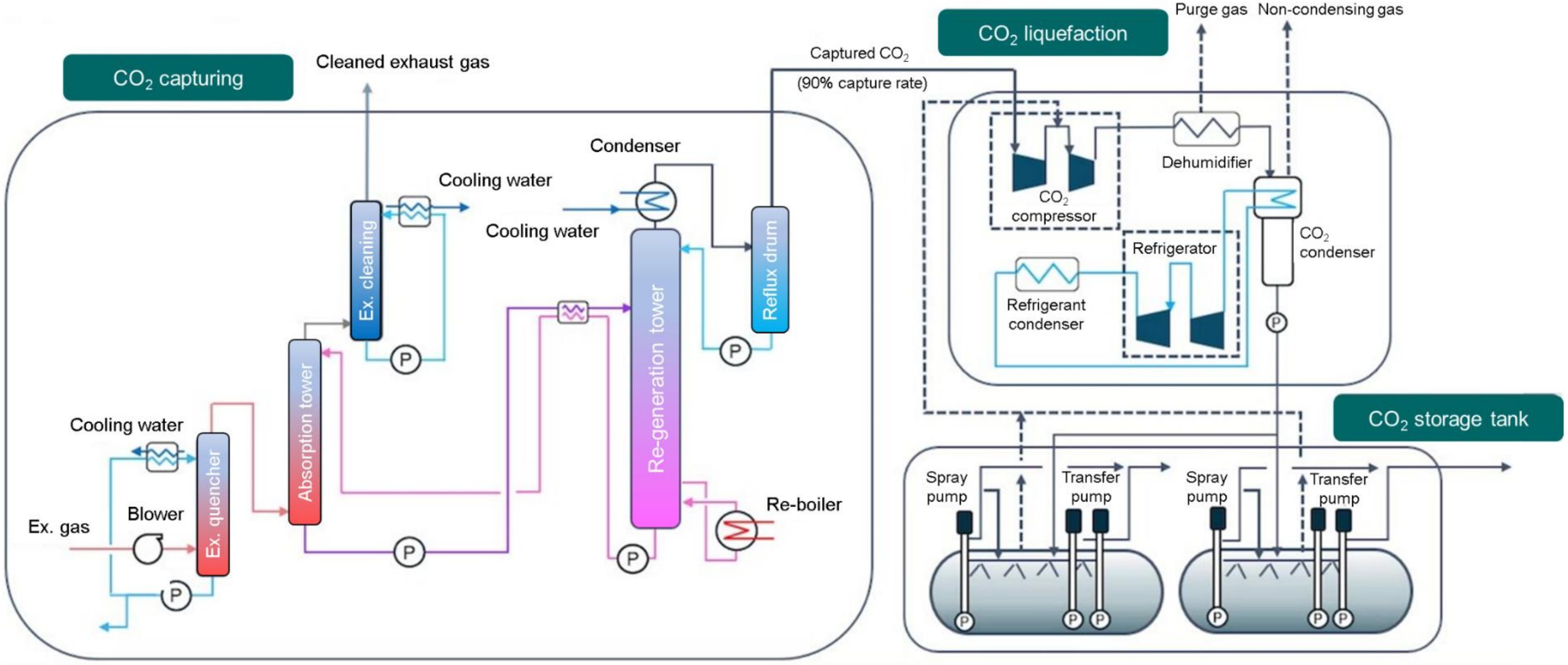


Figure 6: Structure of the post-combustion capture system in the CC-OCEAN project

Source: Mandra, (2022), Onboard carbon capture makes most business sense for large tankers & newbuilds - Offshore Energy (offshore-energy.biz)

One of the challenges of post-combustion capture technology is the size of the system. The function of the capture device dictates that it has to be installed at a considerable height (Monteiro, 2020), and the storage of CO$_2$ often requires the cost of cargo area. These present challenges for the cost of cargo space loss due to such systems and the safety risks. The concept diagram of the post-combustion CCUS technology applied in the plant is shown in Figure 7, and such a structure explains the doubts about the structure of post-combustion capture systems.

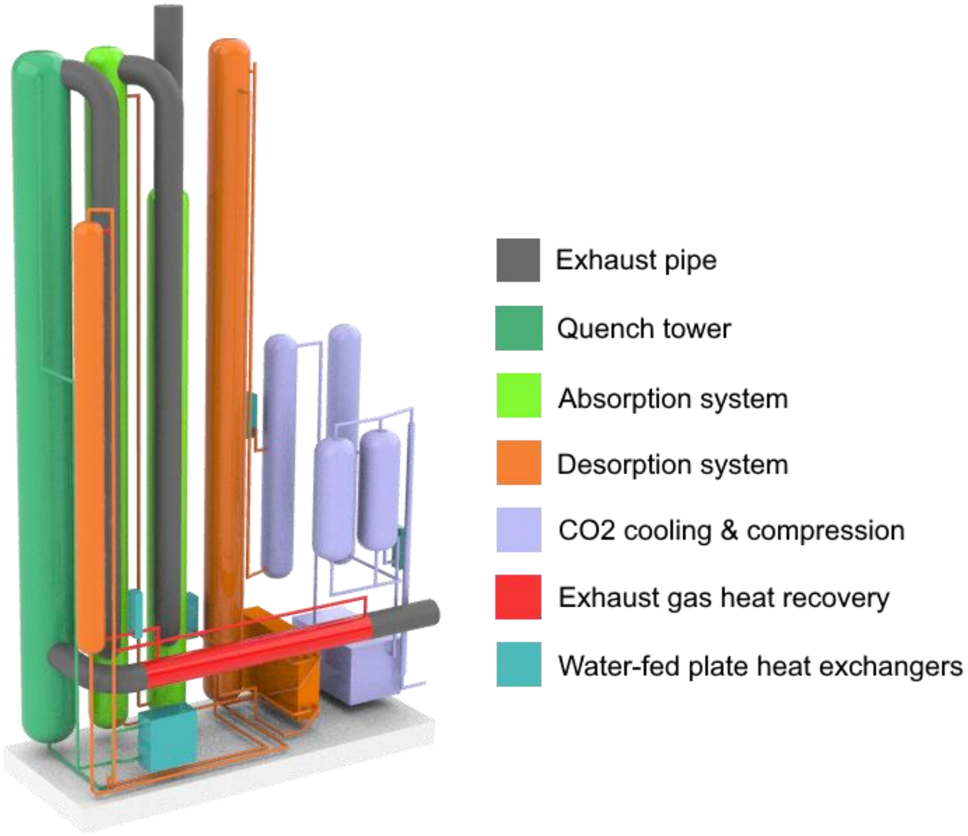


Figure 7: The concept diagram of the post-combustion CCUS technology applied in the plant

Source: Monteiro, (2020), CO$_2$ASTS – carbon capture, storage and transfer in shipping A technical and economic feasibility study: Public Concise Report, p4.

2.3 Demonstration projects onboard ships

Regional projects and cases contain studies on the effectiveness of OCCS, but different pilot projects have selected test subjects with different properties (e.g., ship fuel type, tonnage) and designed different reaction principles and structures. The main pilot projects currently being promoted in the world are introduced as below.

In 2019, the Danish Maritime Development Center launched a project called DecarbonICE (zero2050 Redaction, 2020) with the concept of freezing CO_2 from ship exhaust into dry ice powder, dumping the dry ice powder into streamlined ice blocks, and then dumping it into the deep sea. Since CO_2 ice is heavier than water, it will descend to the seafloor where it will penetrate the sediment and be stored permanently, mainly as CO_2 hydrate. It is noteworthy, however, that the London Protocol regulating transboundary transport and geological sequestration of CO_2 in deep ocean has not yet been widely adopted and accepted globally (with detailed analysis in Chapter 4).

