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Study on Exploring Technical Strategies for Deployment of Ship-Based Carbon Capture Systems in the Marine Industry to Capture Emitted Carbon Dioxide (CO_2) from Marine Diesel Engines to Meet IMO Green House Gas (GHG) Goals 2050

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Abstract

The International Maritime Organisation (IMO) has established aggressive targets for reducing greenhouse gas (GHG) emissions within the maritime sector as a means of addressing the challenges posed by climate change. The use of ship-based carbon capture systems has emerged as a potentially effective approach to capturing carbon dioxide (CO2) emissions released by marine diesel engines. This technology has promise in aiding the International Maritime Organisation (IMO) in achieving its greenhouse gas (GHG) reduction targets by the year 2050. The present study investigates a range of technological approaches for the implementation of carbon capture systems within the maritime sector.

The research starts by emphasising the significance of ship-based carbon capture systems in mitigating CO2 emissions originating from marine diesel engines, taking into account the substantial role played by the shipping sector in world emissions. This paper aims to present a comprehensive analysis of marine diesel engines and their associated emission characteristics in order to get a deeper understanding of the challenges they pose and the possibility for implementing carbon capture technologies.

This study provides a comprehensive examination of several ship-based carbon capture techniques, encompassing amine scrubbing, mineral carbonation, cryogenic separation, and other nascent technologies. The evaluation encompasses an analysis of the strengths and limits inherent in each system, taking into account several criteria like energy consumption, scalability, and technology readiness.

This study investigates the incorporation of carbon capture systems into ships, focusing on the specific obstacles posed by spatial constraints, weight limitations, and the requirement for optimal performance during ships operations. This paper examines the technical issues and techniques that contribute to the effective deployment of systems aboard ships. It explores several aspects such as system design, installation methods, and compatibility with existing infrastructure.

In summary, ship-based carbon capture technologies have significant promise in mitigating CO2 emissions originating from marine diesel engines, therefore aiding the maritime sector in achieving the International Maritime Organisation's objectives for greenhouse gas reduction. This study offers useful insights into the practicality, optimisation, and safety issues of putting carbon capture systems aboard maritime vessels through the exploration of several technological options for their deployment. The results of this investigation make a valuable contribution to the advancement of sustainable and efficient strategies that will propel the shipping sector towards a more environmentally friendly and sustainable trajectory.

Keywords: Carbon capture, Marine Diesel Engine, Shipping, Technology

Contents

Abbreviations

ABS	American Bureau of Shipping
A3C	Advanced Cryogenic Carbon Capture
ASU	Air Separation Unit
BDC	Bottom Dead Centre
CAPEX	Capital Expenses
CC	Carbon Capture
CCC	Cryogenic Carbon Capture
CCR	Carbon Capture and Reuse
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CVI	Content Validity Index
DAC	Direct Air Capture
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
EEA	Exhaust Emission Abatement
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
e-fuel	Electro Fuel
EOR	Enhanced Oil Recovery
EPRI	Electric Power Research Institute
EU	European Union
EU MRV	European Union Monitoring, Reporting and Verification Scheme
GHG	Greenhouse Gas
GM	Metacentric Height
GT	Gross Tonnage

HFO	Heavy Fuel Oil
IACO	International Civil Aviation Organisation
IACS	International Association of Classification Societies
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGCC	Integrated coal Gasification Combined Cycle
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LNG	Liquid Natural Gas
MCFC	Molten Carbonate Fuel Cell
MEPC	Marine Environment Protection Committee (IMO)
MDO	Marine Diesel Oil
NSGA	Non-dominated Sorting Genetic Algorithm
NTQ	New Technology Qualification
OCCS	Onboard Carbon Capture and Storage
OPEX	Operational Expenses
PEMFC	Proton Exchange Membrane Fuel Cell
PIS	Participant Information Sheet
PSA	Pressure-Swing-Adsorption
SBCC	Ship-Based Carbon Capture
SBSTA	Subsidiary Body for Scientific and Technological Advice
SOFC	Solid Oxide Fuel Cell
TDC	Top Dead Centre
TRL	Technology Readiness Level
TSA	Temperature-Swing-Adsorption
UNFCC	United Nations Framework Convention on Climate Change
US SSFC	US Ship Service Fuel Cell
VLCC	Very Large Crude Carrier

WHR	Waste Heat Recovery
WtW	Well to Wake

Chemical formulae

CaCO3	Calcium Carbonate
CaO	Calcium Oxide
Ca(OH)2	Calcium Hydroxide
Ca2SiO4	calcium silicate
CaSiO3	Wollastonite
CH4	Methane
CO2	Carbon Dioxide
H2	Hydrogen
H2O	Water
H2S	Hydrogen Sulphide
MDEA	Monodiethanolamine
MEA	Monoethanolamine
N2	Nitrogen
N2O	Nitrous Oxide
NH3	Ammonia
NOx	Nitrous Oxides
O2	Oxygen
PZ	Piperazine
SO2	Sulphur Dioxide

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CHAPTER ONE

1.0 Introduction

1.1 Background

Marine Diesel engines which run on fossil fuel mainly of Heavy Fuel oil consisting of residual particles and sediments coming out of the refineries are fed into the propulsion of mammoth merchant vessels in maritime sector for last few decades. Continued use of these high-density residual fuels have made shipping transport cost effective and most of the world shipping fleet is presently running on these low-quality fuels (Elkafas et. al., 2022). The emitted exhaust gas imposes a great risk towards our environment, and it is continuing to exert intolerable risks to human society if no steps are taken in coming days.

The industry and stakeholders are researching actively to allocate alternative propulsion fuel in order to get rid of this dirty fuel from marine use. However, to solve these issues, the industry is in the process of adopting to use hydrogen, ammonia, methanol, or methane as probable alternative fuel.

On the other extreme end, the researchers are trying to develop Hydrogen powered engine, Fuel cells, battery powered propulsion etc. on the compelling ground, the use of nuclear power in marine field is becoming an increasingly compelling alternative to some stakeholders (The International Transport Forum, 2018).

Researchers and stakeholders are dedicating the resources to find a solution or combination of alternative fuels which shall bring solution to reduce carbon footprint from marine transport sector. The solutions are still cumbersome for understanding by the industry, rather shipping is becoming confused.

To adopt the alternative fuels and developing technologies such as Hydrogen fuel, green ammonia, methanol, methane and or to the extreme nuclear fuel option requires major modifications to the ships and the logistics of fuel distribution and bunkering. Some of the fuel such as ammonia and hydrogen have major safety concerns. The main purpose of this research is to ascertain the possibility of using carbon capture (CC) technology in ships.

1.2 Aim

The objective of this thesis is to gather information on carbon capture (CC) technology and assess their potential for use aboard maritime vessels.

Given the top-down methodology employed in this thesis, data is being gathered with the aim of identifying overarching technological trajectories for carbon capture (CC). This encompasses both commercially utilised technologies and those that are currently in the developmental stage. In addition, plans are formulated for the advancement of onboard CC applications. In addition to discussing the technological setup and fundamental operational principles of each carbon capture (CC) technique, the objective of this thesis is to provide comprehensive data on the competitiveness, spatial considerations, energy needs, maturity level, and unique benefits and drawbacks associated with each CC technology.

A comparative evaluation of the identified carbon capture (CC) technologies is conducted based on the collected data, with particular emphasis on their use aboard merchant vessels. During the initial phase, the study focuses on evaluating the feasibility of the selected technologies for onboard operation in a broad sense. The subsequent phase involves deliberating on which of the viable technologies holds the most promise for implementation on board. The technology that has been assessed as the most promising is considered the optimal choice in relation to the recognised limitations of the onboard machineries. Due to the distinct requirements associated with retrofitting such equipment, the assessment process differentiates between newbuilding and retrofit applications.

Hence, the focus of this study is restricted to technologies that are compatible with internal combustion engines (ICEs).

The critical discussion revolves around the assessment's findings, specifically examining the viability of carbon capture (CC) for various types of ships and the level of development of the selected CC technologies. Furthermore, there is ongoing discourse on the correlation between the technology that is considered optimal in the evaluation process and the technology that is most likely to be implemented in the field of merchant shipping.

1.3 Research Questions

In accordance with the stated aims, the present study poses the two broad questions:

Which technologies show the best potential for carbon capture on board ships when used in conjunction with internal combustion engines?

What are the significant restrictions, constraints, and criteria that are crucial for the practicality and effectiveness of CC technology implementation on board vessels?

With the aim of finding answers to above questions, it is further subdivided to following specific question areas.

1. What are the existing carbon capture technologies and their applicability to ships, considering factors such as vessel type, engine compatibility, and integration into ship structures?

2. How do different carbon capture systems perform in terms of efficiency, reliability, and maintenance requirements when implemented on ships?

3. What are the barriers and challenges to implementing carbon capture on ships, and how can they be addressed?

4. What are the perspectives of different stakeholders regarding the adoption of carbon capture technologies on ships, and how can acceptance be fostered?

5. What are the policy and regulatory frameworks needed to promote and support carbon capture technologies in the maritime industry?

6. What are the best practices and lessons learned from successful carbon capture projects on ships, and how can they inform future implementations?

7. What are the key recommendations?

1.4 Limitations

The researcher has encountered limitations in terms of the data accessible in existing literature and the data supplied by stakeholders who were interviewed. These limitations were necessary to establish a robust foundation for the evaluation of prospective climate change strategies. The aims of the thesis and the accompanying assessment have been constrained. The primary focus of this thesis is on carbon capture (CC) technology themselves, while excluding any discussion of alternative methods for the storage and use of CO2. The environmental and climatic effects of CC technology are discussed in the background section, but they are not taken into account as a criteria in the assessment. This is because the impact is heavily influenced by the subsequent use or storage of the collected CO2. Moreover, the consideration of social issues, such as the level of acceptance of carbon capture and storage (CCS) in society, is not included in the analysis.

1.5 Methodology

This section elucidates the methodologies employed by the writer to get, analyse, and appraise the necessary information for addressing the study inquiries. Data has been gathered through a comprehensive examination of relevant literature and by conducting interviews and surveys with specialists and potential users of these technologies. A method for conducting a comparative assessment has been devised and provided in Chapter 2.

CHAPTER TWO

2.0 Methodology

2.1 Introduction

This chapter aims to critically assess the procedures employed in this study, encompassing the data collection methods, sampling tactics, and ethical considerations. Therefore, this chapter has presented a comprehensive review of the research, a well-defined methodological framework, and a thorough examination of the data collection procedures, all of which have been fully addressed, justified, and evaluated. Bryman and Bell (2020) assert that research is a methodical undertaking that encompasses several approaches aimed at generating findings through the examination of preexisting information, while also taking into account ethical considerations. This chapter elucidates the many stages of the research process by employing the research onion model (Figure-2.1) proposed by Saunders et al. (2020). This chapter also presented a solid rationale for the specific choices of research procedures that are pertinent to the study aim and objectives.

Figure 2.1 Research onion model, adapted from, Saunders et al., (2020)

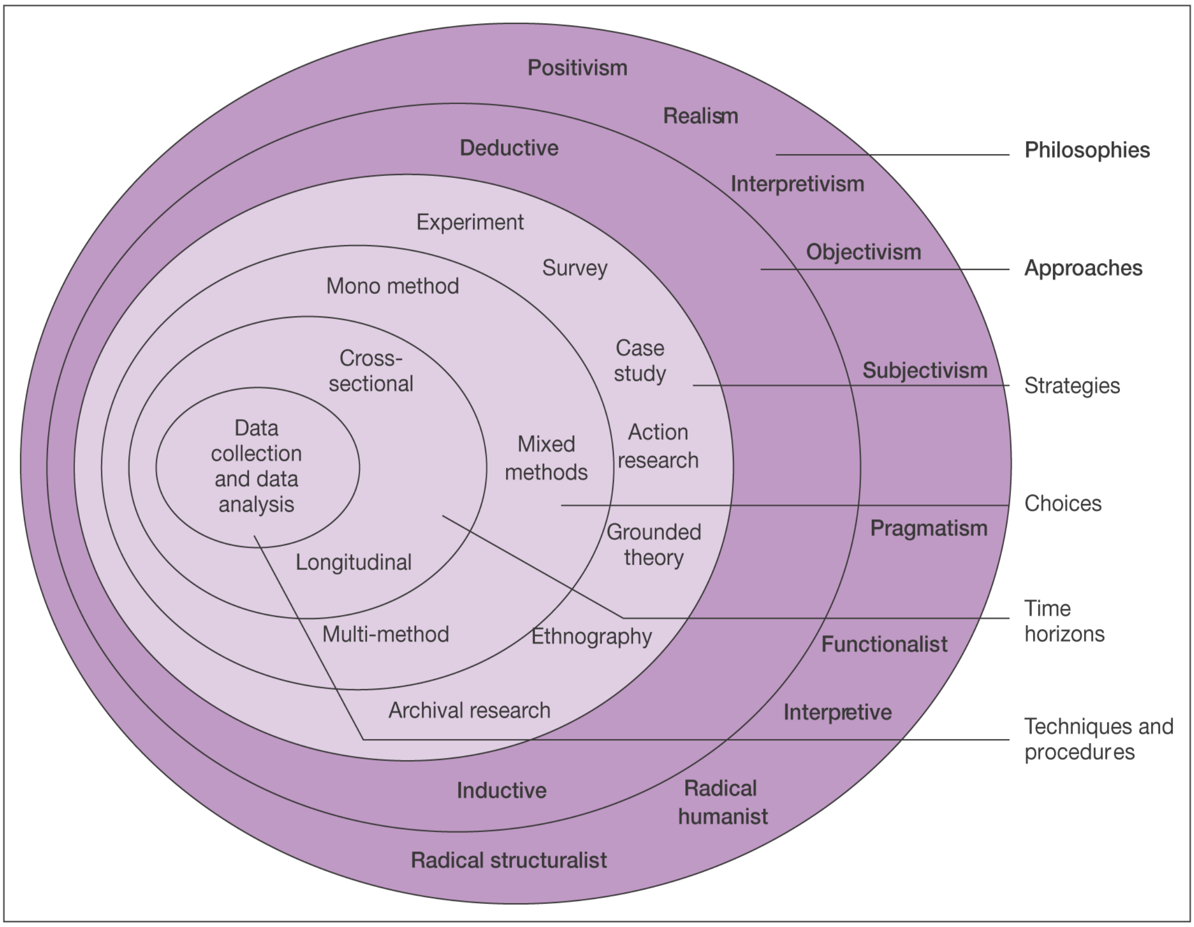


Figure 2.1 depicts the key steps for conducting this research including research philosophy, approaches, strategies, choices, time horizons, and the key techniques and procedures used in this research. Lastly, this chapter constructs a comprehensive examination of the triangulation relationships among various variables, to deliver quality research.

2.2 Research philosophy

Collis and Hussey (2019) claim that research philosophy encompasses a comprehensive understanding and system of convictions derived from the examination of knowledge, reality, and existence. Saunders et al. (2019) argue that positivism employs an impersonal voice, as it embraces the use of quantitative language. In contrast, interpretivism is a theoretical framework that relies on the analysis of evolving decisions as perceived by individuals, using established qualitative terminology (Gilbert, 2019).

The chosen research approach for this study is interpretivism, since it aligns with the purpose of acquiring pertinent data and knowledge. This approach is suitable for conducting an in-depth analysis of individuals' perspectives and attitudes regarding carbon capture in the maritime industry.

2.2.1 Justification:

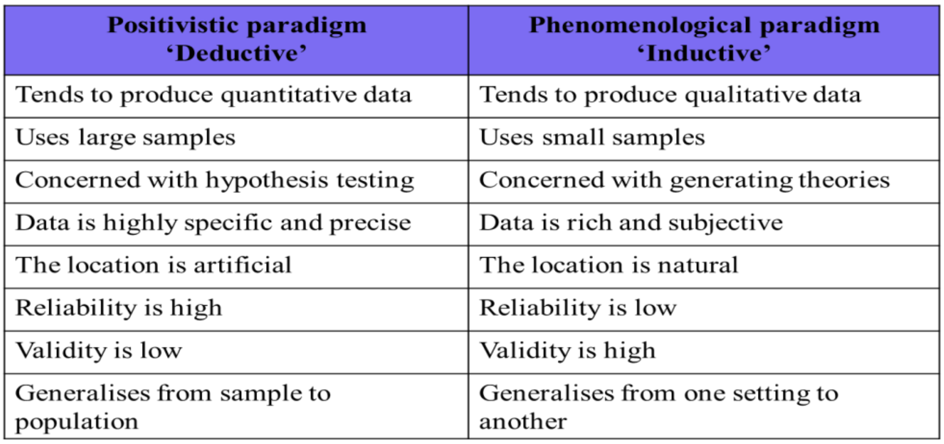
The rationale for choosing interpretivism as the philosophical framework for this study is in its emphasis on human interceding, particularly in relation to individuals' perceptions and perspectives, in the pursuit of applicability of CC within the maritime sector. According to Collis and Hussey (2020), the interpretivist theory centres around comprehending individuals' behaviours or views through the utilisation of a customised subjective frame of reference. Nevertheless, it is important to acknowledge that interpretivism may not fully capture the true perspectives or perceptions of the individuals being studied (Gill and Johnson, 2020). Hence, the utilisation of interpretivism philosophy appears to be more applicable in the context of this study, as it enables the provision of logical justifications and interpretations for the selected research issues through the examination of diverse themes derived from the perspectives of the participants (Creswell, 2020). The interpretivism philosophy was chosen for this study due to its suitability for conducting a theme analysis and its compatibility with qualitative methodologies, which facilitated the attainment of the research objectives.

2.3 Research Approach

The utilisation of the inductive strategy was deemed necessary for drawing conclusions, while the deductive approach was employed to display the outcomes and conduct data analysis (Gilbert, 2019). According to Saunders et al. (2020), the inductive technique involves analysing circumstances by starting with wider ideas and then developing theories, while the deductive approach begins with theories and evaluates them against specific ideas to determine their validity, falsity, or partial support. The present study has employed an inductive technique, which has been recognised as a valuable method for examining individuals' opinions and perspectives on the adoption of Green House Gas GHG) abetment methods within the maritime industry.

Table 2.1 illustrates the fundamental distinctions between the inductive and deductive methodologies. For example, the deductive approach is inclined to generate quantitative data by utilising extensive samples and focuses on hypothesis testing (Collis and Hussey, 2020). On the contrary, the inductive approach is characterised by its tendency to yield qualitative data through the use of limited sample sizes and a focus on theory generation (Saunders et al., 2020). Nevertheless, the data obtained by deductive methodologies exhibits a notable degree of specificity and precision, as well as a shown level of reliability (Malhotra & Dash, 2020). In contrast, the inductive technique places emphasis on the utilisation of extensive and subjective data, which results in a relatively lower level of reliability compared to the deductive approach (Gill and Johnson, 2020). Hence, the present study has opted for inductive research methodologies in order to augment the credibility and dependability of the study's findings and outcomes.

Table 2.1 Deductive vs. Inductive Research, adapted from, Saunders et al., (2020)

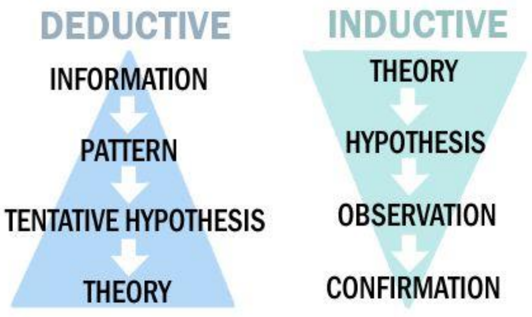


Positivistic paradigm ‘Deductive’	Phenomenological paradigm ‘Inductive’
Tends to produce quantitative data	Tends to produce qualitative data
Uses large samples	Uses small samples
Concerned with hypothesis testing	Concerned with generating theories
Data is highly specific and precise	Data is rich and subjective
The location is artificial	The location is natural
Reliability is high	Reliability is low
Validity is low	Validity is high
Generalises from sample to population	Generalises from one setting to another

2.3.1 Justification:

The inductive approach was deemed most appropriate for this study as it involved gathering information through interviews to develop conceptual understanding. These concepts were subsequently analysed using thematic analysis. As emphasised by Gilbert (2019) and Saunders et al. (2020), the inductive technique involves the exploration of novel concepts that arise from the research process. Hence, the utilisation of the inductive technique was deemed highly appropriate for the attainment of the specified objectives outlined in **Figure 2.2**.