In 2020, the CC-OCEAN project, jointly launched by ClassNK and its local head shipping companies, was the world's first project to conduct OCCS demonstration test on actual voyage. Starting in August 2021, the project conducted about six months of tests and successfully confirmed the feasibility of capturing CO_2 from the exhaust gas of marine engines on board ships, where the operating conditions differ from those on land (“CC-Ocean” CCS System Awarded, 2022).

In 2020, the European Union's Horizon 2020 research and innovation program funded the collaborative development of the HyMethShip project. Using the principle of pre-combustion capture, it takes into account the simultaneous elimination of CO_2, SO_x and PM emissions and offers the possibility of a closed CO_2 cycle using OCCS technology (LR, n.d.).

In 2021, Finland's Deltamarin Group, in cooperation with Wartsila, studied how to use the pre-combustion OCCS system in RoPax ferries. It compared the effectiveness of applying OCCS to RoPax ferries using HFO and LNG fuel, and envisioned a fuel cycle supply system with methane produced by captured CO_2 (Figure 8). After considering factors such as cost-benefit and carbon emission payment, OCCS is considered feasible and more suitable for application on LNG vessels (Deltamarin, 2021).

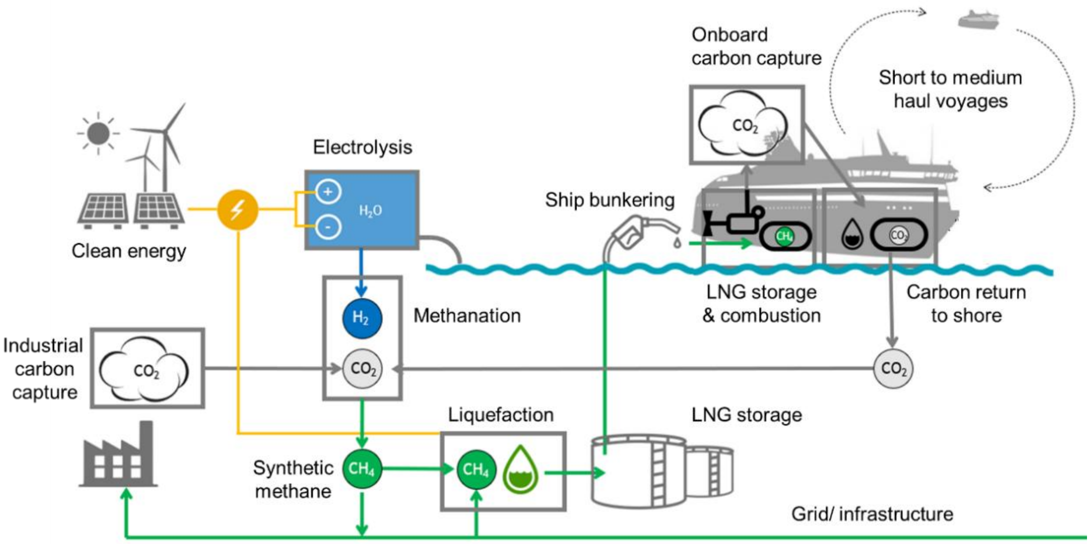


Figure 8: Circulating fuel supply system applied in the Deltamarin project

Source: Deltamarin, (2021), Carbon capture-Case study for a Ropax ship, https://deltamarin.com/blog/carbon-capture-case-study-for-a-ropax-ship/

The Dutch company Value Maritime has developed an OCCS system that stores CO_2 captured from the vessel's exhaust and used a "battery", which refers to a storage facility that can be charged and discharged with CO_2 indefinitely. In October, 2022, the system was installed on the 13,000-gross-ton container ship, Nordica, which was the world's first installation of CCS equipment on an operating vessel (Value

Maritime, n.d.). The value Maritime system earns the initial approval from the classification society ABS in 2023 (Ship & Bunker News Team, 2023).

Also in 2020, the project “CO_2 capture, storage and transfer in shipping” (CO_2ASTS), jointly developed by German and Dutch companies and the knowledge institutes, analyzed the effects of OCCS on three LNG ships: (1) a 1 MW inland ship, (2) an 8 MW dredger and (3) a 36 MW cruise ship. MEA was used as the capture solvent, with the capturing rate to be 75%, 54% and 69% respectively. The LNG-fueled ship is well integrated with carbon capture and liquefaction, and the process can utilize the heat from the exhaust gas and the cold from the LNG vaporization, which greatly reduces the operating cost of the process. The total cost of CO_2 capture for these three cases is estimated at 301 €/ton, 115 €/ton and 154 €/ton, respectively.

In October 2022, Daewoo Shipbuilding & Marine Engineering announced that it had successfully completed the performance verification of the OCCS system onboard a large LNG vessel. The OCCS system is characterized by very low energy consumption compared to other CO_2 capture technologies, and the additional CO_2 emissions from the operation of the equipment itself is relatively low (Wang, 2022).

The marine OCCS system developed by Shanghai Marine Diesel Engine Research Institute (SMDERI), China, has completed the preliminary laboratory test and the carbon capture rate reached 86.3%, which was issued approval in principle (AIP) certificate in February, 2022, by China Classification Society. In July 2022, cooperated with Hong Kong Huaguang Marine and Bureau Veritas (BV), SMDERI design customized the OCCS devices based on two bulk carriers and carried out real-vessel application tests (Xinde Marine, 2022).

In 2022, the OCCS system independently developed by Headway Technology Group (Qingdao) has officially obtained the AIP certificate granted by DNV, RINA and other classification societies, and was scheduled to be tested on board ferries (Zhou & Sun, 2022).

2.4 Concluding remarks

The OCCS technology shows its full potential in the context of decarbonization in the shipping industry. Among the various approaches in the field of carbon capture, pre-combustion and post-combustion capture technologies based on chemical absorption have gained more academic attention. Classification societies and large companies worldwide have collaborated on pilot projects of OCCS technology for operating vessels, and have conducted proof-of-principle and technical feasibility analyses with the aim of improving capture effectiveness and controlling overall costs. Although a complete supply chain and market-based operating model have yet to be developed, the OCCS technology exploration has become a direction that cannot be ignored in the transformation of shipping technology, while rules and guidelines on OCCS piloting and operation are still almost blank on a regional and global scale.

Chapter 3 Necessity and feasibility to incorporate OCCS technology as a potential decarbonized pathway for global shipping

3.1 Economic analysis

In this section, factors affecting CO_2 unit capture costs are analyzed, cost estimation results from current studies and project evaluations are summarized, and an overview of OCCS techno-economic factors is presented.

3.1.1 Cost Analysis

When considering the cost of OCCS application, it mainly includes the annualized capital expenditure (CAPEX), the fixed operating expenditure (FOPEX), the variable operating expenditure (VOPEX), and the annual amount of CO_2 captured. Eq. (1) shows how the cost of captured CO_2 (CCC) is calculated.

$$CCC = \frac{\text{annualized CAPEX} + \text{FOPEX} + \text{VOPEX}}{\text{CO2 captured per year}} \tag{1}$$

3.1.1.1 Annualized CAPEX

CAPEX refers to the costs involved in installing OCCS systems, which are mainly the cost of the system itself, the cost of installation services, and the support systems (Van den Akker, 2017). The cost of the system itself is the equipment cost in the process of capture, liquefaction, cooling and storage. The cost of installation services includes the cost of installation and improvement service, supervision and construction at the shipyard. The support systems include instrumentation and control, piping, electrical equipment and materials, new ship construction cost, steel structure, installation cost, etc. In the estimation, the cost of the installation service and support system is often based on the cost of the equipment itself.