Figure 2.2: Inductive vs. deductive approach, adapted from, Saunders et al., (2020)



Hence, the utilisation of the inductive technique facilitates the acquisition of a comprehensive comprehension regarding the diverse interpretations of the participants through the utilisation of qualitative data (Saunders et al., 2020). However, the inductive strategy involves utilising a conceptual framework as a foundation for doing research, which is aligned with the primary ideas identified in literature studies. Hence, the utilisation of the inductive approach in this study was intended to enhance the clarity and validity of the collected data.

2.4 Research design

According to Bryman (2020), research design encompasses the essential elements necessary for the collection and analysis of data. It serves as a comprehensive plan, structure, and set of practical considerations that guide the process of data gathering. Malhotra and Das (2020) have posited that exploratory and conclusive research designs can be equated with descriptive and causal research designs, respectively. According to Creswell (2020), several research designs, such as exploratory, descriptive, and causal, are employed based on the specific character of the research enquiry. Within the larger classification, the study design can be categorised into four distinct types: Analytical, Predictive, Descriptive, and Exploratory (Gilbert, 2019). The present study has employed Analytical and Descriptive research designs since they align with the attainment of the research objectives.

2.4.1 Justification of research design:

The chosen research strategy for this study is analytical and descriptive. This decision was made in order to establish a theoretical foundation on the concept with the aim of enhancing the understanding of causal linkages among various variables (Bradley, 2019). The utilisation of an analytical research design is appropriate for this study, since Saunders et al. (2020) have noted that this style employs open-ended questionnaires and identifies patterns to gain a deeper understanding of the subject matter under investigation.

In this study, descriptive investigations were employed to elucidate the theoretical underpinnings of the research issue, as discussed by Malhotra and Dash (2020). Conversely, the utilisation of the qualitative approach was employed to analyse and substantiate the data obtained in the descriptive study. Hence, the utilisation of a hybrid research design incorporating both analytical and descriptive approaches was deemed suitable for this study.

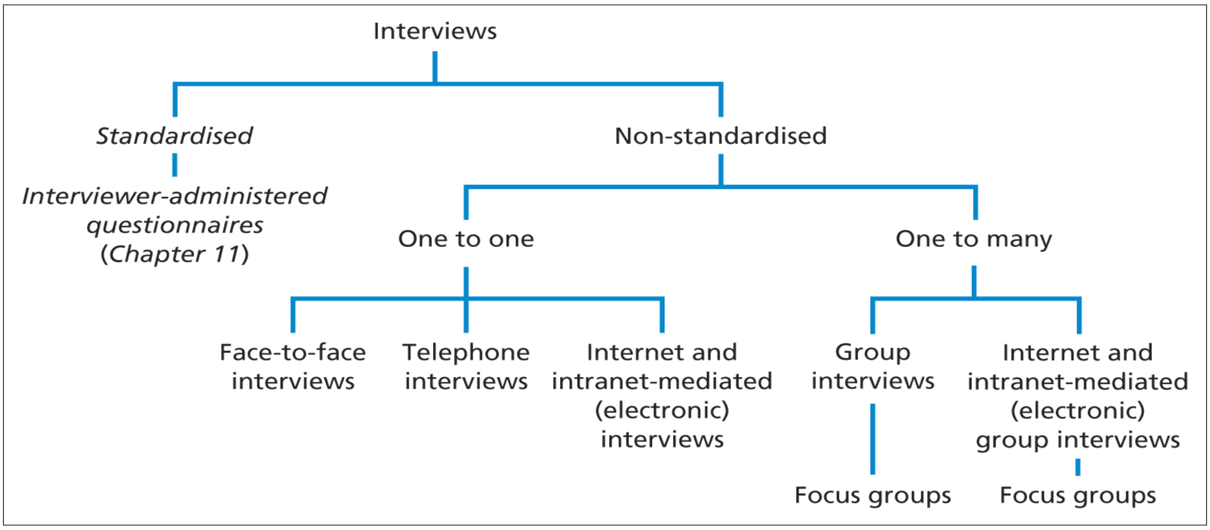
2.5 Research methodology and data analysis method

The objective of this research is to investigate the obstacles associated with the implementation of CC technologies within the maritime sector and to propose potential remedies for addressing this concern. In order to fulfil the purpose and goals of this research, interviews were done to collect pertinent data from the stakeholders involved in the case study. Additionally, a focus group interview was carried out to obtain a comprehensive understanding of the problems related to sustainability. In the field of business research, it is customary to employ two primary data collection methodologies, namely qualitative and quantitative approaches (Collis & Hussey, 2020). The data sources utilised in this study were obtained through interviews and focus group interviews conducted with specialists from the maritime sector. For the purpose of this study, a sample of twenty-five participants was chosen to collect data using interview questions (see Appendix 1). Additionally, a subset of five participants was selected to participate in a focus group interview.

2.5.1 Interview Method:

The present study has undertaken interviews with a total of twenty participants in order to collect their perspectives and impressions. Additionally, a focus group interview was conducted with a smaller subset of five participants to obtain a more comprehensive analysis of the selected research issue. Saunders et al. (2020) believe that the interview serves as a deliberate conversation involving multiple participants, designed to facilitate a comprehensive exploration of the research subject. A range of interview approaches is frequently employed in business and engineering research, encompassing semi-structured, structured, in-depth, and focus group interviews (Gill and Johnson, 2020).

Figure 2.3 Different forms of interviews

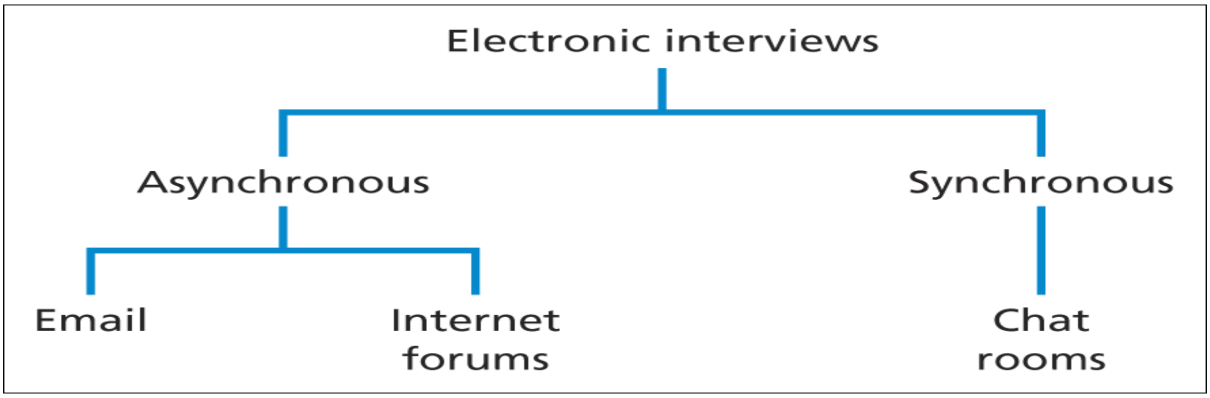


(Adapted from, Saunders et al., 2020)

The present study employed unstructured interview questions, specifically utilising a non-directive approach known as informant interviewing. This methodology allows the interviewers to be guided by the interviewee's perceptions in conducting the interviews. The approach described is characterised by its flexibility, since it allows for interviews to be done on an individual basis using various mediums, such as online platforms or face-to-face interactions (Collis & Hussey, 2020). This study has undertaken an exploratory research investigation, employing in-depth interviews as a suitable method to delve into insights and conduct a thorough analysis of the chosen research subject.

The researcher collected the data online by using social media and relevant notes were collected from the face-to-face interviews.

Figure 2.4 Different forms of online interviews



(Adapted from, Saunders et al., 2020)

This study employed asynchronous interview approaches, utilising data collection methods such as email correspondence and participation in internet forums, including those found on social media platforms. Utilising non-standard or qualitative inquiry methods, such as interviews, might yield comprehensive and intricate data pertaining to the selected research challenge.

2.6 Literature Review

A comprehensive understanding of CC technologies was acquired by a thorough examination of relevant scholarly literature.

In order to assure the reliance on peer-reviewed scientific publications for both literature reviews, Elsevier and Google Scholar were employed. The database provided by Elsevier B.V. encompasses a diverse array of scientific papers in the fields of science and engineering (Elsevier B.V, 2022). In order to refine the outcomes of each search and assure the continued relevance of the articles, the search parameters have been restricted to encompass the period from 2012 to 2022, spanning a duration of ten years.

The search phrase "carbon capture," AND "technology," were utilised inside the category keywords the purpose of conducting bibliographical research on currently existing carbon capture technologies. The abundance of scholarly publications serves as evidence for the extensive study conducted in the field of CC technology.

Specific search in Google Scholar with the key word ‘shipboard’ AND Carbon Capture’ AND ‘Technology’ making it time bound since 2019 resulted about 2170 results in January 2023. These vast number of articles and research papers were then scrutinised for relevance to carbon capture technologies in ships.

Therefore, the literature review has been bifurcated into two distinct sections. This study aims to conduct two comprehensive reviews. The first review focused on the current research on technologies for carbon capture (CC) in a general context. The second review specifically examined the existing research efforts pertaining to the use of CC technology on seagoing vessels.

2.7 Sampling Method

The non-probability sampling method was employed in this study due to the researcher's lack of knowledge regarding the total population number. Malhotra and Dash (2019) classify non-probability sampling into various categories, such as snowball sampling, purposive sampling, and convenience sampling. This study employed convenience sampling as a methodological approach, which facilitated the researcher's ability to conduct the research. Collis and Hussey (2020) argue that the convenience sampling method offers researchers a convenient means to meet their study objectives within limited time constraints. This approach is centred on selecting participants based on their accessibility and availability, allowing for a more efficient data collection process. Therefore, the study's sample size consists of 25 participants, with an unknown total population size. The respondents in this study are stakeholders within the industry. The individuals participating in this study are highly knowledgeable professionals within the maritime sector, possessing expertise that enables them to offer pertinent insights on the practical application of CC ideas.

2.7.1 Justification:

Convenience sampling is classified as a non-probability sampling technique, which is deemed most appropriate for this study due to the fact that the sample is selected depending on the researcher's discretion. Nevertheless, while employing convenience sampling, it is imperative for the researcher to exhibit a sense of assurance in rendering a judgement (Collis & Hussey, 2020). In contrast, convenience sampling involves selecting initial respondents who then refer other subjects, resulting in a significant reduction in research expenses (Saunders et al., 2020). The utilisation of this sampling strategy introduces an element of uncertainty regarding its ability to accurately capture a representative sample of the population, potentially leading to biassed results (Saunders et al., 2020). Fortunately, the convenience sampling method offers a more straightforward approach to data collection by delivering questionnaires to stakeholders within the world maritime community. A total of 25 participants were chosen for the purpose of this study. Tables 2.2 and 2.3 depict the respective roles and areas of competence of the participants who have actively participated in this research study.

Table 2.2 The sample group of the study

Respondent Group	**Positions**	**Roles and Expertise**
Flag State	Principal Surveyor, Senior Marine Engineer Surveyor, Senior Surveyor, Head of Department	Maritime policy lead, Survey and certification of ships structure and machineries as per international standards, Experts on technical maritime matters and international marine conventions.
Classification Society	Principal Surveyor, Regional Chief Executive,	Responsible for sustainable marketing and Maritime customer support. Expert in

	Surveyor	sustainable maritime business operations. Responsible for survey and certification of new building ships and existing ships as per classification rules and IACS requirements.
Ship Owner/Manager	Senior Technical Manager, Engineer Superintendent	Expert on ship operations, manages technical and operational issues of the fleet and the company. Actively involved in ship modification and retrofitting of new or equivalent machineries on board
Ship builder/ Repairer	Managing Director, Technical Director	Managing sales and operating sustainable maritime ship building and repair business.
Ship's Officer	Master, Chief Engineer, Tug Engineer	On board top management on operational and technical matters. Head of Technical management of ships machineries, responsible for sustainable operations of ships.
Other Stakeholders	Port Captain, Senior Lecturer	Specialists in maritime training and seafarers' professional examinations. Expert on port facilities and ships operations in port.

Table 2.3 The sample for the focus group interviews

Respondent	Position	Roles and Expertise
One	Engineering Examiner	Over 20 years of expertise in ship operations, certification of ships and flag state activities.
Two	Managing Director	Over 30 years of experience in shipping, ship repairing and ship building including customer insight.
Three	Emission Reduction Technology Specialist	More than 7 years of expertise in marine field, specially working on alternative marine fuels in a reputed maritime flag administration.
Four	Principal Surveyor	Over 25 years' experience in ship operations, certification of machineries, survey of ships, marine management system auditing.
Five	Senior Technical Manager	Over 35 years of experience in the marine industry including key position in marine fuel testing and advisories.

2.8 Validity

Bradley (2020) emphasised the importance of addressing validity concerns in the research process as it assesses the overall validity of the research. The measurement of validity involves evaluating the validity of data collection instruments, such as interview questionnaires (Collis and Hussey, 2020). In this particular study, the researcher conducted a pre-test of the questionnaires to ensure validity before engaging in actual data collection, thus avoiding any ambiguous results. Additionally, two members of the focus group were contacted in advance to assess the quality and relevance of the questionnaire for study participants. Due to limitations in time and resources, this study chose to utilise cross-sectional investigations instead of longitudinal studies.

2.9 Ethical Issues

Gill and Johnson (2020) emphasised the significance of ethical considerations in the research framework, as they contribute to the credibility and feasibility of the research. In this particular study, the researcher took a deontological perspective, employing an ethical approach throughout the entirety of the research process. The ethical considerations of this study encompassed the following variables in a general sense: -

This study was conducted solely for academic purposes and was not intended for any business or commercial objectives.

The research protocol incorporated measures to uphold anonymity and secrecy, thereby safeguarding the privacy of all people involved in the study. on general, the personal or confidential data were securely maintained on computers that required passwords for access. The important information contained within the data was safeguarded by conducting an analysis in a manner that was fair, consistent, and objective (Creswell, 2020). The data was subsequently destroyed subsequent to the publication of the paper.

Furthermore, this study ensured the avoidance of bias and refrained from publishing any personal information without obtaining prior consent from the participants, thus prioritising their well-being. The researcher ensured the preservation of anonymity, secrecy, and privacy by demonstrating decency and respect towards the participants (Saunders et al., 2020).

In particular, this study abstained from utilising any inaccurate or unofficial data that may potentially have adverse effects on the organisation. Instead, it relied on trustworthy sources and ensured that participants were not deceived (Creswell, 2020). Additionally, it will serve to prevent the inclusion of any data or content that has the potential to induce negative emotional states such as distress, anxiety, or embarrassment among the individuals included in the study.

The researcher demonstrated a conscientious approach by refraining from posing personal inquiries that could potentially elicit emotional distress. Additionally, the researcher employed suitable language and sought permission, so mitigating the risk of disseminating inaccurate information pertaining to the research subject.

2.10 Access Issues

This study examined the access issues that were considered.

The study adhered to ethical principles such as informed consent, the right to safety, and the option to withdraw. Consent was obtained from the participants, and written consent was also obtained from the researcher. The respondents were provided with a consent form, affording them the chance to participate willingly and seek clarification by asking questions.

The inclusion of a Participant Information Sheet (PIS) was crucial to the research procedure, as it provided participants with sufficient information prior to their involvement in the study. The participants will be provided with comprehensive information regarding the study, including a thorough explanation of the potential advantages and drawbacks associated with their involvement. Furthermore, an adequate amount of time was allotted to the participants, and a clear explanation was given to them regarding the objective of this study, as stated by Saunders et al. (2020).

Prior to engaging in the research procedure, participants were provided with informed consent and were afforded the opportunity to decline participation or withdraw from the study. In the event of participant withdrawal, the data is then discarded after a period of three months.

The researcher subsequently employed convenience sampling procedures in order to enhance the convenience of the data collection process. Additionally, a convenient period was designated for gathering feedback from the respondents.

In this study, participants were provided with an opt-out option, allowing them to choose whether or not to participate in the data gathering procedure. The researcher ensured that no pressure was exerted on any of the respondents throughout the data collection process.

2.11 Research Limitations

This study examined several research limitations, including: -

The present study was conducted within a restricted temporal scope, with the researcher adhering to the designated timeframe for data collection and analysis.

The research conducted in this study utilised a sample size of 25, which was deemed appropriate given the specific setting of the research and the limitations imposed by time and resources. Nevertheless, it would have been advantageous to include a larger number of responders in the study.

In this study, no expenses were allocated, and the researcher did the investigation under a limited budget. Additionally, the researcher has assumed the financial responsibility for the production of this paper.

2.12 Summary

This chapter provides an overview of the research processes employed in the present study. This paper elucidates the optimal approach to doing high-quality research through the assessment of reliability, validity, and ethical considerations in measuring. This study employed open-ended questionnaires along with targeted questions and conducted interviews with 25 respondents. This study used a qualitative methodology to investigate the obstacles associated with the implementation of CC system for merchant ships. This chapter elucidates the rationale for using the inductive strategy, since this study has opted for an interview method to do qualitative analysis. Hence, employing an inductive approach is most appropriate for attaining the research goals of this investigation.

This study has employed a thematic analysis approach and conducted qualitative analysis through a pattern or in-depth examination of the primary findings and outcomes. The utilisation of a mixed method is motivated by the objective of yielding outcomes that are both pertinent and acceptable, while also mitigating potential biases inherent in the research process. The subsequent chapter will provide an exposition of the findings, deliberations, and examination of this research endeavour.

CHAPTER THREE

3.0 Overview of Marine Diesel Engine and emissions

3.1 Emissions from Ships and Their Impact

According to Herzog (2000), fossil fuels presently fulfil over 85% of the global energy demand and are projected to remain plentiful into the twenty-first century. Their efforts have played a crucial role in the attainment of the developed world's elevated quality of life. We have acquired knowledge on the implementation of ecologically sustainable methods for extracting energy from fossil fuels, resulting in the reduction of pollutants such as NOx, SO2, unburned hydrocarbons, and particulates. Despite the implementation of these supplementary pollution measures, the cost of power generated from fossil fuels continues to decline. Shipping is not exempt from this trend, as it heavily relies on the consumption of fossil fuels for ship propulsion. Notwithstanding the favourable developments pertaining to fossil energy, its prospects are overshadowed by the environmental and economic risks associated with projected climate change, sometimes referred to as the "greenhouse effect." Carbon dioxide (CO2) is widely recognised as the predominant anthropogenic greenhouse gas, with its major origin being the burning of fossil fuels (Herzog, 2000).

Therefore, it is possible to develop technology to capture and sequester CO2 from fossil fuels in a cost-effective and environmentally sound manner, we will be able to reap the benefits of fossil fuel use for the coming decades without further damaging world environment.

Human civilisation until the end of 18th Century used most environmentally friendly energy to navigate their ships. Abundance amount of wind energy were harnessed by sails to move ships around the world. Both cargo and passenger ships started moving from sails to steam engines during the early 19th Century (Anis,2019).

From mid-20th century, motor ships using Internal Combustion (IC) engines became prominent prime movers in propelling small to biggest marine vessels in the world. These IC engines were developed to burn heavy density, residual fuels, or combination of it to become most cost-effective solution to the shipping industry.