The annualized CAPEX takes into account the capital recovery amount where the total CAPEX is apportioned to each year. It is calculated as CAPEX multiplied by the capital recovery factor (CRF), see Eqs. (2) and (3). The lifetime of the OCCS equipment is assumed to be 25 years and the interest rate is 8% (Feenstra, *et al.*, 2019; Awoyomi, Patchigolla, & Anthony, 2020).

$$CRF = \frac{\mathrm{i}(\mathrm{i}+1)^n}{(\mathrm{i}+1)^n-1} \tag{2}$$

$$Annualized\ CAPEX = \mathrm{CAPEX} * \mathrm{CRF}$$

(3)

3.1.1.2 FOPEX

FOPEX is usually associated with maintenance and labor costs, referring to fixed operating costs that are not related to engine load and involve service and management cost, and operating and maintenance costs, additional port charges, etc. In cost estimation, it is about 3% of the annualized CAPEX (Luo & Wang, 2017; Van den Akker, 2017).

3.1.1.3 VOPEX

VOPEX is related to the consumption of capture materials and the energy costs associated with the OCCS system. Where the energy cost associated with the OCCS system largely comes from the power demand of the system itself and the additional power demand due to the increase of ship resistance, and the change of fuel price needs to be taken into account.

3.1.2 Benefit Analysis

3.1.2.1 Sale of OCCS system products

For the higher purity CO_2 obtained from the absorption by solvent, physical absorption, chemical absorption, membrane capture, etc., it can be sold to possible carbon capture downstream industries, such as oil developers or the food industry, if there is a demand for CO_2 use. As the mature of shore-based CCUS supply chain, it may also be possible to sell CO_2 to relevant receiving units such as the Dutch greenhouse sector (Van den Akker, 2017). In addition to the products of high purity CO_2, there are also OCCS systems under study that may produce $CaCO_3$, which is of greater sales potential.

3.1.2.2 Offsetting of ship emission costs

IMO has already been considering a package of medium-term initiatives for GHG emissions reductions from shipping, which could include a carbon tax or emissions trading scheme. To meet the 2050 emissions reduction target, ships propelled by fossil fuels may have to pay for CO_2 emissions over the next few decades. And with the tightening of policies and the reduction of carbon market share, the cost of carbon emissions shows an upward trend when there is no significant reduction in ship carbon emissions. The relationship between the cost of carbon emissions and the cost of OCCS system trend is shown in the figure 9. With the increase of emission cost and the decrease of OCCS cost, the annual cost of both reached the same level at P point, and the cumulative cost reached the same level at P1 point. If the planned operating time of the system exceeds the time of point P1, the cumulative cost of installing OCCS system onboard is less than the direct emission cost without OCCS used.

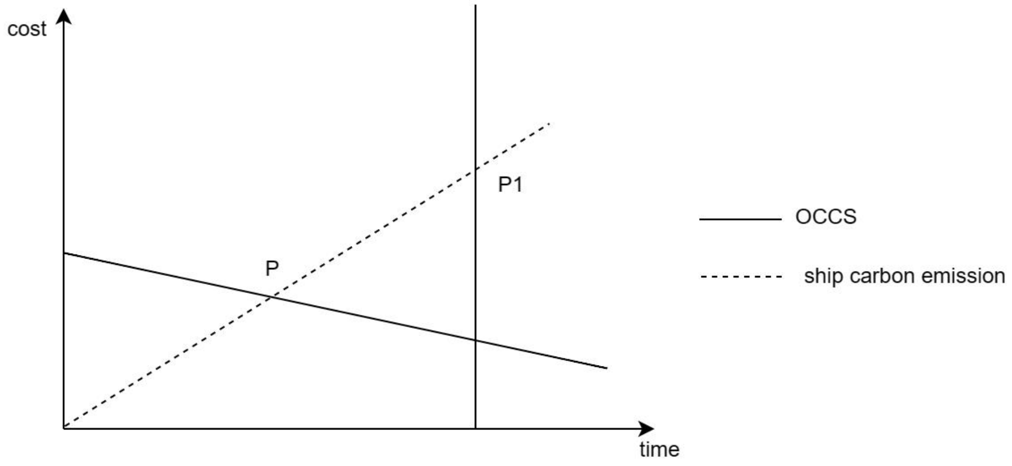


Figure 9: Ship carbon emission payment cost and OCCS system cost trend

Source: Compiled by the Author.

3.1.3 Economic evaluation of the OCCS system

Since the global CCUS supply chain is not yet established and measures for a global carbon tax or carbon trading market for the shipping industry are not yet in place, most researches and projects did not take the benefits into account in the cost analysis of the OCCS system. Based on different propulsion systems, the estimated cost of installing and operating OCCS is shown in the table 2.

From the data in the table 2, it can be found that the carbon capture rate could be available to 60-90%. The total expenditure is dominated by the CAPEX, which accounts for 90% or more of the entire life cycle cost of the OCCS system. The CAPEX is influenced by the power of the ship and the capture rate, which is reflected in that the stronger the ship power, the higher the absorption and storage capacity and cost of the OCCS equipment; and the higher the capture rate, the higher the energy consumption in the absorption and cooling sector of the system, which also increases the equipment cost of the OCCS system. In addition, LNG ships are more economical than those relying on diesel, and the PZ solvents are more economical than the MEA solvents under the same conditions. According to Deltamarin's cost modelling and relevant data from Wärtsilä, the installation of OCCS on newly-built ships requires an additional cost of 5 % to 7 %. Considering the policy impact of the possible carbon emission tax, the pay-back time for applying OCCS systems is approximately 5-10 years. (Deltamarin, 2021)

To sum up, considering the CAPEX and OPEX of the OCCS system, it can achieve a promised capture effect. With the establishment of the supply and sales chain of capture products and the potential pressure of carbon emission policies, the feasibility of the OCCS system as a technical means for ship emission reduction becomes clearer as technology improves.

Table 2: Economic evaluation result of previous researches

Source	**Type of ship**	**Raw materials**	**Engine power (MW)**	**CAPEX (M€)**	**Annualized CAPEX (M€)**	**OPEX (M€)**		**Benefit (M€)**	**CCC (€/t)**	**Capture rate**
						FOPEX (M€)	**VOPEX (M€)**			
Luo&Wang（2017）	diesel	MEA	17	34.99	2.45	1.05	0.09	NM	77.5	73%
Luo&Wang（2017）	diesel	MEA	17	43.06	3.01	1.29	7.38	NM	163.07	90%
Van Den Akker,（2017）	LNG	MEA	3	4.97	NM	0.1		NM	74 €	90%
Van Den Akker,（2017）	LNG	MEA	3	4.97	NM	0.1		0.21	34.71	90%
Feenstra *et al*. (2019)	LNG	MEA	1.28	NM	NM	NM	NM	NM	240	90%
Feenstra *et al*. (2019)	diesel	MEA	1.28	NM	NM	NM	NM	NM	295	80%
Feenstra *et al*. (2019)	LNG	MEA	1.28	NM	NM	NM	NM	NM	320	60%
Feenstra *et al*. (2019)	diesel	MEA	1.28	NM	NM	NM	NM	NM	390	60%
Feenstra *et al*. (2019)	LNG	PZ	1.28	NM	NM	NM	NM	NM	155	90%
Feenstra *et al*. (2019)	diesel	PZ	1.28	NM	NM	NM	NM	NM	205	90%
Feenstra *et al*. (2019)	LNG	PZ	1.28	NM	NM	NM	NM	NM	202	60%
Feenstra *et al*. (2019)	diesel	PZ	1.28	NM	NM	NM	NM	NM	305	60%
Feenstra *et al*. (2019)	LNG	MEA	3	NM	NM	NM	NM	NM	143	90%
Feenstra *et al*. (2019)	LNG	MEA	3	NM	NM	NM	NM	NM	120	90%
Feenstra *et al*. (2019)	LNG	PZ	3	NM	NM	NM	NM	NM	98	90%
Awoyomi *et al*. (2020)	LNG	ammonia	10.8	13.65	0.955	0.029M€	0.54M€	NM	93.6	90%

Note: a. NM means not mentioned. b. The works of Feenstra *et al*. only reflect the proportion of CAPEX and OPEX to the total expenditures, which are about 90% and 10%, respectively (Feenstra, *et al*., 2019). c. It is assumed that 1 € =1.25$.

Source: It is compiled by the author referring to the previous researches as is noted in the table.

3.2 FSA-based Risk Analysis on OCCS

3.2.1 Concept of FSA

Formal Safety Assessment (FSA) derives from the 1988 Piper Alpha rig accident and was later developed and revised by IMO, which is applied in accordance with the "Consolidated text of the Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process (MSC/Circ.1023−MEPC/Circ.392, 2007)". FSA is functioned as a tool for systematic assessment that balances technology and operations, safety and environment through risk analysis and cost-benefit assessment, and has been widely used in IMO regulation development, ship design and construction, shipping safety management and other shipping aspects (Zhang, 2021). FSA usually includes steps such as hazard identification, risk assessment, risk control, cost-benefit assessment and recommendations, as shown in Figure 10. These steps can be used flexibly in combination to achieve different assessment effects, and the following structure process is mainly used in this phase for OCCS assessment.

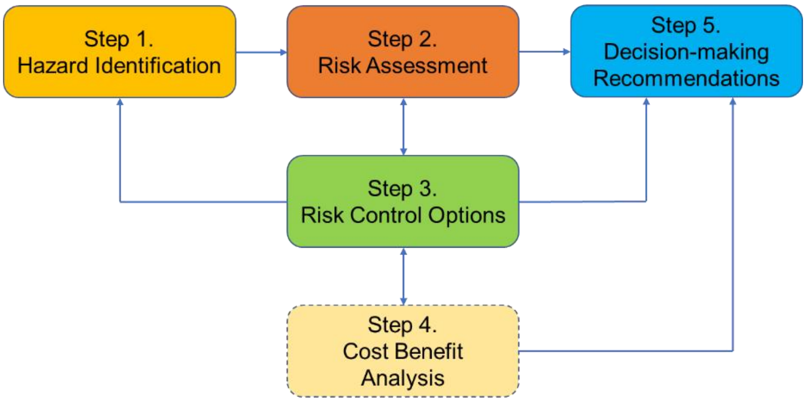


Figure 10: Risk assessment process

Source: Compiled by the author.

3.2.2 Hazard identification

Identification of hazard is to find out the hazardous factors from the assessed items to rank these factors in the order of risk level. It is the basis of FSA. Based on the literature review and the analysis of the OCCS supply chain composition in section 2.1, this paper identifies four types of safety hazards for OCCS: technical, personnel, management, and environmental hazards.

3.2.2.1 The technical hazards

The technical hazards of the OCCS system mainly stem from the complex structure, loss of function and components failure. The post-combustion OCCS system is connected to the ship′s exhaust gas pipeline, and the connection may be loosened due to the wind and waves during navigation or the shaking caused by the ship′s movement, which may lead to gas leakage and other hazards. The process of CO_2 absorption reaction often requires a high temperature and pressure environment. If leak occurs in the pipeline, it may lead to the distribution of toxic substances, causing asphyxiation and heaviness, creating potential threats such as fire and explosion. In addition, there are hazards associated with the aeration of the OCCS system. The use of equipment will accumulate reactants and dirt in the pipeline, which may hinder the ventilation of the OCCS system. Once blocked, CO_2 may back up and cause damage or explosion to other machines on the ship.

3.2.2.2 The personnel hazards

The use and maintenance of new technologies and systems depend on human operations, and the personnel factors in the operation of the OCCS system should be fully considered. Once the crews are not familiar with the newly installed OCCS equipment, they may meet the hazard of maloperation and may not be able to troubleshoot the equipment and cope with the technical hazards analyzed above. At the same time, there may be OCCS equipment failure caused by improper maintenance, which will not only affect the carbon capture effect, but also hinders the safety of navigation if leakage or blockage of the pipeline occurs. What is more, the learning and adaptation of new OCCS equipment may increase the psychological pressure of crew members after the heavy workload, and the use of new equipment is bound to increase the workload of cabin management and maintenance, which may be a reason for fatigue of crew members and thus affect the safety of navigation.

3.2.2.3 The operational hazards

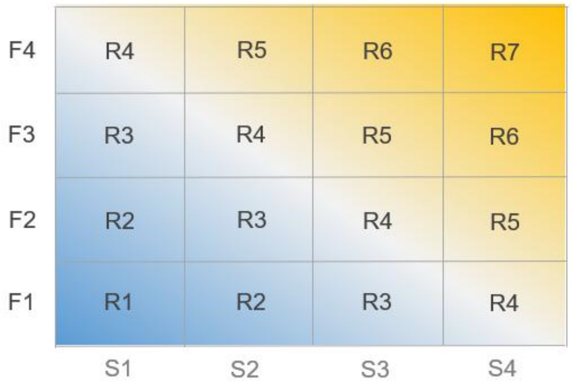
The management hazards in the operation of OCCS system mainly come from the company’s management system and personnel management. As to the mechanism of the company’s management, firstly, the application of OCCS relies on whether a management system that values safety is established, covering operation and maintenance in the scope of management and inspection. Secondly, whether OCCS failure issues are included in the contingency plan also affects the hazard of operation. In the event of the OCCS system and related equipment failures, the advanced arrangement of safe operation will help maintain the safety of navigation. In terms of personnel management, whether the company can enhance the safety awareness of personnel and arrange timely and reasonable personnel training to make them familiar with the use and maintenance of new equipment on board will also affect the safety of the OCCS application.

3.3.2.4 The environmental hazard

The environmental hazards of the OCCS system mainly include navigation environmental risks and onshore disposal risks. During the voyage, the ship may encounter weather conditions like wind and waves, fog, rain and snow, etc., which may cause bumps and affect the smooth operation of the vessel and the onboard equipment. And extreme weather needs the crew to pay more attention to the state of the ship, which may affect the maintenance and operation of the OCCS devices. After carbon capture by ships, CO_2 needs to be unloaded on the shore with qualified reception facilities. If the captured CO_2 cannot be unloaded on the shore in time, the OCCS equipment may not be able to play a role in the next voyage. While carrying excessive CO_2 onboard also increases the safety risk of storage.