Crude oil has become the source of most marine fuels at the present days. Crude oil, which is a fuel of carbon chains, therefore burning any derivatives of these crude oil obviously emits CO2 and this phenomenon became dominant from mid-20th century (Elkafas et al., 2022). Solid fuel such as coal could not sustain its dominance with the development of marine diesel engines which started burning residual fuels. Synthetic fuels though had a presence or possibility of development, but economic competitiveness of residual fuels did not allow further development of synthetic fuels for marine use (Xing et al., 2021).

Development of crude oil refining process in early and mid 20th century played a great role in supply of various grades of fuel oils (Aitani, 2004). Heating crude oil in different temperatures and distillation generated various fractions of the oil. Paraffin and gas oil are known as distillates easily stored and can be used without further treatment were good for gas turbine plants, medium and high-speed diesel engines. Residual fuels which are very viscous and heavy at normal temperature became ideal for burning them in slow speed and some medium speed marine diesel engines. The treatment system was designed and heating it to a temperature where it can easily flow, sprayed, and burn in modern engines made it the ideal energy source for bigger ships and their propulsion plants.

Figure 3.1 Schematic diagram of a high-conversion refinery, adapted from, Aitani, (2004)

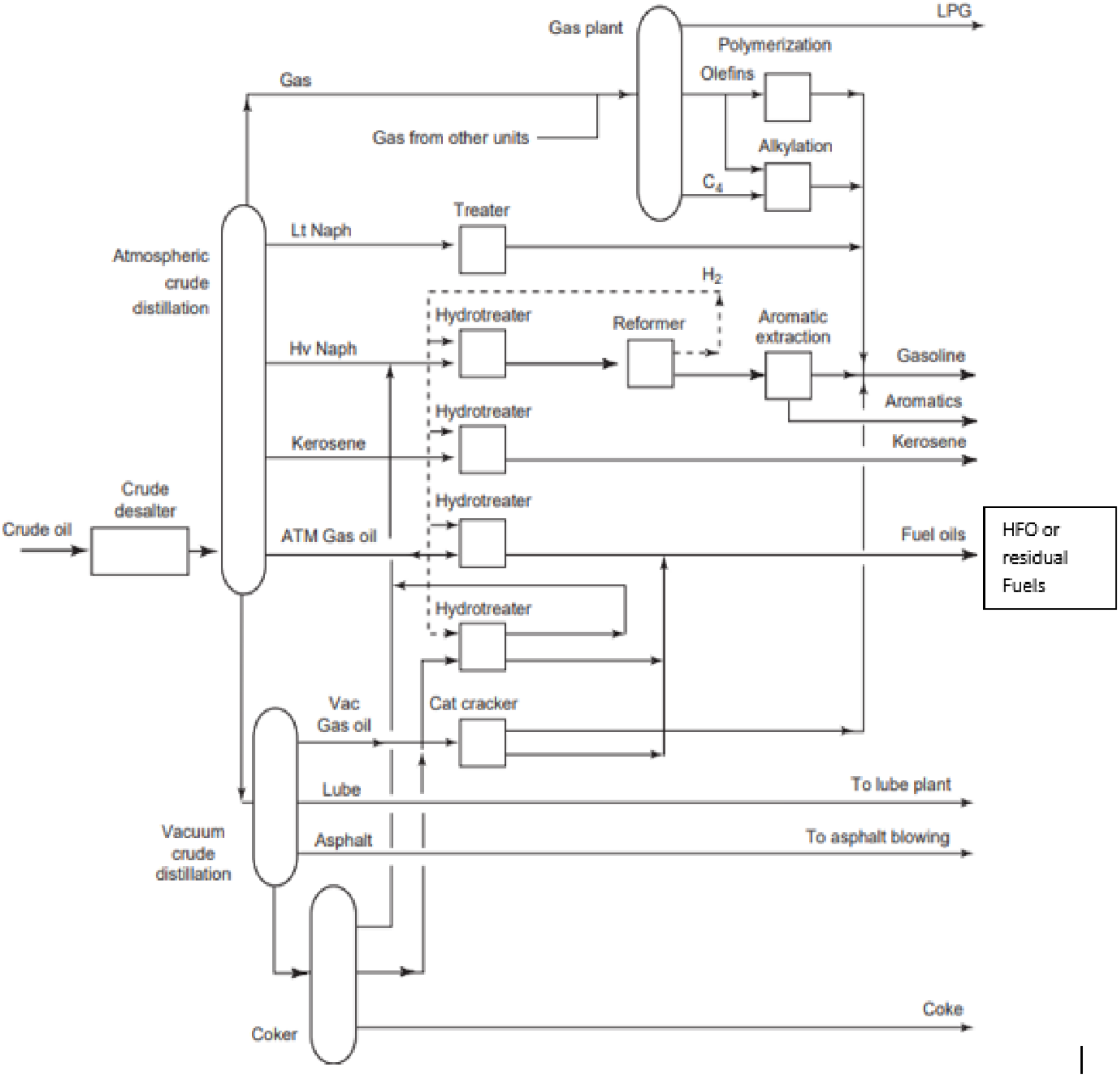


Figure 3.1 shows different levels of fractioning of crude oil and the most HFO are residual oils and also the output from catalytic cracking.

It is crucial to comprehend the reasons behind the significant prevalence of Marine residual fuel, specifically Heavy Fuel Oil (HFO), as the leading category of fuel oil in the shipping industry. To understand this development, we require to find out few of the main factors in different viewpoints such as economic or commercial issues, fuel quality and usability, development of Marine diesel engines in those days. Residual fuel oil is considered to be the least economically useful among the products produced by refiners, as it is often sold at a price lower than that of crude oil (Aitani, 2004).

Residual fuels provide challenges in terms of pumpability due to their potential heaviness compared to water. Additionally, their dispersion can be problematic, often resulting in the formation of tar balls, lumps, and emulsions. Numerous maritime vessels, power plants, commercial buildings, and industrial facilities employ residual fuels or a combination of residual and distillate fuels for the purposes of heating and processing (Aitani, 2004). We require to understand these factors in depth to come out from this era of HFO and make more greener choices in present time.

3.2 Marine Fuel Oils and their properties

Heavy Fuel Oil (HFO) is one of numerous terminologies used to describe a variety of marine residual fuels and distillate fuels. Additional terms frequently employed in this context encompass bunker oil, bunker fuel oil, and residual fuel. All these items share a common characteristic: they are utilised on maritime vessels, and their nomenclature facilitates the differentiation of Heavy Fuel Oil (HFO) from both unprocessed petroleum and other processed substances (Rasmussen et al., 2018).

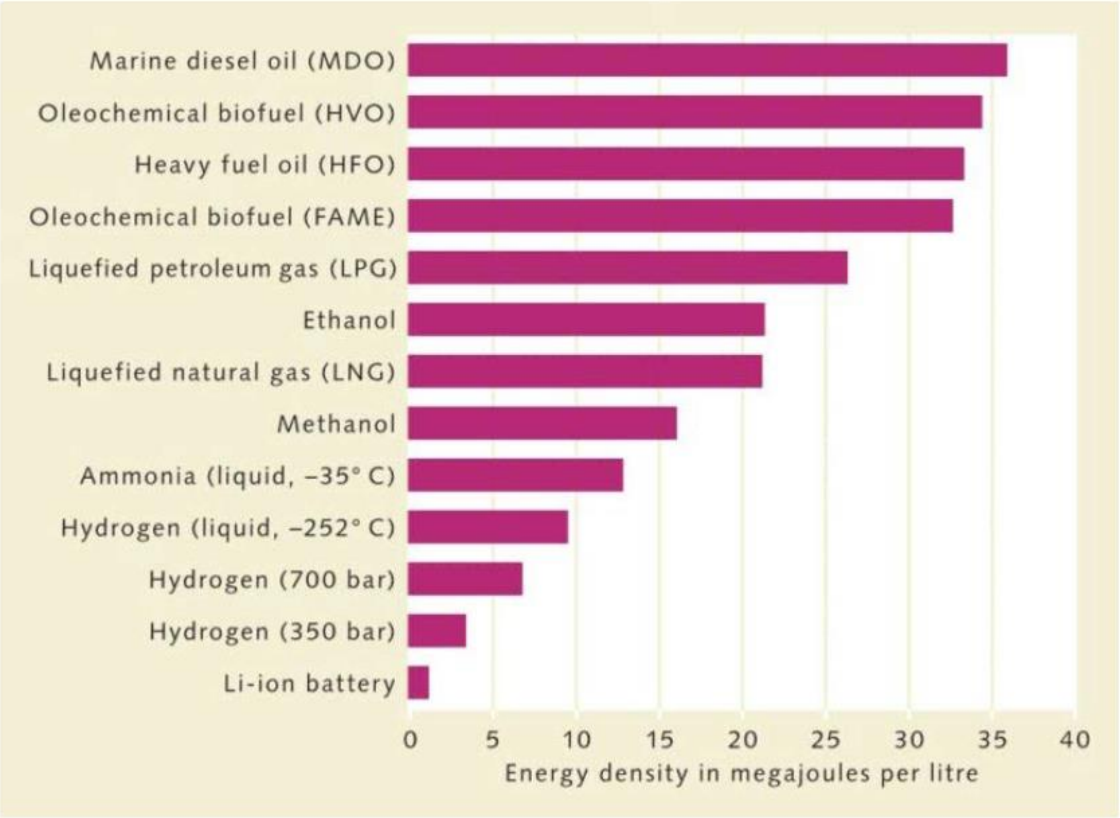
HFO is created by blending residue with cutter stock (distillate diluent, such as marine diesel oil or marine petrol oil) to reach, for example, the necessary viscosity at a specified temperature. There is no standard for the mixture of residue and distillates used to make HFO (Moldestad et al. 2007). The physical and chemical properties of the HFO will thus vary depending on the feed oil's origin (crude oil), the quality or properties of the feed oil, variations in the distillate added to produce the required viscosity, and the different refinery processes. Atmospheric distillation, vacuum distillation, thermal cracking procedures (e.g., visbreaking), and other conversion processes such as catalytic cracking and hydrocracking are examples of blending process. Most residual fuel oils are now generated using vacuum distillation, thermal and catalytic cracking (Rasmussen et al. 2018).

Viscosity is provided at 50 °C as an indicator for the oil's ability to be pumped. HFO varieties are commonly classified based on the "Intermediate Fuel Oil (IFO) Grade system." (Moldestad and Daling 2006). The IFO viscosity categorization system includes a total of sixteen different IFOs, ranging from IFO30 all the way up to IFO700. Due to the fact that the IFO system only defines the fuel's viscosity, all of the other qualities are subject to change.

The predominant product in use, IFO380, accounts for approximately 70% of the overall volume of heavy bunker oils supplied. The product IFO180 accounts for approximately 25% of the total volume of bunker oil available on the market. Moldestad et al. (2007) assert that the remaining 5% is constituted by classes of a different nature (Rasmussen et al. 2018).

Energy density of fuel plays an important role in selection of the category of fuel for energy conversion. It is evident from figure below that HFO and MDO are having highest energy density per litre of fuel.

Figure 3.2 Energy density of various fuel oils (Maelum et al., 2022)



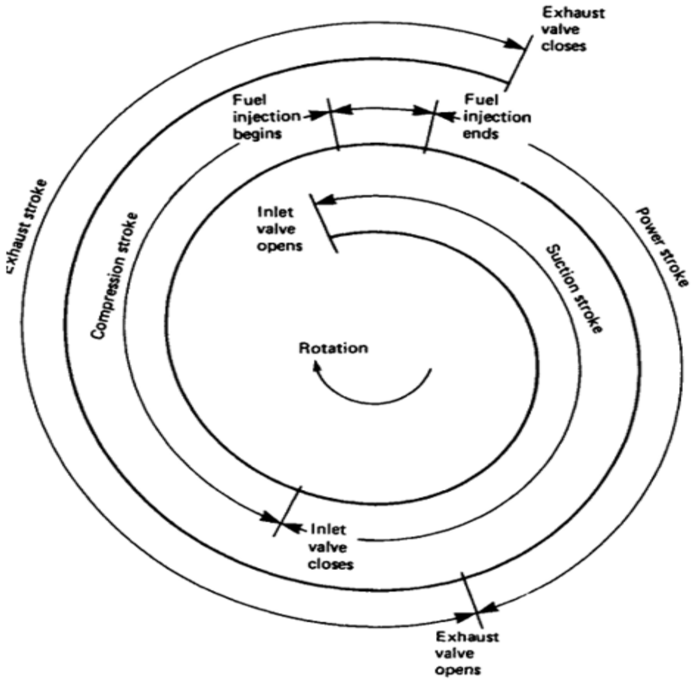
3.3 Development of Marine Diesel Engines

The diesel engines are internal combustion engine. Internal combustion engine works in the principle that high pressure fuel particles are injected in the combustion chamber of the engine where high pressure and hot air when comes into contact with fuel oil mist, combustion occurs. Diesel engine operates on a particular sequence of events. These events are accomplished either by two strokes or four strokes' cycles. The stroke is defined as being the travel of engine piston between its extreme points Top Dead centre (TDC) and bottom dead centre (BDC).

3.3.1 Four-stroke cycle

While describing the operation of marine four-stroke cycle engines, Taylor (1996) mentioned certain characteristics as follows. The four-stroke cycle is accomplished within four strokes of the piston, which corresponds to two complete revolutions of the crankshaft. To facilitate the functioning of this cycle, the engine necessitates a mechanism that enables the opening and closing of the inlet and exhaust valves. The four distinct strokes are known as inlet, compression, power and exhaust. These events are shown diagrammatically on a timing diagram (Figure 3.3). The angle of the crank at which each operation takes place is shown as well as period of the operation in degrees (Taylor, 1996). The variation of angles will differ for various engine types, however, the diagram provided is representative of a typical engine.

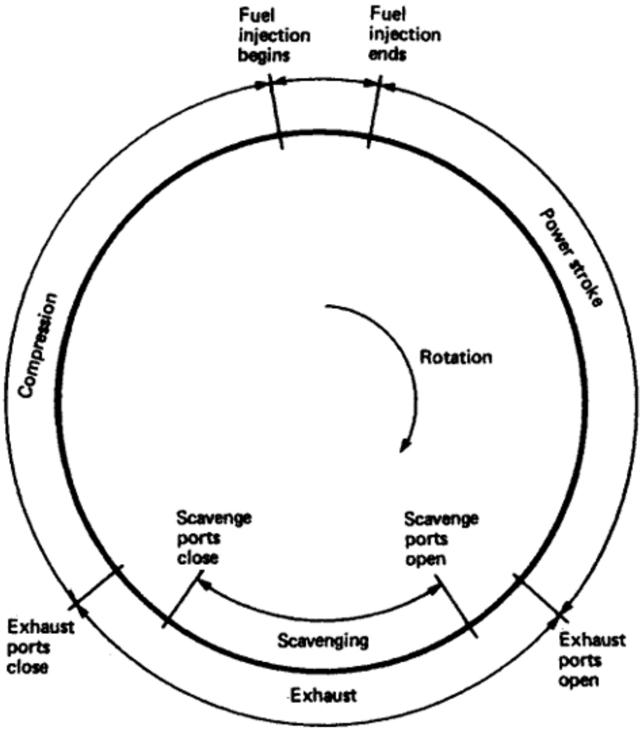
Figure 3.3 Timing diagram four-stroke diesel engine (Taylor, 1996)



3.3.2 Two-stroke Cycle

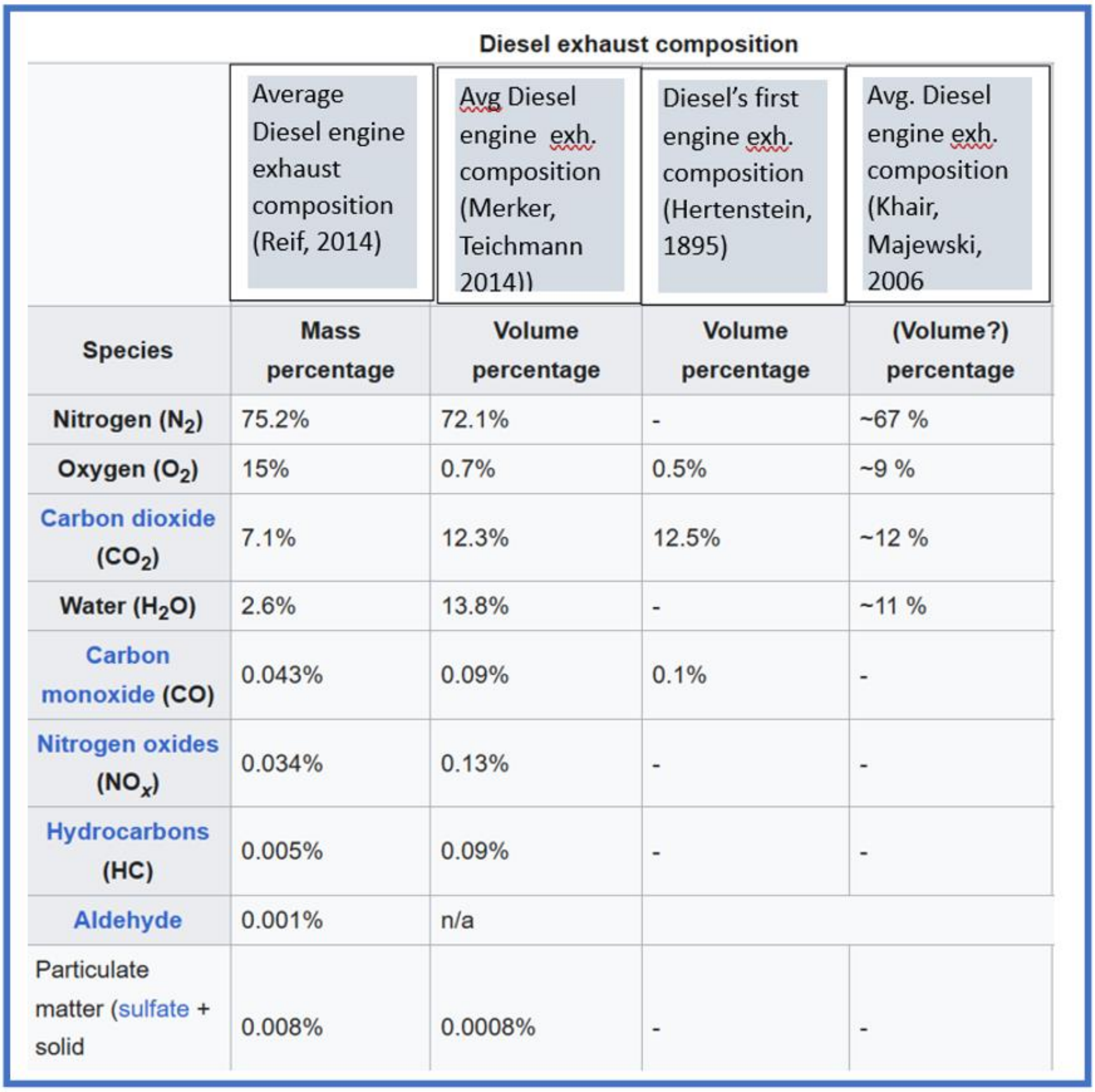
Taylor (1996) described two stroke cycle engine operation as follows. The two-stroke cycle engine completes its operation in two strokes of the piston or one revolution of the crankshaft. To facilitate the efficient operation of this cycle, the engine needs specialised arrangements for scavenging to ensure that each event is completed within a brief timeframe. Initially, it is important to introduce the fresh air by means of pressurisation. The incoming scavenging air is employed to remove the exhaust gases, subsequently replenishing or altering the environment with fresh air. In lieu of conventional valves, ports are typically employed, which are operated by the motion of the piston body to facilitate their opening and closing. Some designs of two-stroke engines also incorporate exhaust valves (Taylor, 1996). Figure 3.4 illustrates the timing diagram of a two-stroke engine.

Figure 3.4 Timing diagram two-stroke diesel engine (Taylor, 1996)



The flue gas composition of HFO combustion in an ICE can vary depending on various factors such as the fuel quality, fuel-air ratio, engine design such as two-stroke or four-stroke cycle as described above, and other operating conditions. However, the typical composition of HFO flue gas in an ICE includes the components shown in Table 3.1 (Resitoglu et al., 2015) and descriptions provided below.

Table 3.1 Exhaust Gas constituents as per different sources adapted from Wikipedia, 2023



Diesel exhaust composition

	Average Diesel engine exhaust composition (Reif, 2014)	Avg Diesel engine exh. composition (Merker, Teichmann 2014))	Diesel's first engine exh. composition (Hertenstein, 1895)	Avg. Diesel engine exh. composition (Khair, Majewski, 2006
Species	**Mass percentage**	**Volume percentage**	**Volume percentage**	**(Volume?) percentage**
Nitrogen (N_2)	75.2%	72.1%	-	~67 %
Oxygen (O_2)	15%	0.7%	0.5%	~9 %
Carbon dioxide (CO_2)	7.1%	12.3%	12.5%	~12 %
Water (H_2O)	2.6%	13.8%	-	~11 %
Carbon monoxide (CO)	0.043%	0.09%	0.1%	-
Nitrogen oxides (NO_x)	0.034%	0.13%	-	-
Hydrocarbons (HC)	0.005%	0.09%	-	-
Aldehyde	0.001%	n/a		
Particulate matter (sulfate + solid	0.008%	0.0008%	-	-

Diesel engine exhaust consists of mainly following gaseous or vapour components.

Carbon dioxide (CO_2): This is the primary product of complete combustion and can compose around 11-15% of the flue gas by volume.

Water vapor (H_2O): This is also a product of the combustion process and can range from 8-15% of the flue gas.

Nitrogen (N_2): This is the main component of air and can account for around 60-70% of the flue gas volume.

Sulphur dioxide (SO_2): If the HFO contains sulphur impurities, it can be converted to sulphur dioxide during combustion. The sulphur content in HFO can vary, but typical values range from 1-5%, which results in a corresponding amount of SO_2 in the flue gas.

Nitric oxide (NO): Formed through reactions between nitrogen and oxygen at high temperatures,

It is well established that amount of CO_2 produced is nearly three folds of HFO burnt in ICE. The amount of carbon dioxide (CO_2) generated per kilogram of Heavy Fuel Oil (HFO) when it is burned in an Internal Combustion Engine (ICE) depends on the carbon content of the fuel and the combustion efficiency.

On average, HFO has a carbon content of around 85-90%. Since the molecular weight of carbon dioxide is 44 grams per mole and the atomic weight of carbon is 12 grams per mole, we can calculate the amount of CO_2 produced per kilogram of HFO as follows:

CO_2 produced (kg) = Carbon content (%) / 100 * (44/12)

Let's assume an average carbon content of 88% for HFO.

CO2 produced (kg) = 88 / 100 * (44 / 12) ≈ 3.07 kg CO2 per kg of HFO burned

Thus, approximately 3.07 kilograms of carbon dioxide (CO2) is generated per kilogram of Heavy Fuel Oil (HFO) when it is burned in an ICE.

3.4 Green House Gas

Most of the heated surface emit infrared radiation. Earth’s surface when heated, it emits infrared radiation. Any gas which has the property of absorbing infrared radiation and reradiating it back to the earth surface produces greenhouse effect. Greenhouse effect is described as the phenomenon of increasing earth’s surface temperature by reradiated heat energy by gases.

Water vapour, Carbon dioxide, methane, nitrous oxides, ozone, and fluorinated gases (CFCs) have contributed towards greenhouse gas effect. (Britannica, 2020)

Water is the naturally occurring vapour which contribute most to greenhouse effect and this effect has made earth surface tenable otherwise earth surface would be -17◦ C. But due to human activities which has increased multiple folds during past centuries contributed towards generation of carbon dioxide and other greenhouse gas.

Human-caused carbon dioxide emissions are widely accepted as the primary driver of climate change across the world. The Intergovernmental Panel on Climate Change (IPCC) has spent the past three decades conducting extensive research into the causes and effects of climate change, publishing a series of assessment reports that have sparked a worldwide desire to reduce greenhouse gas emissions from the burning of fossil fuels (Feron, 2016). Adaptive measures like carbon capture, utilisation, and storage (CCUS) are needed to help green major polluting fossil fuel-based sectors and reduce GHG emissions from their operations.

3.5 IMO studies and findings

International Maritime Organisation (IMO) being the international forum and UN executive body for shipping started their studies and preparation for reducing GHGs from shipping since the introduction of Intergovernmental panel on Climate Change (IPCC) in 1988 (IMO, 2021).

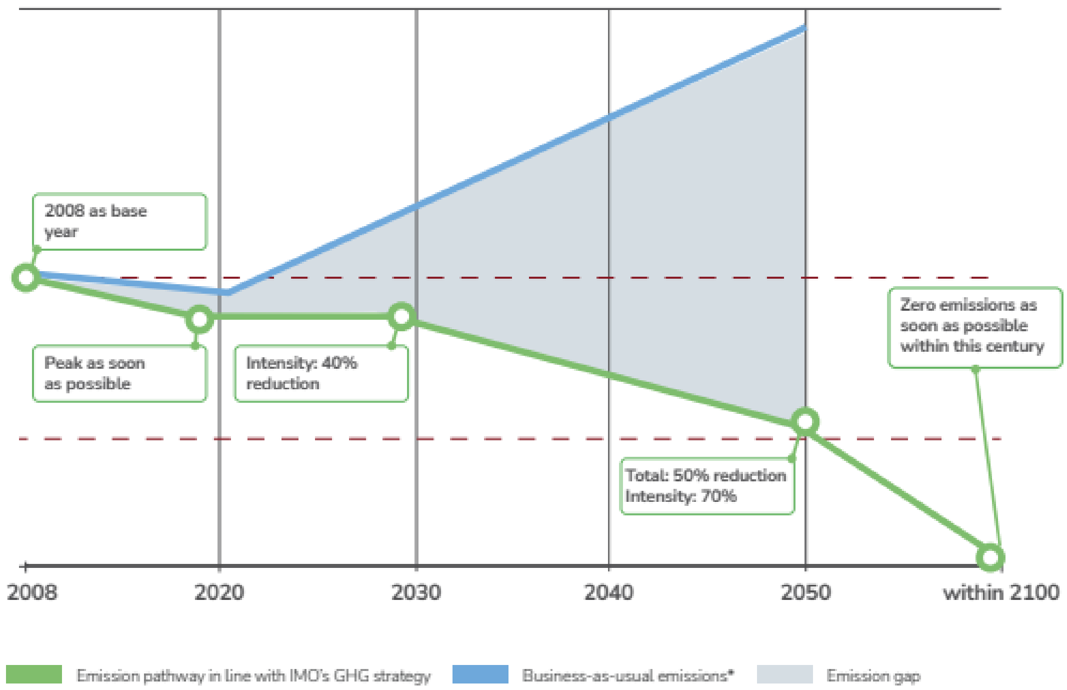
The Kyoto Protocol, which was established in 1997, includes provisions aimed at mitigating greenhouse gas (GHG) emissions from international aviation and shipping. These sectors are treated differently from other sources due to their global operations, which are overseen by the International Civil Aviation Organisation (ICAO) and the International Maritime Organisation (IMO) respectively. Emissions originating from domestic aviation and maritime activities are encompassed within the scope of national objectives for Annex I countries. The International Civil Aviation Organisation (ICAO) and the International Maritime Organisation (IMO) frequently provide updates on their activities to the United Nations Framework Convention on Climate Change (UNFCCC). Neither the terms of the 2015 Paris Agreement on Climate Change (referred to as the Paris Agreement) nor the decisions pertaining to its implementation, particularly those regarding pre-2020 ambition, make any mention of the International Maritime Organisation (IMO) or the International Civil Aviation Organisation (ICAO).

In accordance with Assembly decision A.963(23), the IMO Secretariat is mandated to provide regular reports to the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC) under the specific agenda item addressing "Emissions from fuel used for international aviation and maritime transport." Additionally, the IMO Secretariat is expected to actively engage in relevant activities within the broader United Nations system. The Initial IMO Strategy on Reducing GHG Emissions from Ships, hereafter referred to as "the IMO Strategy," was adopted during the 72nd session of the International Maritime Organisation's Marine Environment Protection Committee (MEPC 72) in April 2018. The International Maritime Organisation (IMO) Strategy encompasses a set of reduction goals for greenhouse gases.

- In order to mitigate the carbon intensity of ships, it is proposed to establish additional phases of the Energy Efficiency Design Index (EEDI) for newly constructed vessels.
- In order to achieve a reduction in the carbon intensity of international shipping, specifically the amount of CO2 emissions per transport operation, a target has been set to decrease it by a minimum of 40 percent by the year 2030, compared to the levels seen in 2008.
- In order to achieve a significant reduction of no less than 50 percent in the overall annual greenhouse gas emissions stemming from global maritime transport by the year 2050, as compared to the levels seen in 2008.

The ambitious target is set to remove greenhouse gas (GHG) emissions efficiently and expeditiously from the domain of international shipping within the current century**. Figure 3.5** shows the IMO GHG targets in comparison to the baseline of 2008.

Figure 3.5 – IMO GHG targets (Source DNV, 2021)



The aggregate greenhouse gas (GHG) emissions of global, domestic, and fishery vessels had a rise from 977 million tonnes in 2012 to 1,076 million tonnes in 2018. The emissions in question encompass carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), which are quantified as CO2e and have experienced a 9.6 percent increase. In the year 2012, the aggregate amount of carbon dioxide (CO2) emissions amounted to 962 million metric tonnes. However, by the year 2018, these emissions experienced a notable increase of 9.3 percent, reaching a total of 1,056 million metric tonnes. (Wissner and Healy, 2023).

In summary, CO_2 emissions from 2.76 percent in 2012, the percentage of shipping emissions in total anthropogenic emissions has increased to 2.89 percent in 2018 (Bouman et al., 2017)

The inaugural plan (IMO Initial GHG Strategy) serves as a comprehensive framework for Member States, delineating the prospective vision for the realm of international shipping, the levels of ambition in mitigating greenhouse gas (GHG) emissions, and the guiding principles that underpin these efforts. Additionally, it encompasses a range of prospective measures at various timeframes (short-, mid-, and long-term) that candidates can do, along with their potential deadlines and implications particular to each state. Furthermore, the strategy not only encompasses the identification of hurdles and bottlenecks, but also includes the recognition of supportive measures. These measures encompass capacity building, technical cooperation, and research and development (R&D).

The proposed strategy foresees the implementation of an updated strategy in the year 2023. The implementation of the data collection system pertaining to the fuel consumption of ships above 5000 GT, commenced on 1 January 2019, will play a significant role in the progression towards the acceptance of the updated Strategy in 2023 (IMO, 2023).

The imperative of implementing carbon dioxide capture and storage is widely recognised as essential in order to effectively mitigate the global temperature increase and maintain it below the critical threshold of 2^0 Celsius. Nevertheless, there exist other justifications for the maritime sector to commence contemplating the use of carbon capture and storage (CCS) technology.

In addition to the need of meeting the International Maritime Organisation's (IMO) targets for 2030 and 2050, it is anticipated that carbon taxes will be introduced. Carbon capture and storage (CCS) emerges as the possible most effective approach to mitigate the escalation of expenses.

Among different strategies, CCS stands out as the most cost-effective approach, particularly when compared to the adoption of renewable fuels which remain prohibitively expensive for maritime applications so far.

CHAPTER FOUR

4.0 Carbon Capture Technologies

4.1 Overview of Carbon Capture Technologies

Carbon capture methods cover a diverse array of procedures that are designed to absorb and mitigate carbon dioxide (CO2) emissions originating from a variety of industrial sources, including maritime vessels. Brief description of commonly used processes is here.

1. Chemical absorption is a method commonly utilised in carbon capture systems. The process entails the capture of carbon dioxide (CO2) emitted by ships by the use of a chemical solvent, often amine-based, or other absorbent substances. The carbon dioxide that has been absorbed can then be removed for the purposes of storage or conversion into valuable byproducts.

2. Membrane separation is a process that use specialised membranes to achieve the selective separation of carbon dioxide (CO2) from other gases present in exhaust streams. This technique is dependent on the differential permeability of carbon dioxide (CO2) across membranes.

3. Cryogenic separation is a technique that use low-temperature procedures to effectively remove carbon dioxide (CO2) from the exhaust gases emitted by ships. The procedure entails the reduction of temperature in the exhaust gases to very low levels, resulting in the condensation and subsequent separation of CO2 from the remaining gases. The carbon dioxide that has been

isolated can thereafter be either stored or used for alternative applications.

4. Adsorption: Adsorption technologies encompass the use of solid sorbents, such as activated carbon or zeolites, for the purpose of capturing carbon dioxide from ship emissions. The sorbents possess a notable affinity for carbon dioxide (CO2), enabling them to efficiently absorb and effectively separate it from the emissions produced by the exhaust gases. The carbon dioxide that has been caught can be subsequently released from the sorbents for the purpose of storage or conversion.

5. Electrocatalytic Conversion: The field of electrocatalytic conversion is a developing area of technology that encompasses the electrochemical transformation of carbon dioxide (CO2) into valuable goods, such as synthetic fuels or chemicals. The aforementioned procedure employs specialised catalysts and renewable power to aid the conversion, so offering a viable route for the use of CO2 and the mitigation of emissions.

6. Hybrid Systems: Hybrid systems integrate several carbon capture methods in order to optimise overall efficiency and boost the rates of carbon capture. By incorporating various capture techniques, such as absorption and membranes, these systems have the potential to enhance the elimination of carbon dioxide (CO2) from ship emissions and enhance their overall efficiency.

7. Oxy-fuel combustion is a technique that entails the use of pure oxygen rather than atmospheric air in the combustion process, leading to a significant increase in the concentration of carbon

dioxide (CO2) in the emitted exhaust gases. Subsequently, the concentrated carbon dioxide (CO2) stream may be caught and separated with greater ease, facilitating its storage or use.

8. Direct Air Capture (DAC): Direct Air Capture refers to a technological process that involves the direct extraction of carbon dioxide (CO2) from the Earth's atmosphere through the utilisation of specialised filters or sorbents. Although not exclusively applicable to maritime vessels, direct air capture (DAC) might potentially contribute to mitigating emissions from ships by absorbing carbon dioxide (CO2) from the surrounding atmosphere.

9. Algae-based systems employ photosynthetic microorganisms, specifically algae, to absorb and transform carbon dioxide (CO2) into biomass via the process of photosynthesis. The implementation of these systems on maritime vessels enables the capture and use of carbon dioxide emissions, therefore offering a promising avenue for the generation of renewable energy or the production of other important commodities.

10. Novel and Emerging Technologies: The ongoing progress and scholarly endeavours are propelling the evolution of innovative carbon capture technologies. Innovative methodologies encompassing carbon nanotubes, metal-organic frameworks, and molecular sieves have emerged as promising avenues for enhancing the efficiency of carbon dioxide (CO2) collection, owing to their distinctive features and capabilities.

4.2 Carbon Capture and Storage (CCS) in Other Industries

In the Texas village of Terrell, work on a novel technological advancement known as carbon capture and storage (CCS) began fifty years ago. During the period spanning the late 1970s and early 1980s, a multitude of commercial carbon dioxide (CO2) collection facilities were developed inside the territorial boundaries of the United States. (Herzog, 2000). The facility in question was an advanced natural gas processing plant that employed pre-combustion carbon dioxide capture technology. This technology was applied to collect CO2 from the natural gas processing stages. The captured CO2 was then transported to an oil field for the purpose of enhanced oil recovery (EOR) and subsequent storage. The name "CCS" has expanded to embrace a global industry, with 26 CCS facilities in operation throughout the world that have successfully captured and stored 300 million metric tonnes of carbon dioxide (GCCSI, 2022).

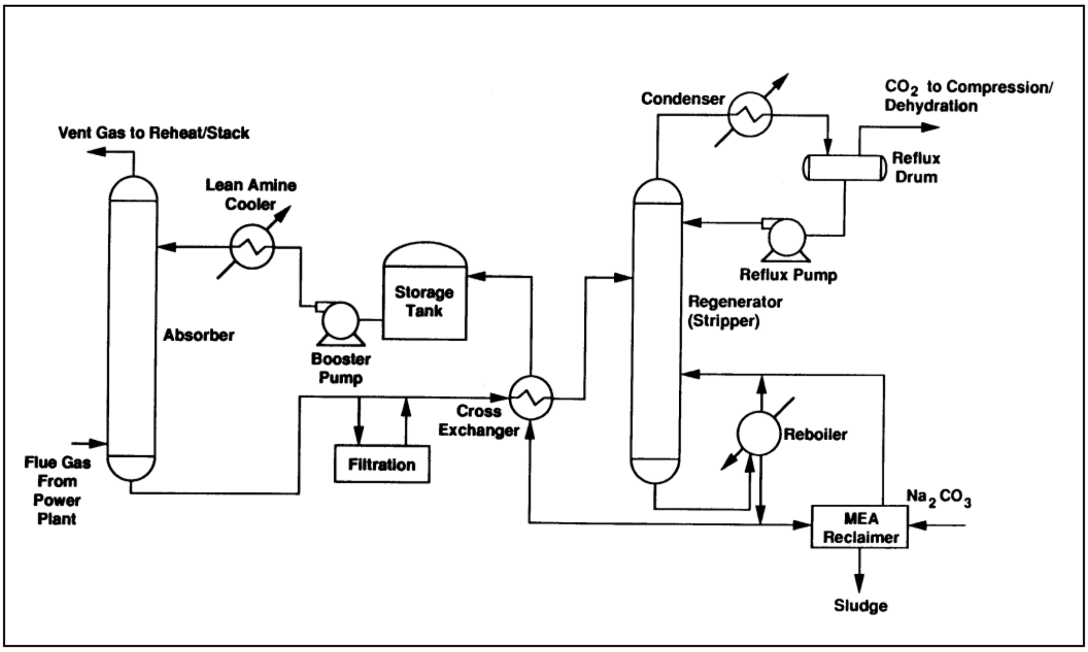
The initial impetus for the concept of separating and capturing carbon dioxide (CO2) from power plant emissions did not primarily stem from concerns regarding the greenhouse effect (Herzog, 2000). However, it garnered attention as a prospective economic provider of CO2, specifically for its application in enhanced oil recovery (EOR) for oil field operations. These operations entail the injection of CO2 into oil reservoirs to enhance the fluidity of the oil and hence boost the productivity of the reservoir.

The escalating costs of utilising the retrieved carbon dioxide (CO2) for enhanced oil recovery (EOR) activities during the mid-1980s resulted in the cessation of operations at these carbon capture facilities.

The commencement of CO2 storage by Statoil of Norway in September 1996 involved the sequestration from the Sleipner West gas production to a sandstone aquifer located at a depth of 1000 m beneath the North Sea. This was a significant milestone as it represented the first instance of a commercial operation for the collection and sequestration of CO2 (Herzog, 2000). The CO2 injection process on the floating rig involves the utilisation of five pipelines, with a weekly injection rate of 20,000 tonnes. This injection rate is equivalent to the emissions output of a coal-fired power station with a capacity of 140 MWe. The financial incentive for the project is the carbon price of $50 per tonne of CO2 in Norway (Herzog, 2000). In order to ensure the continuity and advancement of future projects, a global research endeavour is being established with the aim of monitoring and documenting this undertaking.

Currently, the majority of commercial carbon dioxide (CO2) capture facilities utilise chemical absorption techniques employing a solvent known as monoethanolamine (MEA). The Monoethanolamine (MEA) solvent was developed over six decades ago with the purpose of serving as a versatile and inclusive agent for the extraction of acid gases, including carbon dioxide (CO2) and hydrogen sulphide (H2S), from natural gas streams. In the context of CO2 extraction from flue gas, modifications were made to the technique to incorporate inhibitors that exhibit resistance to both solvent degradation and equipment corrosion. Furthermore, it was imperative to maintain a reduced level of solvent strength, which consequently required the utilisation of substantial equipment and a significant amount of energy for regeneration (Leci, 1997). The process facilitates the interaction between flue gas and a monoethanolamine (MEA) solution within the absorber, as depicted in Figure 4.1.