3.2.3 Risk assessment

According to FSA, risk assessment on the operation of OCCS devices is based on the frequency of risk occurrence and the consequences of risk events. Referring to the risk analysis of the supply chain of OCCS in the literature and the risk assessment framework for onshore CCUS technology (IMO, 2012), this section takes the risk matrix method to qualitatively evaluate the above transport risk factors. The frequency of risk occurrence is the ratio between the number of risk events and the total amount of equipment used, and is qualitatively distinguished into four categories: frequent (F4), common (F3), occasional (F2), and rare (F1). The consequence is the evaluation of the effect of the loss of personnel and economy, etc., and is distinguished into four degrees of severity: extremely severe (S4), severe (S3), less severe (S2), and slight (S1). Risk assessment is carried out with the frequency of risk occurrence and severity of accident consequences as variables, which can be classified as 7 levels according to the matrix method, as follows shown in Figure 11.



F4	R4	R5	R6	R7
F3	R3	R4	R5	R6
F2	R2	R3	R4	R5
F1	R1	R2	R3	R4
	S1	S2	S3	S4

Figure 11: Risk Matrix Model

Source: Compiled by the author.

Based on the above matrix model, the results of risk assessment are shown in the following Table 3.

Table 3: Risk Assessment Table for the OCCS Application

FI	**TYPES**	**RISKS**	**FREQUENCY**	**SEVERITY**	**ASSESSMENT**
1	Technical	Loose pipeline	F2	S3	R4
2	Technical	High temperature and pressure	F4	S3	R6
3	Technical	Pipeline blockage	F2	S3	R4
4	Personnel	Unfamiliar personnel	F3	S2	R4
5	Personnel	Missed operation	F2	S2	R3
6	Personnel	Fatigue	F3	S3	R5
7	Management	Safety	F1	S3	R3

		mechanism			
8	Management	Emergency planning	F1	S3	R3
9	Management	Personnel training	F2	S3	R4
10	Environmental	Weather	F3	S2	R4
11	Environmental	Onshore acceptance	F2	S3	R4

Source: Compiled by the author.

3.2.4 Risk control options

Based on the above hazard identification and risk assessment, measures to cope with different types of hazards and risks are summarized as follows.

To deal with technical risks, technical standards for the OCCS system should be formulated to structurally reduce the risk of loose piping; requirements should be put forward for OCCS materials to avoid the risk of leakage and explosion in the high temperature and high-pressure reaction environment. What is more, systematic risk assessment for a routine inspection of device function and performance shall be carried out, to promptly detect abnormal conditions such as pipeline blockage for timely treatment.

To deal with personnel risks, the personnel management and training system should be improved, so that the crew can be familiar with the structure and operation of the new OCCS equipment in a timely manner, and be in a healthy working state to reduce maloperation. At the same time, a supervision and mutual inspection mechanism can be established to actively discover abnormalities in equipment use and maintenance, and reduce the influence of human factors.

To cope with management risks, the safety element should be strengthened to the company's management system to form a top-down division that attaches importance to safety and strive to cultivate a safety culture. Moreover, the weight of safe operation should be strengthened in crew training, by standardizing the safety operation procedures and conducting regular emergency drills, covering equipment failures and hidden dangers in operation, etc.

To cope with the environmental risk, the shipping route should be reasonably planned, and the weather factors, navigation conditions and the situation of CO_2 reception facilities in the destination port should be considered in advance. In the early stage of OCCS application, it is possible to cooperate with designated ports to establish a ship CO_2 capture transportation and transfer chain, so as to achieve a safer and more efficient application of carbon capture in shipping.

3.2.5 Decision-making and recommendations

Through the analysis of measures proposed for different hazards in the previous section, some common recommendations for improving the risk control level of OCCS devices are obtained.

3.2.5.1 Refinement and development of technical standards

The construction of new OCCS equipment should meet the relevant ISO technical requirements and obtain technical certification from authorized institutions, so as to effectively control the safety risks caused by device design problems and quality problems. Also, the safe operation of OCCS equipment can increase the crew′s attention to equipment safety and avoid misuse to a certain extent. In addition, the construction of shoreside CO_2 reception facilities also needs to be standardized and certified to ensure the matching with the onboard equipment and safe unloading.

3.2.5.2 Respond to the challenges posed to crews by the OCCS systems

On the one hand, personnel training should be strengthened to familiarize crew members with the proper operation and maintenance of the equipment. On the other hand, attention should be paid to the burden of new learning and equipment used on the crew as one of the factors causing fatigue issues. The human factor issue is often difficult to solve from the crew side, and measures to strengthen the system and management should be considered to reduce human errors.

3.2.5.3 Enhancement of enterprise security management

Companies that install OCCS equipment onboard should incorporate the OCCS equipment safety management into the scope of the company's safety management system, as well as into the scope of emergency response capability training and regular company supervision. Risks in equipment use can be effectively prevented through emergency training and mutual supervision. At the same time, the companies should incorporate route planning and onshore receiving facilities into their operating decisions, so as to achieve the environmental and economic functions of carbon capture while ensuring safety.

3.3 Concluding remarks

This section studies the current stage of the OCCS technology from the perspective of economic and risk analysis. On the one hand, the economic analysis concludes that the emission reduction effect and economic performance of OCCS technology are optimistic and could become an option for shipping emission reduction in the future. On the other hand, the risk analysis finds that the risks of OCCS technology depend to a considerable extent on the formulation and implementation of rules to deal with. Therefore, there is a need to review international rules related to OCCS application and to further develop regulations and guidelines for OCCS equipment and operations. This will play an important role in promoting the advancement of OCCS technology, establishing a safe and sustainable OCCS supply chain, and increasing public awareness of OCCS technology.

Chapter 4 Establishment of a regulatory framework

Through the risks and economics analysis, the future of OCCS technology is predicted to be increasingly clear, and the CCS technology has broadened the solutions to reduce carbon emissions in the shipping sector. Accordingly, the regulatory framework developed by IMO should adapt to the trend of technological progress to provide regulations and guidelines for the OCCS technology. Existing conventions and codes relating to OCCS should be assessed, including regulatory areas that may be affected by CCS technology with respect to CO_2 transportation, geological storage of CO_2, energy efficiency, and GHG emission reduction. Also, development of new regulations and guidelines should be considered that include a certification procedure to ensure that OCCS equipment is approved by authorities to be competent to perform the intended function, as well as to ensure that the captured CO_2 is properly disposed of.

4.1 Current IMO Policies Relating to OCCS

The current legal framework related to OCCS is mainly about the storage and transportation of CO_2 onboard, the sequestration and utilization of captured CO_2 products offshore, and the changes brought by the installation of OCCS equipment to the operation and environmental impact of ships, which are related to the London Protocol, the IGC Code, the MARPOL Convention, and related guidelines.

4.1.1 The London Protocol

4.1.1.1 The Protocol and Amendments

The existing IMO document most closely related to carbon capture technology is undoubtedly the London Protocol, which came into force in 2006 and aims to protect the marine environment from marine pollution caused by the dumping or burning (IMO, 2006b). The Protocol established a “reverse list”, prohibiting the discharge of all wastes into the ocean, except for the exception in Annex 1, which allows for dumping at sea with certain permits. At the early stage, deep-sea geological storage or sequestration was considered dumping in the ocean. When the captured CO_2 is geologically stored or transferred across the border, the requirements of the London Protocols should be followed. Annex 1.8 of the London Protocol lists that CO_2 collected during carbon capture can be sequestered at sea if the requirements listed in Article 4 are met. The requirements of Article 4 are as follow:

> *4 Carbon dioxide streams referred to in paragraph 1.8 may only be considered for dumping, if:*
>
> *.1 disposal is into a sub-seabed geological formation; and*
>
> *.2 they consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture and sequestration processes used; and*
>
> *.3 no wastes or other matter are added for the purpose of disposing of those wastes or other matter.*

In addition, cross-border transport of CO_2 for the geological storage is prohibited under Article 6 of the 2006 London Protocol, which may cause difficulties for the development of CCUS technology. An amendment adopted in 2009 addressed this issue by providing for the cross-border transport of CO_2 and disposal if the countries involved in the transboundary transport of CO_2 into their bilateral arrangements and agreements (IMO, 2009). Since the London Protocol requires a two-thirds majority of vote for entry into force, the amendment has not yet been obtained (Rein, 2022).