Figure 4.1 Schematic diagram of the post-combustion absorption process, (Herzog, 2000)



After the selective absorption process, the MEA transfers the carbon dioxide (CO2) to a stripper. The solution containing a high concentration of CO2 in monoethanolamine is subjected to heating within the stripper unit in order to release CO2 in a state of high purity. Subsequently, the absorber is replenished with a new supply of the lean monoethanolamine solution.

4.3 CO2 Capturing Technologies in Details

The combustion of carbon-based fuel (fossil fuels) emits significant amounts of CO2. The carbon dioxide (CO2) can be either emitted into the atmosphere or utilised within manufacturing facilities for the production of various commodities, such as those found in the food processing sector. However, only a small portion of the carbon dioxide produced is reused by the manufacturing industry, and the majority of the carbon dioxide eventually ends up in the atmosphere. Various solutions have been devised and put into practise within the industry to effectively capture carbon dioxide from gaseous mixtures. The classification of technology is contingent upon the level of gas purity and its state in relation to the prevailing ambient conditions. The overarching goal of all carbon capture and storage (CCS) technologies is to produce carbon dioxide that can be stored in a geological formation. To make this a reality, carbon dioxide must be compressed to a liquid state so that it can be easily transported through pipelines and eventually pumped into a geological formation. As a result, the CO2 compression stage can be considered a component of the CCS system. CCS technologies are currently classified as either pre- or post- combustion systems. These technologies are named based on whether the carbon is eliminated before or after the combustion of fossil fuels (Lopez et al., 2018). Another CCS technology, known as oxyfuel or oxy - combustion, is still in the early stages of development and will take some time before it is commercially viable.

Currently, there exists a wide range of physico-chemical techniques aimed at capturing and sequestering carbon. These techniques are collectively referred to as carbon capture and storage (CCS) technologies. The carbon capture and storage (CCS) process encompasses three fundamental stages, namely CO2 capture, CO2 transit, and CO2 storage. CCS operations often rely on the utilisation of gasses from major individual sources, such as power stations and cement production units. Typically, the separation of carbon dioxide from other exhaust components involves the implementation of the following well known and used procedures: (i) chemical absorption, (ii) physical adsorption, (iii) cryogenic distillation, and (iv) membrane separation.

There is continuous development in this field and several other CC processes are also researched for industrial applications which are not researched and referenced in this publication.

4.3.1 Adsorption

Adsorption is a deliberate process that entails the deliberate formation of a physical and chemical interaction between the surface of the adsorbent material and carbon dioxide (CO2). To restore the adsorbent material, the absorbed carbon dioxide (CO2) is then eliminated through the use of pressure swing adsorption (PSA) or temperature swing adsorption (TSA) techniques. Temperature swing adsorption (TSA) is a process wherein the adsorbent, which has reached its saturation point, is subjected to elevated operational temperatures. This increase in temperature leads to the disruption of physical and chemical bonding within the adsorbent, resulting in the separation of the adsorbed reactants. In the process of pressure swing adsorption, the pressure is decreased in order to attain the desired outcome. Temperature swing adsorption (TSA) is commonly employed in situations when the concentration of CO2 is insignificant, while pressure swing adsorption (PSA) is the preferred method when the CO2 concentration is high (Casas et al., 2023). The advantage of pressure swing adsorption lies in its ability to replenish the adsorbent within a very short amount of time. Zeolite and amine sorbents are widely utilised physical adsorbents in various applications (Jiang et al., 2015).

4.3.2 Physical Absorption

The physical absorption process can be categorised into two distinct stages. The aforementioned processes are absorption and stripping, respectively. The absorption process entails the interaction between the treated gas and the solvent stream, resulting in the physical capture of

CO2 by the solvent (Wilberforce et al., 2019). Carbon dioxide (CO2) and the solvent, often in a saturated state, are supplied to a heating process in order to generate a lean solvent and release CO2 at the highest point of the stripping chamber. Electrostatic forces cause CO2 to dissolve in the liquefied solvent.

Physical absorption works best in low temperature and high-pressure environments. Other factors, such as high temperature but low pressure, influence physical desorption.

When compared to chemical absorbent, physical absorption has superior absorption characteristics (Romano et al., 2010). Its regeneration can be accomplished with a low-energy depressurization operation. This explicates their superiority in the area of pre-combustion carbon capture systems. They possess utility within integrated gasification combined cycle (IGCC) power plants, wherein they serve the purpose of extracting carbon dioxide from synthesis gas, facilitating natural gas treatment, and enabling acid gas recovery. It is important to acknowledge that the physical utility of absorbent capacity is more pronounced at lower temperatures. According to Schell et al. (2012), it is crucial to reduce the temperatures of treated gas streams before absorption.

4.3.3 Cryogenic Separation

In order to separate the gas, this method uses multiple compression applications at ambient pressure and temperature. Liquid carbon dioxide can be created using this method. It is perfect for capturing large amounts of carbon dioxide. Because it consumes less water, less expensive chemical agents, is corrosion resistant, and has less of an impact on the environment in terms of pollution, this technique can also be utilised in place of amine-based scrubbing methods. This idea works with liquid CO2 and ambient pressure as well. As a result, they contribute economically to CO2 transmission. Additionally, cryogenic separation has some restrictions (Zheng et al., 2017). The low working temperature range makes it energy-intensive, which raises the cost of operation. When ice forms in a cryogenic method, the piping system frequently becomes obstructed, which limits the pressure drop and poses a safety risk. It is crucial to reduce the amount of moisture before the separation process as a result. The initial expense of using this technology is increased by this process (Wilberforce et al., 2019).

4.3.4 Membrane Separation

The phenomenon that causes membrane separation is the Knudsen diffusion principle. CO2 diffuses across the membrane proportionate to its partial pressure gradient. When CO2 partial pressure is high, non-facilitated membrane technology is used to remove CO2 from natural gas. Because flue gas carbon dioxide is lower, more energy is required for carbon capture because compression work is needed to sustain enough driving power. Permeability affects membrane selectivity. Despite its many benefits, including as low environmental impact and degradation, incorporating it into an existing power plant is difficult. Researchers are studying strategies to avoid this problem. Researchers advocate facilitated transport membrane separation. Mobile or liquid phase carriers transfer CO2 as bicarbonate. This increases CO2 membrane permeability and selectivity. Mixed matrix membranes are also new (Kang et al., 2015).

The Mixed matrix membranes are composed of polymer membranes fillers. Fillers such as zeolite, mesoporous silica, and zeolitic imidazolate are commonly employed in many applications. These modified membranes are cheaper and more permeable. These membranes are strong and heat resistant. Gas membrane contactors are another novel membrane-separation technique. These membranes don't use Knudsen diffusion principle. They demonstrate the membrane system's compactness and the highly selective nature of the amine-based absorption mechanism. The membrane's resistance limits mass transport (Wilberforce et al., 2019).

In addition to the aforementioned diverse carbon capture technologies, it is important to note that the procedures and phases involved in capturing carbon dioxide also exhibit variability. It is outlined in following sections.

4.3.5 Pre-Combustion Approach

According to Lueking and Cole (2017), this technique involves the separation of carbon dioxide from fossil fuels before commencing the burning process. It involves the chemical reaction between fuel and oxygen gas, resulting in the production of hydrogen, carbon monoxide, and fuel gas. According to Alonso et al. (2017), the extraction of carbon dioxide results in the acquisition of a stream of hydrogen fuel that is free from impurities. Carbon dioxide can be acquired using integrated gasification procedures.

The initial crucial stage in the extraction of carbon from fuel involves the conversion of the fuel into a more readily capturable state. Coal-fired power plants commonly undergo a chemical reaction involving coal, steam, and oxygen gas under conditions of high temperature and pressure. The aforementioned procedure results in the production of a fuel consisting of carbon monoxide (CO) and a mixture of hydrogen, commonly referred to as syngas. The aforementioned gas has the capability to undergo a combustion process, resulting in the production of energy within a power plant. During the second stage of this procedure, carbon monoxide undergoes a chemical transformation into carbon dioxide through a reaction with steam. The outcome of this process is the generation of carbon dioxide and hydrogen. The process of capturing carbon dioxide involves the utilisation of the glycol solvent Selexol. The utilisation of the Integrated Gasification Combined Cycle (IGCC) method results in significant energy loss during carbon dioxide capture due to the involvement of the shift reactor and other stages in this particular process. The implementation of pre-combustion carbon dioxide capture in power plants fuelled by natural gas is also a plausible concept, as suggested by Wilberforce et al. (2019).

4.3.6 Post-Combustion Approach

According to Wilberforce et al. (2019), fossil fuels or other combustible materials containing carbon are when burned, the carbon dioxide that is released into the atmosphere is captured via post-combustion carbon capture (PCC). Scientists consider chemical reaction to be the best method for removing CO2 from flu gases coming from pulverised coal plants or bigger diesel combustion engines, however this method also needs a amine solvent such as monoethanolamine (MEA). First, the flue gas is cleansed in an absorber-chamber. About 85% to 90% of the CO2 produced is captured with the aid of the absorber. CO2 rich solvent is introduced into a different column known as the regenerator or the stripper. In the second vessel, steam is used in the CO2 release process. This method results in extremely concentrated CO2. The gas is both compressed and transported to a storage place. The procedure involves recycling the lean solvent by forcing it back into the absorber.

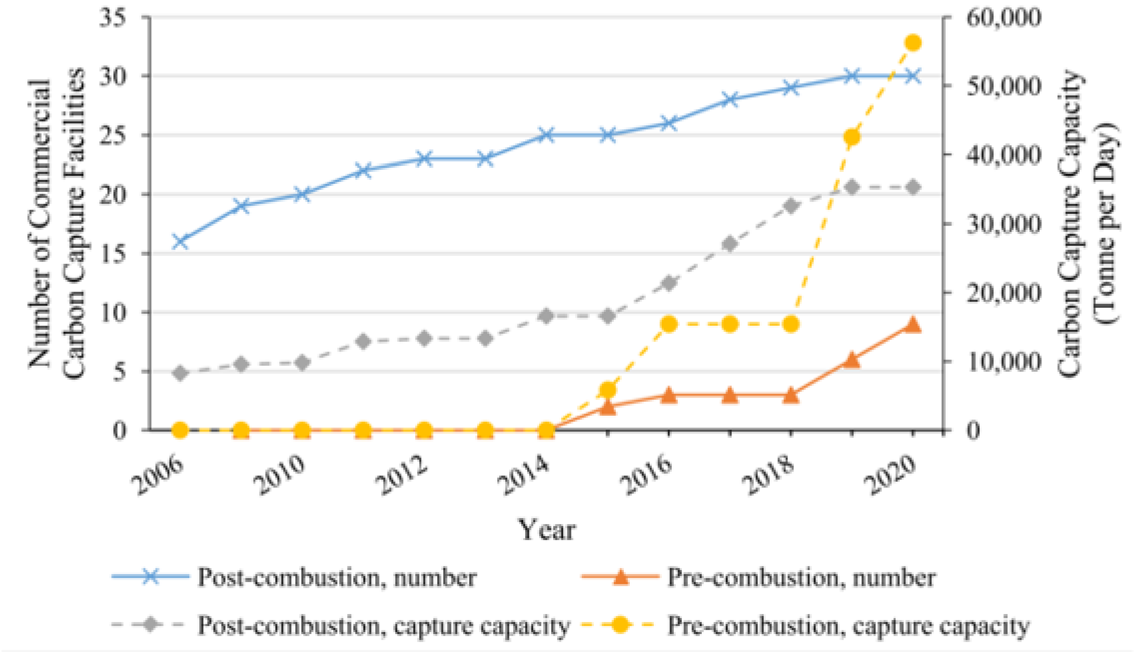
Both a natural gas-fired boiler and a pulverised coal power plant may capture carbon dioxide using this technological method. Even while the flue gas carbon dioxide concentration in coal plants is frequently higher than that of a natural gas combined cycle (NGCC), it is still possible to achieve significant removal efficiency with amine-based capture systems. Since there are no contaminants in natural gas, the flue gas stream is extremely pure. This means that no cleanup will be required in order to successfully capture CO2.

4.3.7 Oxy-combustion Approach

As an alternative to post-combustion capture process, the oxy-combustion method, has recently been developed. Pure oxygen is used in the combustion process in this method, which lowers the levels of nitrogen. Additionally, ash particles are removed from the flue gas stream, leaving behind only CO2, water droplets, and some pollutants like sulphur dioxide. A method for removing the water vapour involves compression and lowering the temperature of the flue gas. Pure carbon dioxide is the only byproduct of this procedure, and it is stored immediately. The elimination of an expensive CO2 collecting device for post combustion is one benefit of oxy-combustion over post combustion. Cost is heavily impacted by the air separation unit for production of clean oxygen by air separation unit (ASU). To satisfy the appropriate environmental standard, additional gas transformation is frequently needed to reduce the concentration of air pollutants. Since burning with pure oxygen produces a temperature higher than that of air, oxy combustion is required to maintain the boiler's ideal operating temperature (Wilberforce et al., 2019).

Looking to the emplyment of CC approaches in industrial perspective it is evident that recent uptake of pre-combustion CC process in terms of capacity has surpassed post-combustion capacity in world context, which is noticeable from below (Figure 4.2) statistics, though number of post-combustion project are more .

Figure 4.2 Carbon capture commercial projects worldwide (Wilberforce et al., 2019)



It is important to acknowledge that every carbon capture method possesses distinct merits, drawbacks, and obstacles when implemented in maritime vessels. When choosing and implementing technology for carbon capture from ships, it is imperative to thoroughly evaluate factors such as scalability, energy demands, cost, and compatibility with ship designs. The selection of technology is contingent upon a multitude of aspects, including the distinct attributes of the vessel, its operating necessities, and the economic and regulatory milieu.

In order to attain sustainable marine transportation, it is imperative to prioritise the development and successful integration of efficient carbon capture technology on ships. These technologies have the capacity to substantially diminish the environmental footprint of the maritime sector and make a valuable contribution to worldwide endeavours aimed at mitigating climate change. However, further study, collaboration, and innovation are required to maximise the efficiency of these technologies, guarantee their economic feasibility, and promote their extensive use in the maritime industry.

CHAPTER FIVE

5.0 Research and Survey outcome

5.1 Main Online Survey and Sampling process

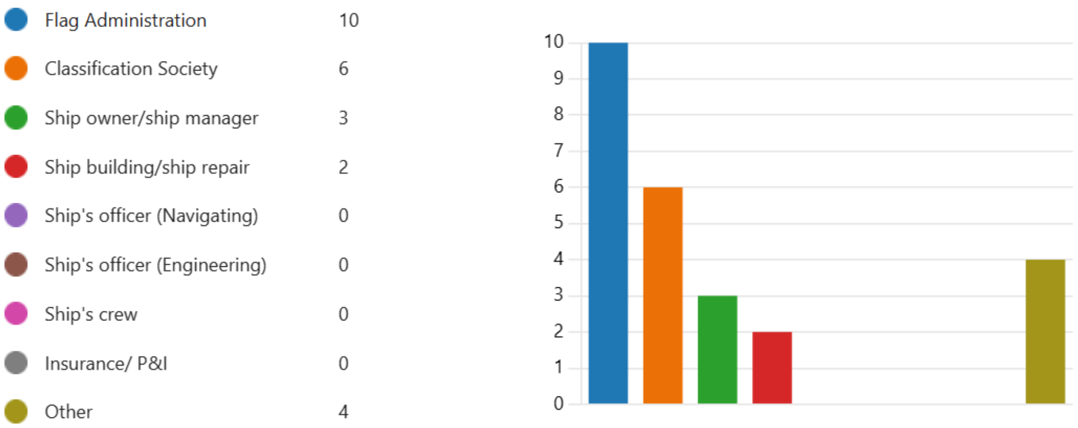
In order to assure the collection of accurate and relevant data for analysis, exhaustive questionnaires were designed for the mixed-mode survey in Microsoft Forms. As per principle mentioned by Davis (Davis, 1992) and Polit et al., (Polit, et al., 2007) maritime professionals and stakeholders validated the survey questionnaires using the "Content Validity Index (CVI)" method. Using Microsoft Form, online survey questionnaires with single-answer and multiple-choice options and checkboxes for selecting individual and multiple responses were created. Respondents were requested to participate in research by answering survey questionnaires (SQs) which is included in Appendix 1.

In order to create a sample that accurately represents the views of experts, we implemented a purposive sampling approach to carefully choose participants who satisfied predetermined criteria. The survey link was provided to experts who hold positions as emission reduction specialist, Flag administration positions, Classification society surveyor and specialists, ship superintendent, ship masters, chief engineers on board ships.

5.2 Analysis of survey data

The data analysis for the survey involved the utilisation of MS Forms and Excel spreadsheet formulas and graphics. Upon the receipt of survey responses, the collected data was subsequently stored in PDF format and downloaded in CSV format to facilitate subsequent analysis. The charts present the distribution of responders expressed as a percentage for each variable. The caption of each graphic indicates the total number of replies as "N = Number of Participants." A total of 25 professionals completed survey comprising 10 experts from flag administration, 6 surveyors and specialist from Class Society, 3 ship owner and ship managers, 2 Chief Engineers and 2 Masters. The survey finding depicts that majority of responses received from flag administration experts and class society specialists who are at present state most learned member among the stakeholders on the subject matter and discussions. The figure 5.1 below shown the distribution of respondent in simple graph.

Figure 5.1 Distribution of participants group in survey



5.3 Results and discussion

Important findings related to technical matters are discussed in following sections. Out of 25 respondents 21 responded with ‘yes’ that CC is important for reducing the emissions associated with ships. However, with the timeline of 2023, 2040 and 2050 carbon capture scenarios the expert’s assessment and opinion shifted and diminished over the timeline. On the question of IMO direction to consider the concept of well to wake (WtW) for carbon emissions from ships operation, 19 responded with ‘yes’. Below figures 5.2 to 5.4 show the shifts in graphical representation.