Currently, cross-border transport of CO_2 is achieved by allowing the 2009 amendment to be applied provisionally pending the entry into force of the Contracting Parties that deposited the provisional application declaration of the amendment (IMO, 2019).

4.1.1.2 The Guidelines

Within the framework of the London Protocol, IMO also developed two guidelines. In the year 2006 when the Protocol was into force, the “Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures” was developed, providing for countries the environmental risks of CO_2 Sequestration in Sub-Seabed Geological Structures (CS-SSGS) for assessments and the management strategies catering to it (IMO, 2006a). The 2009 amendment to the London Protocol was to make carbon capture and transboundary transport possible, and therefore the 2012 Specific Guidelines for Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations (LC 34/15, annex 8) was developed to regulate such activities. It presents advices on how to capture and sequester CO_2 in a manner that is relevantly environmental-friendly to the ocean. The CO_2 allowed for geological storage should take into account its source, quantity and composition; physical and chemical properties and environmental impact, etc., and shall be licensed by the Parties and reported on regularly. The unified reporting format is shown in IMO Report LC/SG 31/16 (Annex 8).

In general, the London Protocol imposes requirements on marine geological storage of CO_2 and adjusts to the needs of technological development. Due to the insufficiency of countries that adopted the 2009 amendment, with only Korea, the Netherlands, Denmark and Norway formally submitting their provisional declarations of application as of 2021, the cross-border transport of CO_2 still lacks a unified international solution. As CCS technology matures and OCCS technology continues to be explored, the status quo of relying mainly on bilateral agreements or arrangements rather than internationally harmonized standards for management should change.

4.1.2 Safety-Related Standards: The IGC Code

Currently, there are no specific regulation for the installation and operation of OCCS equipment on ships. The International Code for the Construction and Equipment of ships Carrying Liquefied Gases in Bulk (IGC Code) for the transport of CO_2 should be followed for retrofitting ships for the function of storing and transferring the captured CO_2. The IGC Code became mandatory in 1986 through SOLAS Chapter VII and provides international standards for the construction and equipment of ships carrying liquefied gases at sea in order to ensure safe navigation and reduce potential pollution. Chapter 19 of the Code covers the minimum requirements for the transport of CO_2 (High Quality) as well as CO_2 (reclaimed quality), including the need to equip at least a type 3G ship (the simplest form of gas carrier with moderate leak-proof protection measures) and to comply with the special requirements of paragraph 17.21 and 17.22 respectively. Special attention should be paid to the "triple point" of CO_2 cargo, i.e. the temperature and pressure at which the solid, liquid and gaseous states coexist in thermodynamic equilibrium (Engineering ToolBox, n.d.). The phase diagram of pure CO_2 is shown below in Figure 12. According to the special requirements of 17.21 of the IGC Code, continuous monitoring of the CO_2 concentration shall be guaranteed to ensure that the pressure of the cargo tank storing CO_2 reaches 0.05 MPa above the triple point pressure.

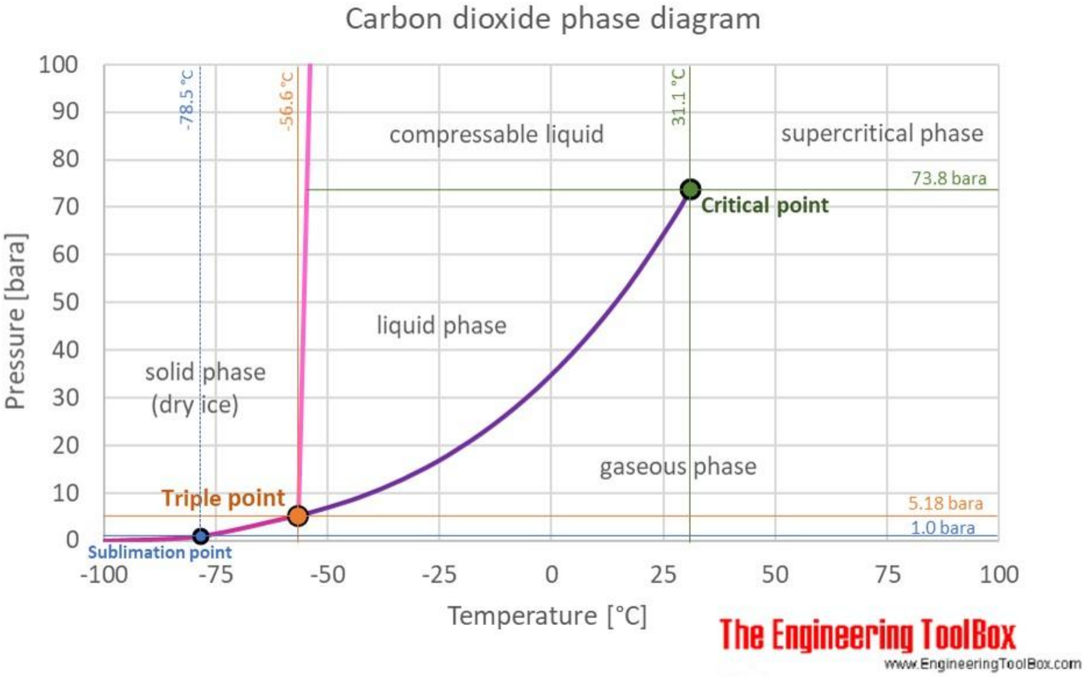


Figure 12: Carbon Dioxide Phase diagram

Source: Engineering ToolBox, (n.d.), Carbon Dioxide - Thermophysical Properties, https://www.engineeringtoolbox.com/CO2-carbon-dioxide-properties-d_2017.html

It has been suggested that OCCS technology may be implemented on gas carriers first because they already have well functioned systems for the safe transport, handling and conditioning of captured CO_2 (MEPC 79/7/16, 2022). What is more, concerning the safety issues of CO_2 transport and storage onboard, the vessels for CO_2 barging and transfer are more similar in structure to the 3G class of vessels to which the IGC rules apply.

4.1.3 MARPOL-Related Standards

4.1.3.1 Requirements on EEDI, EEXI & CII

Air pollution control, including greenhouse gases, is regulated in the International

Convention for the Prevention of Pollution from Ships (MARPOL) Annex 6, which includes provisions that may be affected by the installation of new OCCS equipment, including Article 24 on EEDI, Article 25 on EEXI, and Article 28 on CII. EEDI and EEXI promote energy efficiency and reduce GHG emissions from shipping by reflecting the level of ship energy efficiency. The CII records the actual operational carbon intensity of a ship and is rated for management by the competent authorities. Calculation on these indices apply the Tank-to-Wake (TtW) methodology, which could not reflect the CO_2 capture factor on board in the current formula (MEPC 79/7/22, 2022).