Figure 5.2 CC Technology deployment potential with timeline 2030

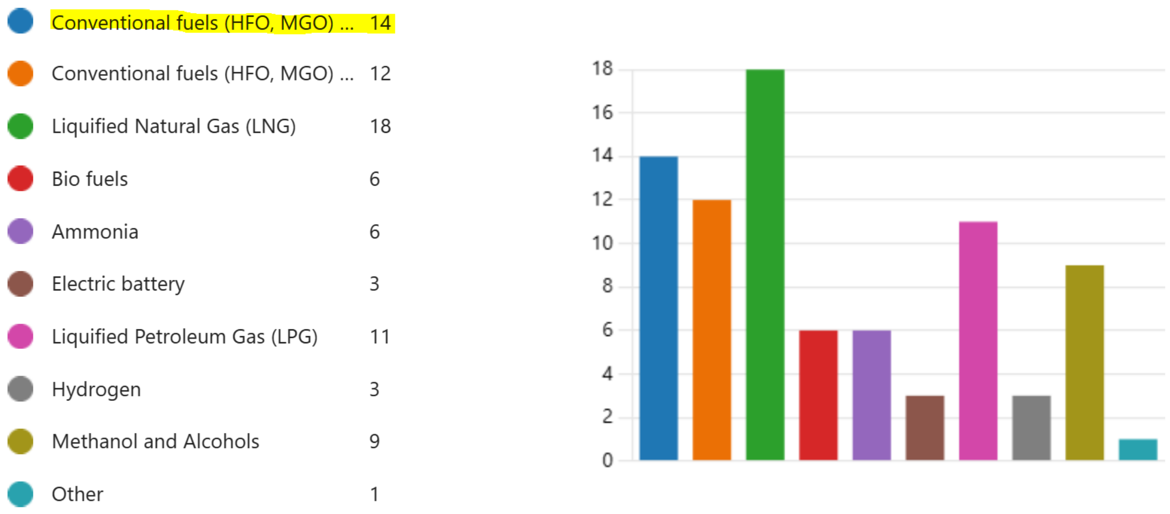


Figure 5.3 CC Technology deployment potential with timeline 2040

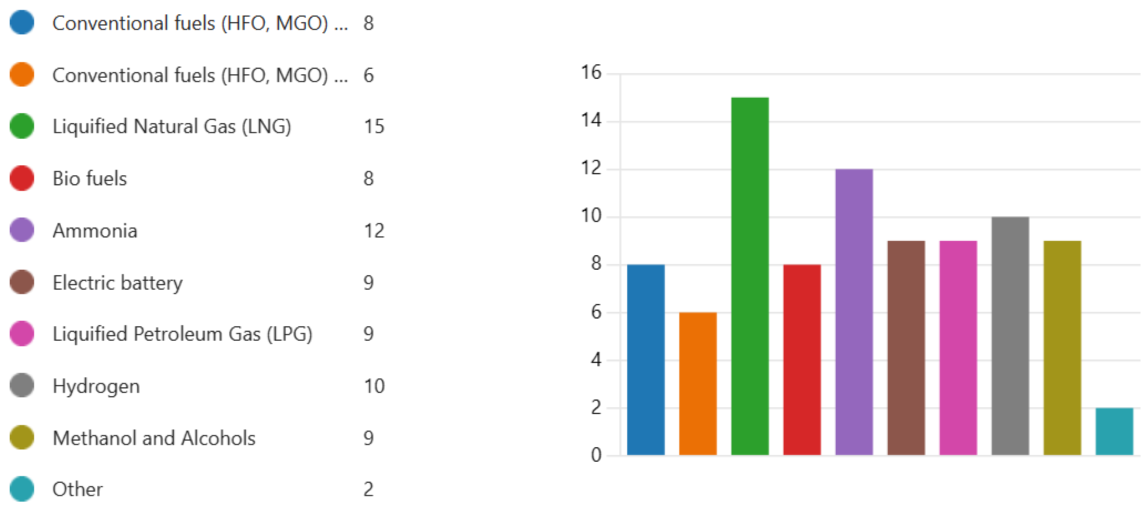


Figure 5.4 CC Technology deployment potential with timeline 2050

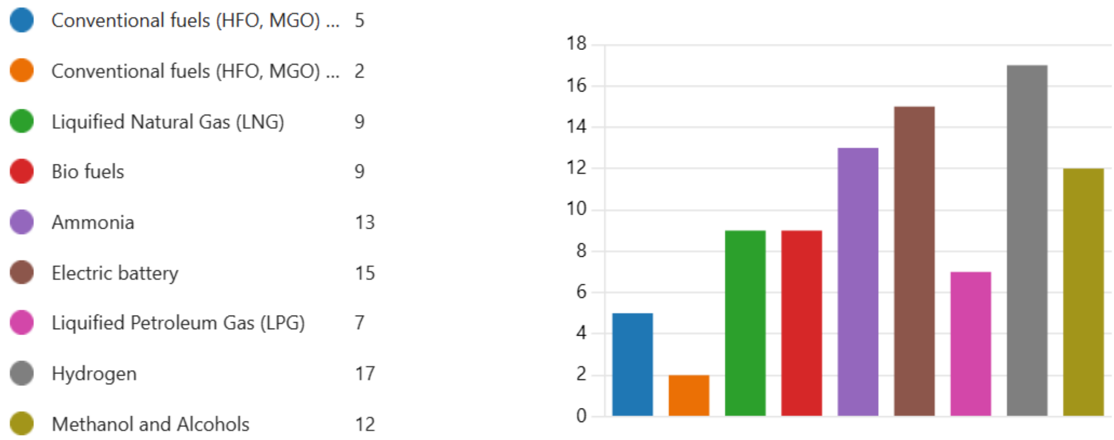
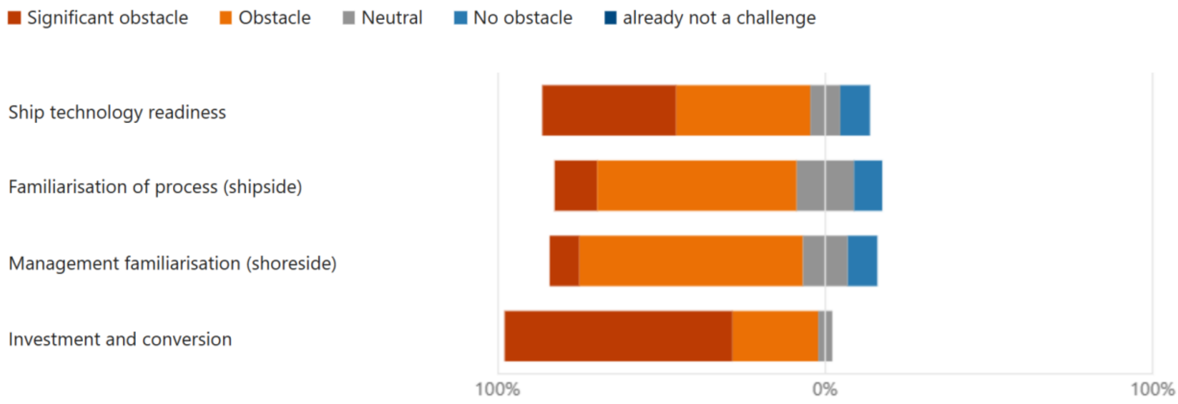


Figure 5.5 Carbon emissions calculation to consider WtW

5.3.1 Summary of technical challenges associated with retrofitting commercial vessels with CC systems

The primary obstacle identified among the options presented was the difficulty in finding a CC system that is compatible with the existing infrastructure. This was followed by the crew's lack of knowledge with the new technology. Similar outcome also pictured when the question was differently presented for CC from ships ICEs and that was ‘Ship technology readiness’ at the top. One of the primary issues identified in the literature reviews is also the compatibility and modification of existing engine and space orientation. The training and familiarisation of crew members with upcoming technological improvements in ship operations are recognised as significant challenges in the pursuit of International Maritime Organisation (IMO) greenhouse gas (GHG) targets. It is imperative that these challenges are promptly addressed.

Figure 5.6 Challenges and obstacles in Carbon capture from ship’s engine



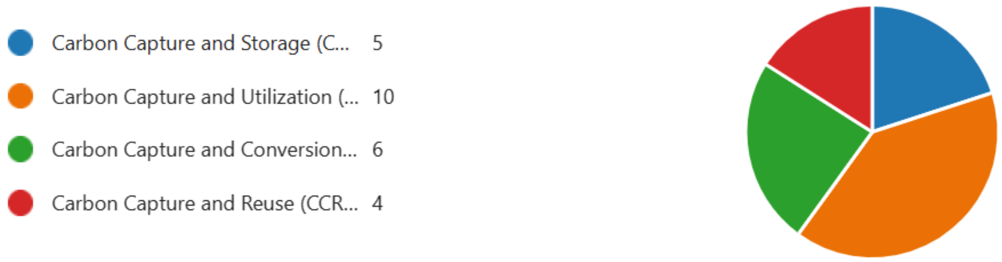
5.3.2 Summary on energy conversion method in coming decades

The specialists were presented with three sets of inquiries pertaining to various energy conversion techniques in the years 2030, 2040, and 2050. The prevailing consensus among experts suggests that internal combustion engines (ICE) are expected to maintain their dominant position in the years 2030 and 2040. In the year 2030, a total of 20 ticks provided for the ICE in survey, but in the year 2040, the number of ticks decreased to 16. However, it is expected that by 2050, there will be a move away from internal combustion engines (ICE) as the major energy conversion process. Fuel cells, renewable energy sources such as wind and solar power, and nuclear energy are significant conversion mechanisms, notwithstanding the continued presence of internal combustion engines (ICEs).

5.3.3 Summary on possible utilisation of captured carbon from ICE

The researchers were provided with four different options and requested to rank them based on their efficacy in utilising captured CO2 from ship engines. The majority of participants, specifically 10 individuals, picked Carbon Capture and Utilisation (CCU) as their top choice among the options of Carbon Capture and Storage (CCS), Carbon Capture and Conversion (CCC), and Carbon Capture and Reuse (CCR).

Figure 5.7 Carbon capture and utilisation possible solution for shipping



5.3.4 Summary on achievement of IMO 2050 Green House Gas (GHG) target

Among the sample of 25 participants, 12 individuals provided a response of "may be," while 8 participants reacted affirmatively with "yes," and 2 participants responded negatively with "no." When examining the broad scope of the question, assuming that the phrases "may be" and "yes" imply the possibility of achieving the stated goals, it is encouraging to observe that experts maintain a positive perspective towards the attainability of the International Maritime Organisation's (IMO) 2050 greenhouse gas (GHG) objectives. One notable result of this research is the continued belief by professionals and stakeholders in the attainability of the stated objective, despite the acknowledgment of various hurdles and multifaceted pressures.

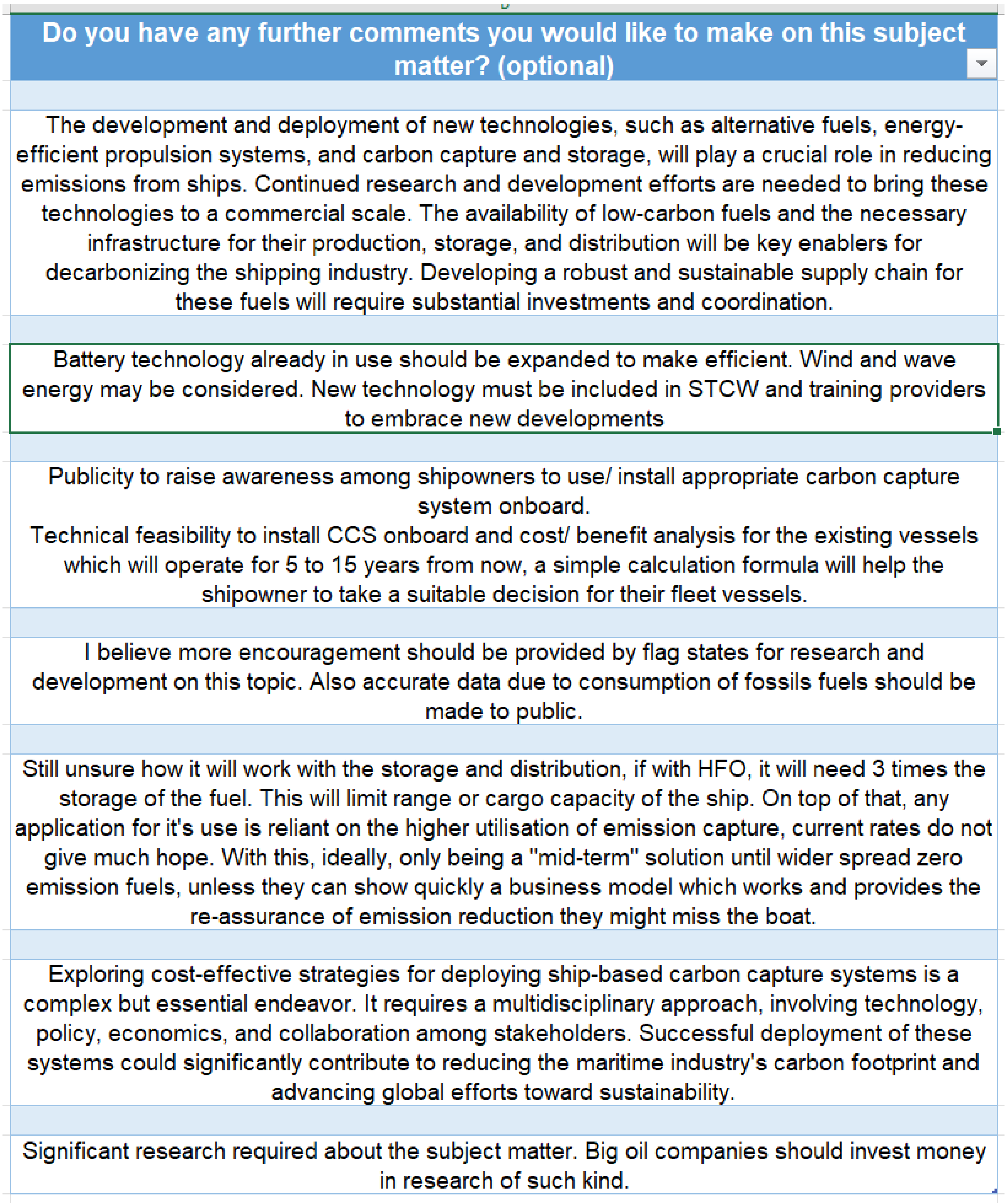
Figure 5.8 GHG target achievement potential

5.3.5 Summary on specific recommendations from professionals

When experts were encouraged to provide free text, they highlighted a few specific areas which provide in table 5.1 below. They can be summarised as follows.

1. The utilisation of publicity as a means to enhance awareness among shipowners.
2. Additional support and commitment from flag states is necessary to further promote and advance research and development efforts.
3. Carbon capture has the potential to serve as a viable solution in the medium future, but its successful implementation necessitates the development of a robust business model.
4. It is recommended that major oil corporations allocate resources towards the advancement of research and development pertaining to carbon capture systems.

Table 5.1 Important comments from experts



Do you have any further comments you would like to make on this subject matter? (optional)
The development and deployment of new technologies, such as alternative fuels, energy-efficient propulsion systems, and carbon capture and storage, will play a crucial role in reducing emissions from ships. Continued research and development efforts are needed to bring these technologies to a commercial scale. The availability of low-carbon fuels and the necessary infrastructure for their production, storage, and distribution will be key enablers for decarbonizing the shipping industry. Developing a robust and sustainable supply chain for these fuels will require substantial investments and coordination.
Battery technology already in use should be expanded to make efficient. Wind and wave energy may be considered. New technology must be included in STCW and training providers to embrace new developments
Publicity to raise awareness among shipowners to use/ install appropriate carbon capture system onboard. Technical feasibility to install CCS onboard and cost/ benefit analysis for the existing vessels which will operate for 5 to 15 years from now, a simple calculation formula will help the shipowner to take a suitable decision for their fleet vessels.
I believe more encouragement should be provided by flag states for research and development on this topic. Also accurate data due to consumption of fossils fuels should be made to public.
Still unsure how it will work with the storage and distribution, if with HFO, it will need 3 times the storage of the fuel. This will limit range or cargo capacity of the ship. On top of that, any application for it's use is reliant on the higher utilisation of emission capture, current rates do not give much hope. With this, ideally, only being a "mid-term" solution until wider spread zero emission fuels, unless they can show quickly a business model which works and provides the re-assurance of emission reduction they might miss the boat.
Exploring cost-effective strategies for deploying ship-based carbon capture systems is a complex but essential endeavor. It requires a multidisciplinary approach, involving technology, policy, economics, and collaboration among stakeholders. Successful deployment of these systems could significantly contribute to reducing the maritime industry's carbon footprint and advancing global efforts toward sustainability.
Significant research required about the subject matter. Big oil companies should invest money in research of such kind.

CHAPTER SIX

6.0 Carbon Capture Technology for Ships

The subject of inquiry of this chapter pertains to the implementation of carbon capture technology specifically designed for maritime vessels.

6.1 Review of Existing Carbon Capture Technologies for Ships

Several CC processes available technologically, and they can be used by employing three different approaches, as mentioned in the preceding Chapter Four. The approach and process that is best suited to shipping must now be determined. The models, construction, and capacity of propulsion machines that use fossil fuels vary as well. As a result, using a single process for all vessels may not yield desirable results in terms of reducing shipping's carbon footprint. We must evaluate all options and determine which is best for which sector. Domestic and international shipping fleets are both diverse, as are their modes of operation and energy consumption.

Since CCS technology is still relatively new to the maritime industry, there is very little historical data available on carbon capture and storage up to this point. However, if we look at statistics from other industries pertaining to CCS, it becomes clearly evident that the post-combustion absorption procedure was the most common one. The architecture of the ship's existing engines and the retrofitting of carbon capture systems make it possible to use post-combustion technology. The author aims to concentrate study on various post-combustion CC technology only as Technology Readiness Level (TRL) are mature for considered alternatives.

6.2 Considering Technology Readiness Levels (TRL)

The primary objective of this section of study is to assess the most viable carbon dioxide (CO2) capture technologies developed for application in the shipping Industries.

This review began with the compilation of technologies listed in the IEAGHG Report titled "Assessment of Emerging CO2 Capture Technologies and their Potential to Reduce Costs" from December 2014 (2014/TR4). Though this paper mainly focused on shore-based power generation sector but it provided a solid baseline on TRL for different CC technologies.

The assessment of the development of emerging technologies in the IEAGHG Report is conducted using a nine-point numerical scale known as the Technology Readiness Level (TRL). This scale is based on the descriptive descriptions put forth by the Electric Power Research Institute (EPRI). The aggregated information can be found in below table.

Table 6.1 Technology Readiness Level (TRL), adapted from IEAGHG 2014/TR4

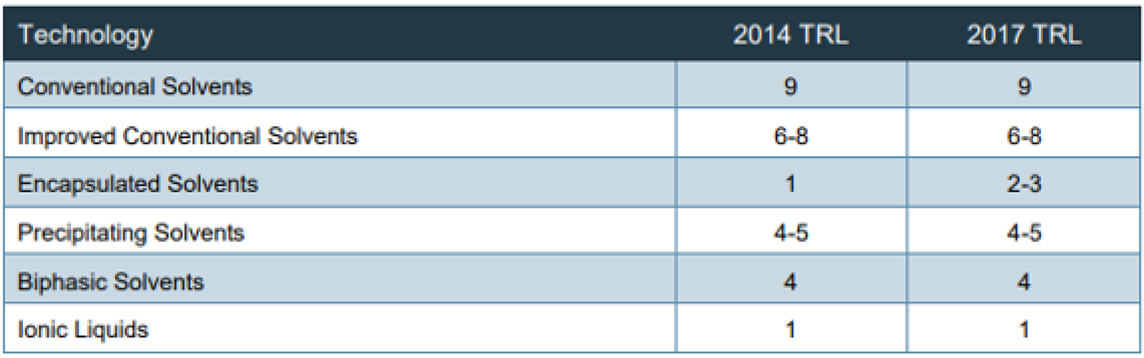
Demonstration	9	Normal commercial service
	8	Commercial demonstration, full scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant

		environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles, observed, initial concept

The definitions of Technology Readiness Level (TRL) utilised in this report remain same. The Technology Readiness Level (TRL) is not a definitive measure of the timeframe required for commercialization, as it fails to account for the challenges associated with resolving any outstanding development concerns.

TRL for Conventional solvents such as MEA, PZ etc (Amines) is at 9 in the scale of 1-9, 9 being the highest. Mineral carbonation was not assessed in IEAGHG 2014 report but in 2017 it has been assigned the TRL 5. MCFC carbon capture technologies similarly were not assessed in 2014 but it gained TRL 7 in 2017 assessment for industrial and power generation sector in shore-based industries. Therefore, it is evident that technology readiness for these CC processes is attaining readiness for normal commercial services.

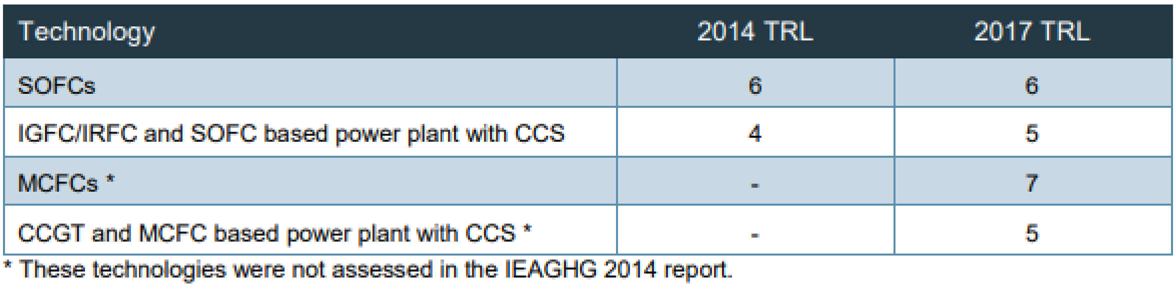
Table 6.2 TRL for post combustion CC Technologies, adapted from Literature Review 13333-8820-RP-003 Rev. 2A, Wood, 2018



Technology	2014 TRL	2017 TRL
Conventional Solvents	9	9
Improved Conventional Solvents	6-8	6-8
Encapsulated Solvents	1	2-3
Precipitating Solvents	4-5	4-5
Biphasic Solvents	4	4
Ionic Liquids	1	1

Mineral Carbonation *	-	5

TRL for Fuel cell CC technologies



Technology	2014 TRL	2017 TRL
SOFCs	6	6
IGFC/IRFC and SOFC based power plant with CCS	4	5
MCFCs *	-	7
CCGT and MCFC based power plant with CCS *	-	5

* These technologies were not assessed in the IEAGHG 2014 report.

Carbon capture systems have the capability to mitigate the release of carbon dioxide into the atmosphere resulting from the combustion of fossil fuels. The process entails the capture of carbon dioxide (CO2) from the emissions of power generation systems and industrial establishments, followed by its storage in a safe and controlled environment, such as subterranean geological formations or depleted oil and gas reserves (Rajabloo et.al., 2023).

The use of these CC technology on maritime vessels necessitates addressing a distinct and essential concern, namely, the mitigation of cargo space decrease. The issue at hand mostly affects ships due to their restricted space constraints, as opposed to industrial sites that are specifically designed to accommodate the chosen technology. In this context, the size of different solutions becomes a critical factor, influencing the decision-making process when selecting one system over another. The significance of this aspect becomes even more pronounced when endeavouring to retrofit existing vessels with the aim of reducing their emissions. In such instances, the incorporation of novel technologies must contend with existing systems and devices already present on board, making substantial modifications often unfeasible (Al Baroudi et.al)

While considering feasibility of employing CC technologies in maritime operations apart from TRL few more criteria mentioned in below required also to be considered (Havenstein and Weidenhammer, 2021).

1. Impact on safety and stability: Does the installation of CC technology onboard have a detrimental impact on the safety and stability of the ship? What is the impact of additional installations on the metacentric height (GM) and its influence on stability? Do the operational personnel face any additional hazards or an elevated risk? What would be the potential consequences for the vessel in the event of a failure of the CC plant? The technology that poses the least risk to the safety of the ship and has the least impact on its stability is considered the most favourable.

2. Impact of Ship's Movement and Vibration: Does the movement of the ship at sea have a detrimental effect on the CC technology? Is it possible for vibrations occurring aboard to have a negative impact on the efficiency of the CC plant? The

technology that exhibits the least susceptibility to movement and vibrations is considered to be the most highly regarded.

3. Variations in energy demand: Can the technology effectively maintain reliable operation in the presence of fluctuating energy demand? The energy consumption of a vessel is subject to variation due to its multiple operation modes, resulting in varying fuel usage and corresponding fluctuations in the generated mass flow of CO2. The energy consumption may undergo fast fluctuations, particularly while manoeuvring and cargo operations.

The CC plant is required to effectively respond to these variations, meaning it must have the capability to supply a enough amount of fuel to generate the necessary energy prior to combustion, or effectively capture CO2 from an exhaust gas flow that is subject to fluctuations after combustion. The technology that exhibits the highest capability to effectively address the variable energy demand while reliably capturing CO2 in such circumstances is regarded as the most favourable.

4. Impact of Impurities in Fuel/Exhaust: What is the influence of impurities present in the fuel/exhaust stream on the technology? Is the proposed approach for capturing carbon dioxide (CO2) viable for all engine and fuel variations, or does it have limitations specific to certain engine or fuel types? The technology that exhibits the least susceptibility and highest tolerance towards contaminants in the fuel/exhaust stream is considered to be the most superior.

Further evaluation in terms of constraints for installing them on board either in existing vessels or newbuilding were taken into consideration.

I. Additional weight: Ships are specifically engineered to accommodate a predetermined amount of cargo, referred to as deadweight tonnage (DWT). The displacement weight (DWT) is being reduced due to the installation of a carbon capture (CC) plant, the intermediate storage of captured carbon dioxide (CO2), and the inclusion of necessary chemicals.

   Hence, the technology that imposes the least weight, thereby minimising the reduction in the transport capacity of ships, is deemed to be the most favourable in the evaluation.

II. Investment costs: The shipowner places significant weight on the early investment costs. The high expenditures associated with investment in this particular technology may render it economically unfeasible, hence prolonging the payback period of the investment. There exists a positive correlation between lower investment costs and higher rankings of technology.

III. Operational costs: The expenses associated with the day-to-day functioning of a business or organisation, commonly referred to as operational costs, are a crucial aspect What is the cost associated with capturing one metric tonne of carbon dioxide? The primary sources of operating costs are derived from the use of energy and consumable resources. The assessment ranks technologies higher based on their operational efficiency and cost-effectiveness, with a particular emphasis on minimising operational expenses for the CC plant.

IV. Crew familiarisation and training: does the crew require extensive traing and familiarisation to operate and maintain on board CC systems? Hence, the evaluation prioritises the technology that exhibits the lowest training requirements as the most favourable.

V. Energy requirements: It is necessary for all energy needed to operate the plants aboard a ship to be generated internally, meaning that the energy required for the operation of the CC plant must be produced by generators located onboard the ship. The operational costs, namely those related to fuel and maintenance, are being driven up by a growing demand for energy. Hence, the evaluation prioritises the technique that exhibits the lowest energy requirements as the most favourable.

VI. Capture Rate: What is the maximum achievable rate of CO2 capture? Given the increase in energy consumption, it is necessary to inquire about the potential carbon reduction rate that can be attained. The evaluation of the technique is enhanced as a result of increased CO2 capture.

VII. Space Requirements: The main function of merchant vessels is the transportation of commodities and passengers. Consequently, the value of a ship is heavily influenced by the amount of space available for cargo utilisation. The more efficient the utilisation of space for the installation of the CC plant and the designated tanks for onboard storage of CO2, the greater the cargo capacity and potential revenue. The ranking of the CC approach increases as the required space decreases.

VIII. Engine modification: Is it feasible to make alterations to the currently installed engine(s) or is it necessary to replace the engine in order to operate with CC technology?

IX. Fuel: Is it necessary to modify the fuel and/or fuel system in order to comply with the specifications of the CC technology?

X. The necessity for repowering: It is necessary for the power needed to operate the CC plant to be produced on the vessel. In the event that the currently installed equipment on board is incapable of supplying an adequate amount of power, it becomes necessary to install supplementary generators. This results in an augmented investment and an escalation in operational expenses and additional emissions.

Ships possess a considerable lifespan, and it is imperative to retrofit new technologies onto current maritime fleet to mitigate emissions and align with the objectives outlined in the Paris Agreement (Bullock et al., 2020). Therefore, last three criterion VIII – X require special consideration for retrofitting in existing ships.

The study conducted by the researcher have taken into consideration the views and practical evaluation of the stakeholders on above aspects which is represented in Chapter Five

6.3 Potential Carbon Capture Technologies and their TRL

Drawing upon material gathered from literature sources and expert interviews, Harvenstein and Weidenhammer (2021) provided a comprehensive overview of carbon capture (CC) technologies for shipboard operations (Harvenstein and Weidenhammer, 2021). The subject thesis covers several aspects of these technologies, such as process setup, current applications, prices, space requirements, as well as unique benefits and downsides associated with each method, which are elaborated in following paragraph.

Moreover, the study undertaken about the implementation of the specified technologies on board has undergone a thorough evaluation, and the results of this research are given in a concise manner.

The assessment accomplished takes into account a range of restrictions and criteria pertaining to the suitability of various carbon capture (CC) technologies for use on board vessels. The safety considerations pertaining to both the ship and its crew, together with the unique characteristics of shipboard applications such as the ship's movement and vibration, as well as the variable energy requirements, are taken into account. Additionally, the specific conditions related to marine fuels are also considered. The unique restrictions of the shipboard application have been discovered and examined, including the occupied space, added weight, and energy requirement. Furthermore, the study takes into account the expenses associated with each carbon capture technology, as well as their respective maturity levels and achievable capture rates. In order to implement carbon capture (CC) technologies on existing vessels, many considerations were explored. These included evaluating the modification of the fuel system, the possibility of replacing the current engine, and assessing the limitations in power availability for operating the CC unit.

Three post-combustion carbon capture (CC) technologies have been advocated as the most viable options for implementation alongside internal combustion engines (ICEs). These technologies, namely absorption by NH3, membrane separation, and cryogenic separation (A3C) were thoroughly examined and evaluated. All of these methods were determined to be promising for onboard carbon capture by Harvenstein and Weidenhammer (2021). They also pointed that cryogenic separation method has the most economically viable capture rate; however, it is still in its early stages of development and requires the maximum amount of energy. While membrane separation is considered to be the method that occupies the least amount of space and adds the least amount of weight, it requires considerable pretreatment of the flue gases, which is also associated with a high energy need for this technology.

The technology of NH3 absorption was determined to have the greatest spatial requirements in the comparison. However, it exhibits a low level of power consumption and offers benefits in relation to the use of sulphurous particles in exhaust gases. Additionally, it has attained the highest Technology Readiness Level (TRL) thus far. Among the three technologies considered, the study (Harvenstein and Weidenhammer, 2021) identifies the absorption process utilising an aqueous ammonia solvent as the most favourable technology for shipboard applications, including both newbuildings and retrofit solutions for existing vessels.

One notable drawback associated with the utilisation of this particular solvent is the occurrence of ammonia slip (Molina and Bouallou, 2015). Numerous scholars have conducted investigations on the subject of ammonia losses. Ammonia slip is effectively mitigated through the incorporation of additives into the solvent, as demonstrated in studies conducted by Seo et al. (2012) and You et al. (2008). The recommended method for post-combustion capture of CO2, which is the primary greenhouse gas, is often chemical absorption utilising monoethanolamine (MEA) due to its notable reactivity with CO2. However, it has been widely acknowledged in the literature that the process of regeneration in MEA systems requires a significant amount of energy and is susceptible to various degradation processes (Franco et al., 2009; Gouedard et al., 2012; Pellegrini et al., 2011). Consequently, academic endeavours have been directed towards enhancing and advancing the quality of solvents utilised for the purpose of carbon dioxide (CO2) extraction (Amann and Bouallou, 2009, Chen et al., 2013). For example, the use of ammonia solvent has proven effective in eliminating gases like NOx and SO2 (Duncan, 2003). In more recent studies, aqueous ammonia solvent has been proposed as a viable substitute for CO2 capture (Li et al., 2003, Yeh et al., 2005, Yeh and Bai, 1999). One of the advantages of ammonia solution is its lack of deterioration and improved stability, particularly in comparison to oxygen.

Other issue with ammonia is health hazard. Ammonia, a gas known for its harmful and irritating properties, has been found to have negative impacts on the respiratory tract, eyes, sinuses, and skin of both humans and animals. These effects include conditions such as asthma, chronic bronchitis, conjunctivitis, calcific band keratopathy, and skin irritation. This information has been supported by studies conducted by Tasistro et al. (2007), Rollins and Barnes (2010), Kearney et al. (2014), and Nemer et al. (2015). An ammonia concentration exceeding 0.7 parts per million (ppm) is associated with a strong, irritating smell. In the range of 50 to 150 ppm, ammonia exposure can cause significant coughing and excessive production of mucus in humans (Leduc et al., 1992; Rollins and Barnes, 2010). Therefore, using ammonia as solvent in shipboard carbon capture system requires careful designing, space orientation and health consideration.

The implementation of carbon capture technology holds promise in substantially mitigating the carbon emissions associated with the shipping sector (Bortuzzo et al., 2023). Nevertheless, it is important to note that the current state of technology in this field is still in its nascent phase, especially in comparison to shore based industrial systems. Consequently, there are noteworthy obstacles that must be addressed, such as financial implications and technological limitations (Burima et. al., 2022).

Within this framework, extensive research conducted by the authors Bortuzzo and others have facilitated the identification of three distinct Carbon Capture technologies (Bortuzzo et. al., 2023). These technologies have the potential to be implemented aboard ships, therefore effectively mitigating the overall carbon footprint associated with the shipping sector. The following technologies are enumerated below:

This study explores three different carbon capture systems;

1. CC with Amines
2. CC with Molten Carbonate Fuel Cells (MCFCs), and
3. CC with Calcium Hydroxide.

The researcher of this study after considering reviewed literatures on the basis of energy requirements, space orientation, health and safety issues on board want to consider these potential CC technologies as the forerunner in mitigating GHG emissions from ships.

6.4 Carbon Capture with Amines

The use of amine solvents for post-combustion carbon capture is a widely acknowledged and recognised technological approach (Bortuzzo et. al., 2023). The procedure entails the use of amines as solvents for the purpose of capturing carbon dioxide from the exhaust gas stream (Parekh et. al., 2023).

Amines are a category of organic compounds characterised by the presence of nitrogen atoms that are covalently bound to one or more carbon atoms. The amines may be classified into three fundamental groups, namely primary, secondary, and tertiary amines. Primary amines are characterised by the presence of a nitrogen atom directly connected to a single carbon atom. In contrast, secondary amines exhibit a nitrogen atom bonded to two carbon atoms, while tertiary amines include a nitrogen atom attached to three carbon atoms.

MEA is an acronym that denotes Monoethanolamine. This particular substance is classified as an organic amine. Monoethanolamine is synthesised by the chemical process involving ammonia and ethylene oxide. The chemical formula of MEA is C2H7NO, and its molecular structure comprises a hydroxyl group (-OH) bonded to a primary amine (NH2) group.

Certain amines like MEA, have the ability to undergo a reaction with carbon dioxide (CO2) resulting in the formation of carbamates (Block and peter, 2023). This reaction involves the loss of an electron by the nitrogen atom, which then forms a bond with CO2. Nevertheless, tertiary amines (NR3) can undergo hydrolysis, a chemical reaction facilitated by water, resulting in the creation of a hydrogen carbonate ion (HCO3−), as seen below equation 1 (Yamada, 2021).

$$CO2 + NR3 + H2O \rightarrow HNR3+ + HCO3- \qquad (1)$$

Absorption being the most used CC system in the shore-based industries and power plants, several research were carried out using amines as absorbing medium for use in maritime industries. Zhou and Wang (2014) conducted an initial examination into the use of CCS systems, focusing specifically on the solidification and storage of CO2 in ships. This work is considered one of the early contributions in the literature on this topic. The study conducted by Wang et al. (2016) delved into the numerical analysis of computational fluid dynamics results and experimental findings in their subsequent research. The initial comprehensive examination of solvent-based carbon capture and storage (CCS) systems implemented on maritime vessels is credited to the research conducted by Luo and Wang (2017). The enzymatic process of CO2 hydration in oscillating structured packed-bed columns was investigated by Iliuta and Larachi in their study conducted in 2017 (Iliuta and Larachi, 2017). Awoyomi et al. developed a novel approach in research in 2019 wherein the simultaneous collection of CO2 and sulphur oxide was achieved within the context of a CCS system used on maritime vessels. The study conducted by Awoyomi et al. (2019) examined the utilisation of ammonia for the purpose of capturing emissions. The investigation focused on analysing the concentration of ammonia as well as the various engine loads. Feenstra et al. (2019) conducted a study in which they examined two distinct engines and two distinct solvents for a vessel, employing two different types of fuels, namely diesel and LNG. Trivyza et al. (2018) conducted a study focused on the evaluation and enhancement of energy efficiency and emission mitigation strategies for an Aframax tanker. The research explored various methods, including the utilisation of liquefied natural gas (LNG), diesel fuel, exhaust gas recirculation, selective catalytic reduction, scrubber technology, fuel cell applications, and carbon capture and storage (CCS) systems. The investigation also considered the influence of environmental conditions on them. The optimisation approach employed in this work was the non-dominated sorting genetic algorithm (NSGA) - II, as described by Trivyza et al. (2018). In their subsequent research, which was published in 2019, the authors conducted an investigation of the life cycle cost (LCC) of a cruise ship, focusing on four distinct carbon tax schemes. According to Trivyza et al. (2019), the use of Pareto analysis leads to the determination that the most optimal approach for attaining the International Maritime Organisation's 2050 objective involves the simultaneous utilisation of liquefied natural gas (LNG) as a fuel, waste heat recovery (WHR) system, and carbon capture and storage (CCS) system.

In 2021, Güler and Ergin conducted an examination of the utilisation of solvent-based CCS systems on various sizes and types of ships. The objective of this study was to examine the impact of hydraulic design parameters of separation columns on the efficacy of CCS systems in merchant vessels. The aim was to achieve a 50% reduction in the energy efficiency design index (EEDI) or energy efficiency existing ship index (EEXI) value, as compared to the baseline energy efficiency design index (EEDI) phase 0. Moreover, the objective of this study was to ascertain the most viable way for controlling CO2 emissions in various types and sizes of ships. This was achieved by conducting a comparative analysis between the CCS system and alternative CO2 capture systems, considering their efficacy in lowering CO2 emissions and associated costs. In order to achieve the objective, the process modelling software Aspen HYSYS is employed to simulate the solvent-based CCS and power systems of a VLCC tanker as well as various sizes of LNG carriers, including Q-Max, Q-Flex, and traditional LNG carriers. The simulation of waste heat recovery systems (WHR) in the vessels is also conducted. Next, an analysis is conducted on the expenses of CCS systems in relation to CO2 collection, taking into consideration several dimensional characteristics that impact the hydraulic designs of these systems. The investigation focused on analysing the various costs associated with the CCS system, including the expenses related to MEA composition, freight loss, WHR loss, liquefaction equipment, liquefaction power, capture equipment, capture power, and heat prices for the VLCC ship. Subsequently, a comparative analysis is conducted between the expenses associated with solvent-based CCS systems and the expenditures incurred by using LNG and implementing speed reduction techniques for VLCC tankers and various capacities of LNG carriers. The phenomenon of boil-off gas arises within the cargo tanks of LNG carrier vessels when the temperature exceeds the authorised storage temperature for liquefied natural gas. The expulsion of the gaseous substance in a state of boiling is vital from the containment vessels. The use of boil-off gas as fuel is a key feature in the operation of emerging gas injection main engines, and its significance was examined in the study conducted by Güler and Ergin (2021).

6.4.1 Ship Based Carbon Capture with Amines- Process Description

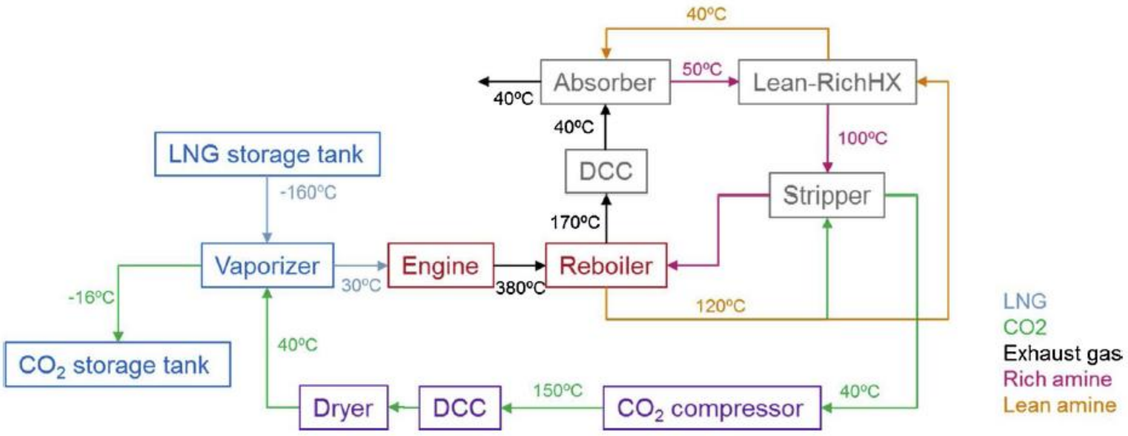
In a typical post-combustion process, the flue gas comes into contact with a solvent used for CO2 collection in a counter-current manner within the absorption column. Carbon dioxide (CO2) undergoes a phase transition into the liquid state, during which it engages in a chemical reaction with the solvent to predominantly produce carbamates. The gas depleted of CO2 is discharged into the atmosphere from the upper portion of the absorber. The solvent containing a high concentration of CO2 is transferred to the stripper column. The reboiler is supplied with heat at the lower section of the stripper column. The use of heat induces the reversal of the carbamate formation reaction, leading to the regeneration of the amine compound and the liberation of carbon dioxide. In Ship-Based Carbon Capture (SBCC) system, the provision of heat is facilitated by the utilisation of ICE exhaust gas. The emission of carbon dioxide (CO2) occurs in a gaseous state at the uppermost section of the stripper column. In order to achieve a cost-effective method of storing carbon dioxide, it is necessary to convert it into a liquid state. The lean amine solution is returned to the absorption column, so completing the cycle.