The application of OCCS system results in additional CO_2 emissions due to the CO_2 capture operation of support systems (e.g., ventilation, heating, compression processes). Thus, it would result in lower energy efficiency performance and higher operational carbon intensity of the ships in the current algorithm without considering the carbon absorption effect of OCCS equipment, which is clearly inconsistent with the original intention to accelerate carbon reduction in shipping. Therefore, from the perspective of regulatory improvement, the calculation of EEDI, EEXI, and CII needs to be revised to correctly reflect the energy efficiency and carbon intensity levels of ships operating OCCS equipment.

Before the completion of the regulatory update process, the authority can issue exemptions related to these system tests according to paragraph 2 of Article 3 of the MARPOL Convention, Annex VI, to encourage and promote the sea trial activities of shipping green transformation technologies such as OCCS. There are currently no internationally harmonized exemption guidelines under clause 3.2, so the uniform approach to grant such exemptions should be developed that could be issued by maritime authorities to ships trailing OCCUS technology.

4.1.3.2 The LCA Guidelines

In addition to the EEDI, EEXI, and CII related regulations analyzed above, the formulating Guidelines on Life Cycle GHG Intensity of Marine Fuels (LCA Guidelines) applies the Well-to-Wake methodology, i.e. the combination of a Well-to-Tank (WtT) part and a TtW part, which assesses emissions from the fuel production to the end-use by a ship. Such a methodology shall also incorporate the effects of OCCS capture into the calculation.

4.1.4 Potential Incentive Policies

Reporting carbon reductions from the use of OCCS technology to a data collection system, and possibly subtracting them from the calculation of vessel emissions, could be used for possible future development of MBM, such as a carbon trade system or a tax-levy system.

To sum up, the MARPOL Convention does not currently cover CO_2 captured onboard into part of the ship waste, and there is a lack of international regulations for CO_2 captured reception facilities in ports, as well as technical guidance for the design, transport and offloading of captured products from the OCCS system. The provisions of the MARPOL Convention are yet to be updated and developed with regard to energy efficiency, carbon intensity calculation, and new technology seaworthiness exemptions.

4.2 Discussions at the IMO Meeting

The discussion on CCS in the shipping industry has appeared in IMO meetings in the last two years. At the 76th meeting of the MEPC Committee in 2021, Korea submitted two documents for the first time, arguing that the application of CCS technology onboard ships may play a positive role in reducing GHG emissions from shipping, and proposing amendments to the existing GHG rules. While at the latest meeting, the 79th meeting of MEPC committee (MEPC 79) in 2022, China, Norway, Korea and other countries submitted a total of 7 documents covering technical discussions and regulatory development advices for OCCS, which were deferred to the next meeting. MEPC 79 pointed out that the accounting, storage and disposal of OCCS technology, as well as the related certification scheme, should be considered by a holistic approach to ensure that the technology achieves the carbon reduction effect and the captured carbon is not released back into the atmosphere.

4.3 Departmental Regulations on OCCS

As the pace of OCCS technology trials and evaluations accelerates worldwide, the American Bureau of Shipping (ABS) has taken the lead in 2022 with the release of *Requirement for Onboard Carbon Capture and Storage*, the first regional OCCS technology rule, which sets out the requirements for the Classification approval on wet scrubbing post-combustion technology of carbon dioxide capture. Additional statutory requirements and approvals will be required for flag administration of vessels using OCCS systems （ABS, 2022）. The requirements regulate the arrangement and installation of OCCS systems onboard, and propose separate functional standards for the capture and absorption systems, the CO_2 compression and refrigeration systems, and the monitoring and alarm systems. The regulation also provides for the requirement on the survey of OCCS systems during the manufacturing, installation and testing phases.

Harmonization of technical requirements is difficult due to the wide range of OCCS technology applications, the wide variation in the construction of different principal equipment, and the potential use in combination with other EEA equipment.

However, the ABS effort still plays an essential normative role for the wet scrubbing post-combustion CO_2 capture technologies, which are most likely to be further developed in shipping. At the same time, the development of technical requirement also plays a significant role in inspiring the refinement of the regulatory system and increasing market and community awareness of the OCCS technology.

4.4 Overview of the current legal structure

The analysis in sections 4.1-4.3 cover current international norms related to OCCS technology as well as regional guidelines. The legislative structure of the system is shown in Table 4. The international legislation relating to cross-border transport of CO_2, sequestration, transport safety and anti-pollution needs to be further revised to meet the technological development. The departmental specialized rules in the regulation of post-combustion capture technology provide regulatory experience and inspiration for possible OCCS-specific legislation from the international aspect.

Table 4: Current status of OCCS legal regulation

Type	Field	Rules	Need of efforts
Relevant international legislation	cross-border transport & sequestration	London Protocol	Continue the process of legalizing cross-border transport and sequestration
	Transport safety	IGC Code	Revise as appropriate when CO_2 capture and storage requirements are clarified
	anti-pollution	GHG rules (EEDI/EEOI/CII)	Revise to cover the role of the OCCS
Departmental specialized legislation	Installation, maintenance, & survey	ABS regulation	Provide legislative experience
		ClassNK guideline	

4.5 Policy Recommendations

4.5.1 General structure needed

The current status of OCCS-related legislation reveals that there is a lack of regulation and norms in the shipping sector. Regulations for new technologies may include the development of new specialized rules as well as the modification of existing provisions. The proposed legislative framework is shown in Figure 13. Regarding the development of new standards, on the one hand, there is a need to implement uniform and operational exemptions considering the difficulties in complying with existing shipping carbon reduction policies for new OCCS technology trial voyages; on the other hand, standards regarding the installation and operation of the OCCS equipment, the verification and certification of its effectiveness, and the onshore reception facilities need to be uniformly regulated. Regarding the revision of existing policies, the calculation of EEDI/EEXI and CII should take into account the emission reduction effect of OCCS; and the implementation of revised and developed technical regulations also needs effective supervision by the authorities, which shall be updated in the survey and inspection guidelines.

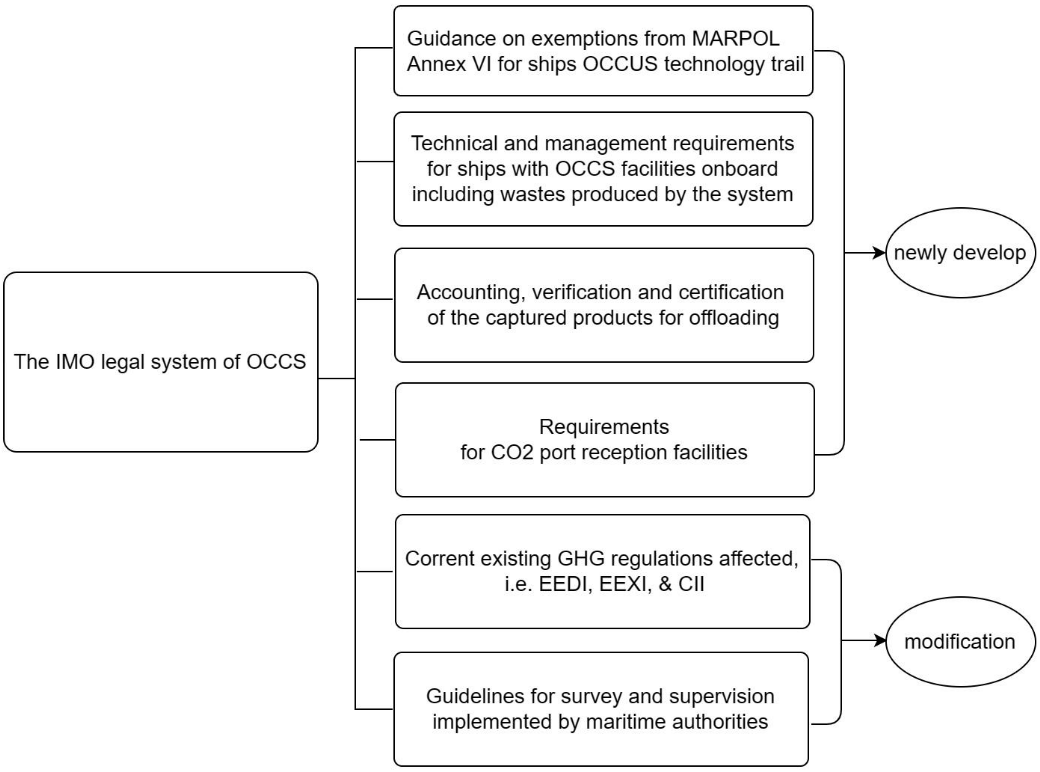


Figure 13: Proposed legal structure of OCCS from the IMO aspect

Source: compiled by the author

4.5.2 Actions for the first stage

Since the current OCCS technology is mostly in the experimental stage and the experience of real shipboard application is not yet mature, it is proposed to carry out the OCCS legislation in two stages. In the first stage, the development of exemption guidelines for trailing ships, the classification of the captured products should be of priority, and the verification and certification of the captured products should be regulated so that the calculation on EEDI, EEXI and CII could be modified to be more accurate.

According to paragraph 2 of Article 3 of the MARPOL Convention, Annex VI, maritime authorities could issue an exemption from specific provisions for ships to conduct trails for the technological development of GHG emission. It is proposed to develop the guideline for exemption of ships testing OCCS systems from certain energy efficiency control and emission reduction requirements under the MARPOL convention. In the guidelines, it is proposed to exempt MARPOL Convention 24,25,28 and to clarify the process of granting exemption by maritime authorities. In the prescribed process, the ship owner or operator should provide information on the exemption condition, such as the arrangement plan and the test objectives; while the maritime authority should review the application materials and carry out a survey to confirm whether the actual situation onboard meets the exemption conditions, and grant an exemption on the basis of satisfactory results. The guidelines may also set the format of the exemption.

The classification of capture products and the verification of their purity and quality should also be carried out as well. In the absence of clarity, the captured CO_2 products may be inadvertently classified as a hazardous material (commodity) or pollutant (waste) onboard (IEA, 2022) , which affects whether the OCCS-specific regulation is hazardous material management or anti-pollution rules. Although there is a possibility of air pollution, the captured carbon dioxide is more suitable to be a dangerous product and a commodity. Therefore, the possible OCCS technology legislation shall be also more concerned with the safety issues in installation and operation management. In addition, the verification of the capture products is also the focus of the stage. The application of different OCCS systems differs in the proportion of CO_2 and the type and impact of impurities in the capture products. With reference to the management of hazardous materials, different proportions of capture products shall be subject to different standards for landed disposal. Recording and monitoring requirements should be defined in order to verify OCCS system compliance and actual CO_2 capture levels. The verified CO_2 capture can be discounted in the CII calculation to more accurately reflect the carbon intensity level of the ship. In contrast, the EEXI and EEDI calculations use one-off certification, pending more adequate results of test projects to provide accurate discount factors (IMO, 2022).

4.5.3 Actions for the second stage

In the second stage of legislation, when more experience in testing is obtained, specialized rules for OCCS should be formulated. The development of OCCS requirements should not limit the direction of technological development by restricting specific technological paths, but should be guiding and functional norms. In this regard, the EGCS guidelines can be a reference. Since the engineering technologies of different manufacturers vary greatly, the exhaust gas cleaning system (EGCS) guidelines are based on the performance of the equipment, not on the design. The EGCS system compliance is verified through periodic emissions check or real-time monitoring, and requires rigorous monitoring records and data reporting procedure. The specification for OCCS technology should focus on whether the capture performance is achieved, with attention to the safety level of system installation and operation, and ensure compliance through inspection, monitoring, and certification procedures. Requirements for port reception facilities are likely to be developed based on more experience practices shared by countries and consider regulatory convergence with land-based CCUS rules.

4.6 Concluding remarks

The purpose of this section is to explore the recommendations for the OCCS technology regulation. The current status of policies related to OCCS technology is analyzed, and it is recognized that some of the regulations need to be improved and revised, while new specialized legislation needs to be developed. The IMO discussion on OCCS technology is reviewed, and it is found that some countries that have carried out OCCS projects are in an active manner in advocating the sorting and updating of relevant IMO instruments. Finally, policy recommendations are made for international legislation on the OCCS technology, including a regulatory framework and two stages of regulatory revision focus. It is emphasized that the improvement of legislation should not restrict the choice of technology paths, but should remove regulatory barriers.

Chapter 5 Conclusion

As the global decarbonization process accelerates, carbon capture methods become a potential transition initiative for GHG emission reduction in shipping. This paper focuses on the development status and potential of the OCCS technology. It attempts to provide an overall evaluation of the application of OCCS technology through literature analysis, technical principal elaboration, economic analysis and FSA-based risk analysis, to argue the necessity and feasibility of policy measures to regulate the use of such technology, and to propose the direction of policy development.

This paper collects the hot spots of OCCS technology research in recent years and lists the characteristics of trail projects conducted worldwide. The entire supply chain of OCCS system capture, consisting storage, transportation and utilization sections, is presented, and the principles and characteristics of pre- and post-combustion capture methods for OCCS systems are illustrated with typical cases. In general, research and studies focus on improving the technical principles and structure of the OCCS systems, while pilot projects on a global scale focus on technical feasibility verification and cost reduction. Based on the current state of the OCCS technology development, it is recognized that the process of its technological development needs to be better evaluated to justify the need to develop a matching international regulatory process.

In this paper, the prospects for the OCCS technology and the need for policy measures are assessed in terms of economic and risk analysis. In the economic analysis, the cost of the OCCS system is analyzed from the COPEX, the VOPEX and the FOPEX, and the potential profit is analyzed from the sale of capture products and the offset of carbon emission costs. By comparing the results of existing cost estimates, the overall level of carbon capture cost control and capture effectiveness is derived. In the safety analysis, the potential risks in terms of technology, personnel, operation and environment are analyzed using the FSA method, and the risk levels are evaluated, pointing out the need for regulatory actions to control the risks.

Finally, this paper explores the policy measures for the OCCS technology. Firstly, the current conventions and departmental guidelines regarding the OCCS technology are listed. It is pointed out then that the improvement of the legal framework shall include the revision of existing rules to remove regulatory barriers, and the formulation of specialized rules to facilitate the development of the technology. Finally, a six-part legal framework is envisioned and it is recommended that the policy framework for the OCCS technology should be developed according to two stages.

OCCS technology is updated and developed very rapidly, and this paper attempts to outline the latest level of technological development and to make reasonable evaluation to its prospects. With reference to the economic and safety analysis methods of onshore CCUS technology, innovative assessment is presented for the application of the OCCS technology to the shipboard working environment. In terms of policy measures, only new departmental specialized guidelines by ABS and ClassNK are issued, and this paper presents the first proposal for policy development from a global legislative perspective, which is of value for possible technical regulation development. However, due to the limitation in the information obtained and individual capacity, the comprehensiveness and completeness of the OCCS technology development assessment and policy development is limited. The policy approach shall be refined as the OCCS technology development becomes more mature.

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