Figure 6.1 illustrates the suggested amalgamation of a post-combustion carbon dioxide (CO2) collection system with a liquefied natural gas (LNG) powered vessel, displaying approximate temperature levels (Feenstra et al., 2019). In this context, the thermal energy required for the reboiler process is supplied by the high-temperature exhaust gas. Additionally, the liquefaction of CO2 is facilitated by the cooling effect resulting from the evaporation of LNG. Hence, the SBCC system demonstrates a high level of integration with the pre-existing units.

Feenstra et al., investigated two carbon dioxide (CO2) absorption solvents, namely a solution containing 30% (weight) monoethanolamine (MEA) and another solution containing 30% (weight) piperazine (PZ) .

It was considered ships that are fuelled by LNG, it is possible to utilise the LNG vaporisation unit as a heat sink for the CO2 liquefaction unit, hence eliminating the need for a separate refrigeration unit. When considering ships powered by diesel fuel, it is necessary to have a specialised refrigeration unit.

Figure 6.1 Schematic representation of SBCC with MEA solvent and LNG as fuel (Feenstra et al., 2019)



The successful implementation of carbon dioxide (CO2) capture on a ship necessitates the integration of a post-combustion CO2 capture unit beside CO2 storage tanks, in conjunction with the ship's units. As mentioned earlier although there is existing proven technology for the capture and liquefaction of CO2 in industrial settings, the idea of implementing and running these units on cargo ships is a relatively new notion that presents several obstacles and opportunities.

6.5 Carbon Capture with Molten Carbonate Fuel Cell (MCFC)

Several studies have been conducted to examine the application of fuel cell technologies on ships, both in theoretical and practical contexts. These investigations have utilised high temperature fuel cells, such as molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs), as well as low temperature fuel cells, such as proton exchange membrane fuel cells (PEMFCs) for Component sizing and energy management for ship’s power systems (Haseltalab et al., 2021).

Molten carbonate fuel cells, often known as MCFCs, are a specific kind of fuel cell that have been recognised as an efficient method for removing carbon dioxide from waste gas (Bortuzzo et al., 2023).

Electrolytes in MCFCs come from a combination of several carbonate salts. These cells need to be heated to high temperatures, namely approximately 650 degrees Celsius, in order to melt the carbonate salts.

In order for the fundamental reaction to take place inside of an MCFC, the heated anode has to be supplied with a hydrogen-rich gas (H2). This aids in the dissolution of the carbonate ions and makes it possible for them to function as electrolytes during the oxidation of the hydrogen into H+ ions.

On the other hand, the cathode has to have a constant supply of carbon dioxide (CO2) in order to avoid the depletion of the carbonate ions that are formed as a result of the reduction of oxygen that is coupled to the CO2. That CO3(2–) carries the charge through the electrolyte to a nickel anode on the other side, where it reacts with hydrogen to yield water, two electrons, and CO2. The outlet gas is around 70% CO2, and the balance is H2 and H2O—a mixture better for carbon capture, storage, and utilization than raw flue gas, which is 10% CO2 diluted in nitrogen. Because of this, the generation of carbon dioxide gas from the system is essential for the MCFC that is collected there.

6.5.1 Molten Carbonate Fuel Cell Chemical Balance

To construct low-carbon power output integrating MCFCs, particularly material balances, the core chemistry and projected thermal performance to be noted from the literature. The MCFCs undergo the following reactions when operated at 650°C (Spinelli et al., 2015).

Hydrocarbon Reforming (CH_4 only shown)
$CH4+H2O \rightleftarrows 3H2+COCH4+H2O \rightleftarrows 3H2+CO$

Water-gas shift
$CO+H2O \rightleftarrows H2+CO2CO+H2O \rightleftarrows H2+CO2$

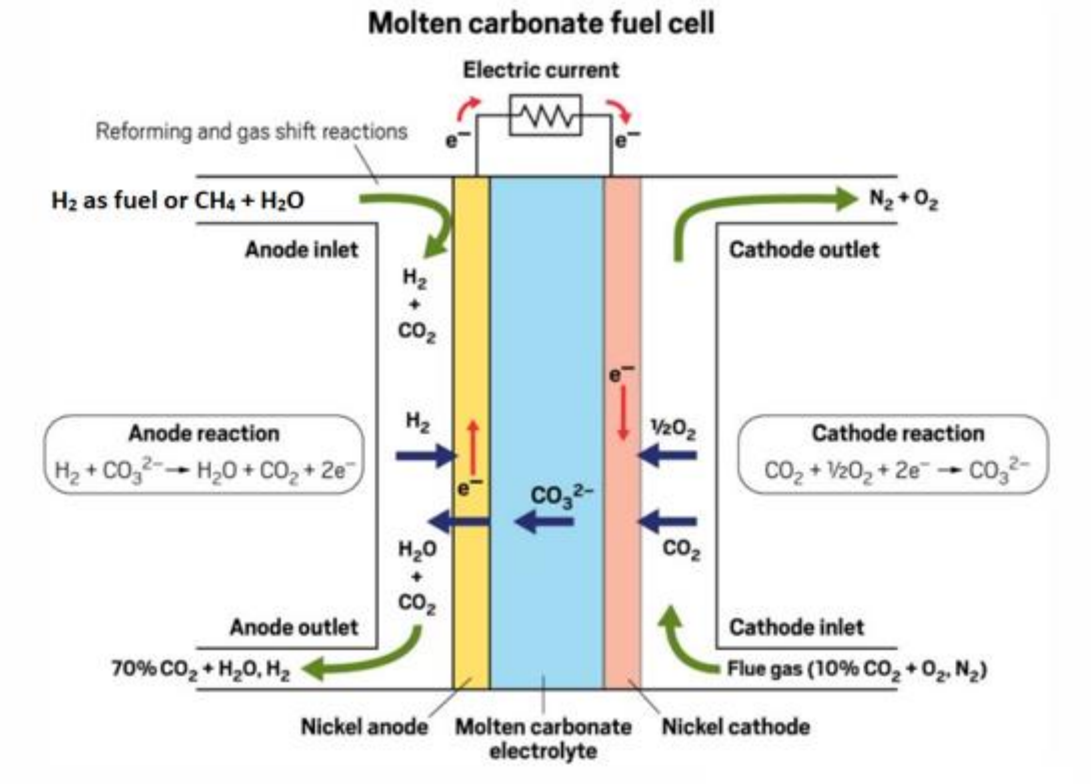
Hydrogen conversion at anode
$H2+CO=3 \rightarrow H2O+CO2H2+CO3= \rightarrow H2O+CO2$

CO_3 formation at cathode
$1/2O2+CO2+2e- \rightarrow CO=31/2O2+CO2+2e- \rightarrow CO3=$

Theoretical overall reaction
$CH4+2H2O+2O2+4CO2 \rightarrow 4H2O+5CO2CH4+2H2O+2O2+4CO2 \rightarrow 4H2O+5CO2$

After carefully examining the material balances that were presented in the published research (Spinelli et al., 2015), it was discovered that it was possible to make the assumption that the reforming reaction would finish under these conditions, while the shift reaction would reach around 70 percent conversion.

Figure 6.2 Molten Carbonate Fuel Cell basic components, adapted from Int. J. Hydrogen Energy/IEA



The ability to separate carbon dioxide from the original cathodic flow, via the CO3⁻⁻ ions transit through the electrolyte, is unique to the mechanism of CO2 transport across the MCFC. This may be advantageous when the MCFC is used as a carbon capture system and fed with exhaust gases from a fossil-fuelled marine diesel engine.

MCFC are economically feasible at power output capacities of medium to low power (less than 10 MW) (Discepoli et al., 2012). One configuration that may be interesting would be to utilise them to capture CO2 from internal combustion engines that are employed as power generating systems or main propulsion plants on ships. These types of engines are often utilised on board ship that have an overall electric power output that ranges from less than a megawatt (MW) to a few tens of MW.

6.5.2 Ship Based Carbon Capture with MCFCs- Process Description

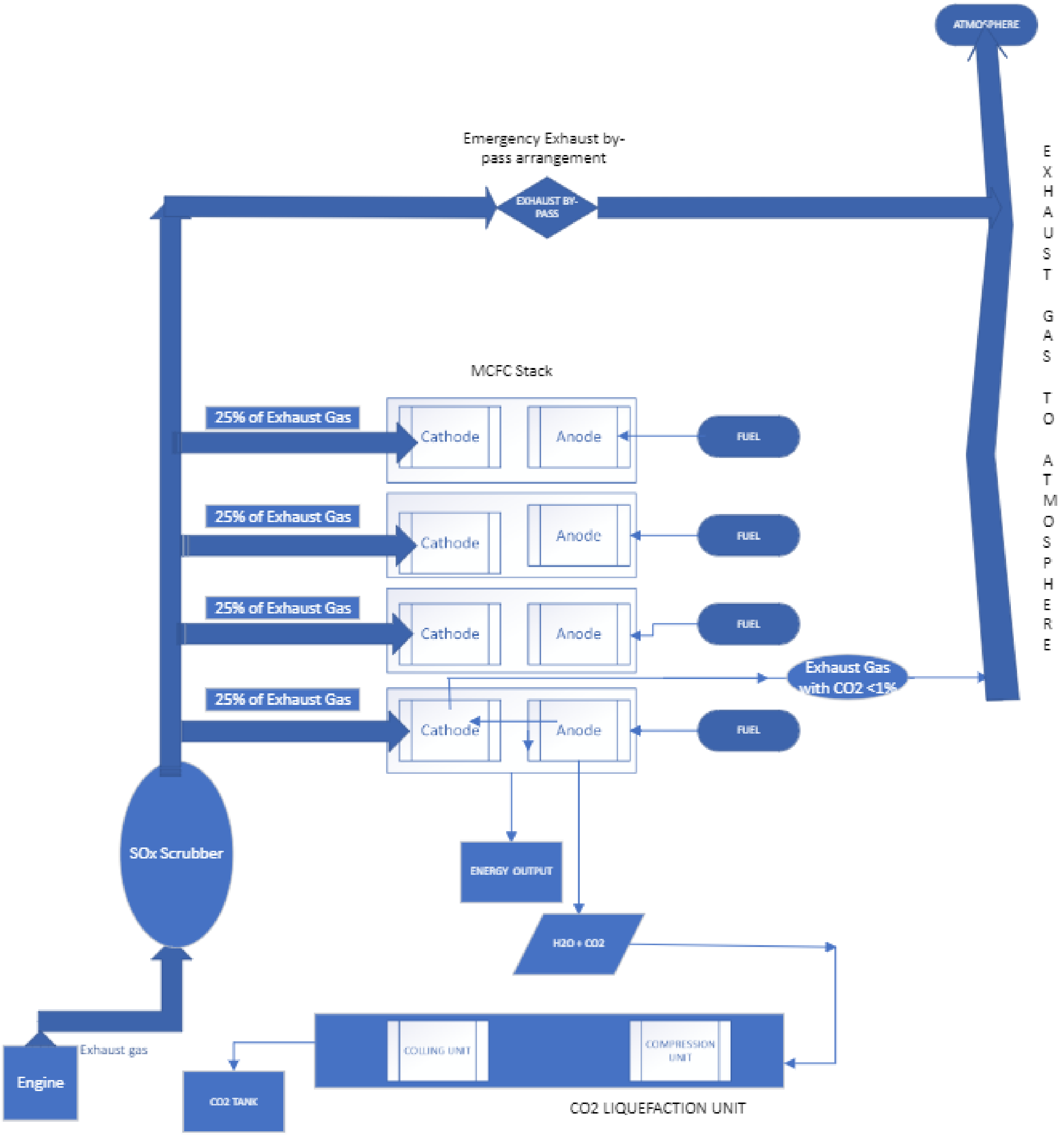
The procedure begins with the engine's exhaust emissions being sent to a SO2 scrubber. In the typical MCFC cathode, around 25% of the exhaust gases, including CO2, are collected and mixed with O2. In contrast, the anode is powered by a fuel source. Because MCFCs operate on hydrogen (H_2), any fuel that provides hydrogen by external reforming/cracking or directly within the cell might be utilised aboard ships, including LNG, bio-LNG, hydrogen, ammonia, syngas, and others.

The MCFC's output may be summarised as follows:

> The anode will produce H2O + CO2, which will be sent to a CO2 liquefaction plant for further processing. The CO2 will be delivered to a compression unit, then to a chilling unit, and lastly to a designated tank where it will be maintained liquid at low temperature and pressure. CO2 will then be discharged in port and carried to a storage location.
>
> The cathode output will be exhaust gas with a CO2 content of <1%, which will be released into a funnel with the untreated exhaust gas if any and ultimately into the atmosphere.
>
> Auxiliary electrical power output from MCFC fuel cells

Following a review of the available data on MCFC technology, the author constructed a prospective carbon capture system appropriate for installation on board a vessel, as shown below in schematic diagram.

Figure 6.3 Schematic for MCFC stack for CC from ICE, adapted from Bortuzzo et al., 2023



(The diagram only shows output from one MCFC unit, other MCFC units will have similar output of CO2, energy, and exhaust gas with CO2 <1%)

It is obvious that employment of several MCFC fuel cells stack in parallel to exhaust gas flow line could extract nearly 99% of the CO_2 from exhaust gases generated from shipboard auxiliary and main diesel engines.

In the study conducted by Alkaner et al. (2018), a life cycle assessment was carried out to evaluate the utilisation of a molten carbonate fuel cell (MCFC) stack in comparison to diesel engines aboard a vessel. This evaluation was conducted within the context of the European CSHIP-Fuel Cell Technology in Ships project.

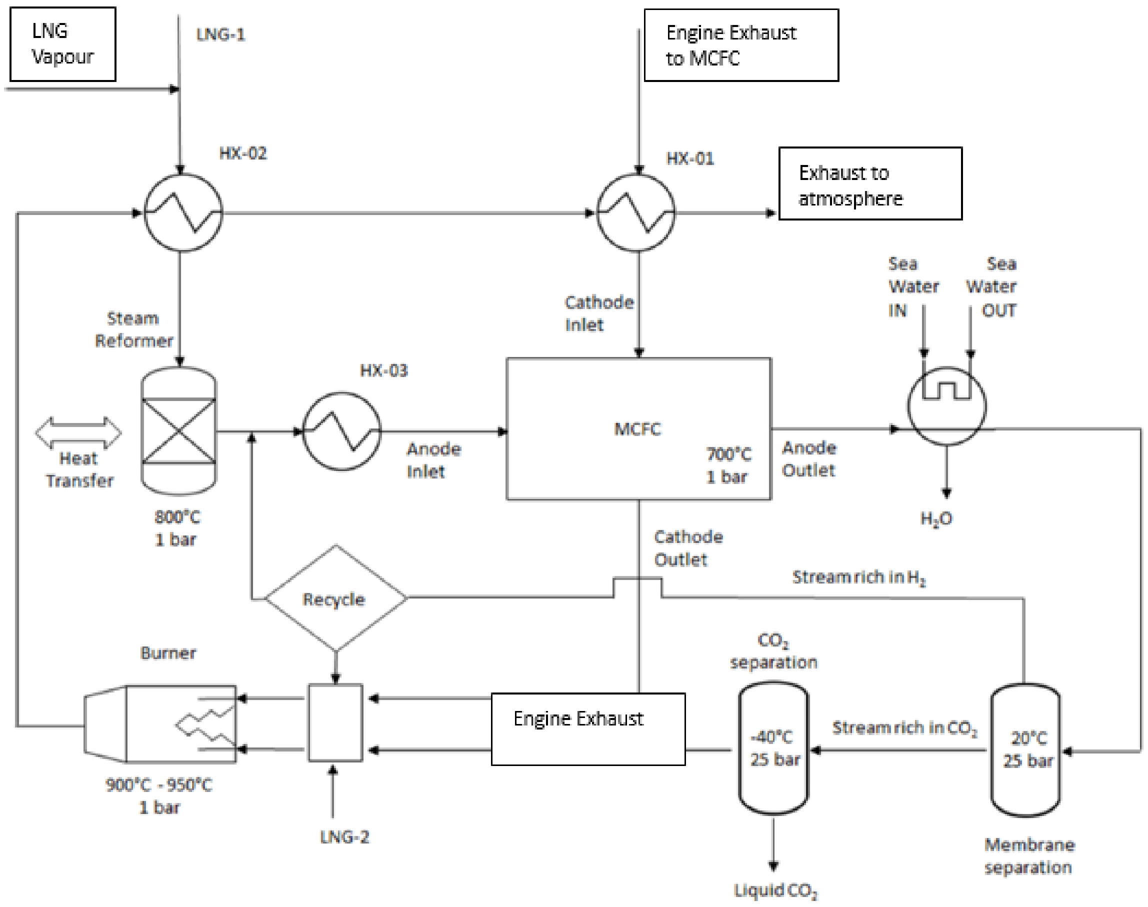
Regarding MCFC, the vessel Viking Lady, as part of the Norwegian/German FellowSHIP project, was the pioneering vessel to utilise MCFCs as auxiliary propulsion systems. This involved the installation of 500 cells, generating a power output of 320 KW. Notably, the Viking Lady successfully operated for a duration of 18 hours (Ovrum and Dimopoulos, 2012). The Italian MC-WAP project investigated the application of a 500 kW MCFC stack as a supplementary power source for both cruise and commercial ships (Specchia et al., 2008).

The US Ship Service Fuel Cell (US SSFC) project examined the use of MCFC to bridge the disparities between current fuel cell technologies and the specific needs of fuel cells employed in naval contexts. As part of this endeavour, a 625kW stack was assessed and developed (Elkafas et al., 2023).

The complete substitution of combustion engines with one or more fuel cell stacks cannot be seen as a straightforward proposition. It is evident that fuel cells have been in testing for quiet sometime in the maritime industry to use them as means of power source. Therefore, combining these fuel cells as carbon capture machines would reduce carbon footprint of the maritime industry.

Bosio et al., (2023) examined two distinct retrofitting options for passenger vessels that utilise high temperature fuel cells. These options pertain to vessels operating with either HFO or LNG. There are two potential approaches to achieve emission reduction: (i) utilising Solid Oxide Fuel Cells (SOFCs) to generate electricity instead of engines, resulting in a 20% reduction in emissions, or (ii) decreasing engine power by around 10% and compensating for the power demand by employing Molten Carbonate Fuel Cells (MCFCs) with Carbon Dioxide (CO2) capture technology. Both fuel cell stacks were simulated using a basic one-dimensional model in order to provide an initial approximation of the system's capacity. Both methods shown the ability to mitigate CO2 emissions, thereby enabling the tested vessels to comply with the requirements set forth by the International Maritime Organisation (IMO). Nevertheless, it has been noted that the implementation of solid oxide fuel cells (SOFCs) would necessitate a significant overhaul in the ship's machinery arrangement and design. Conversely, the utilisation of molten carbonate fuel cells (MCFCs) offers a comparatively simpler retrofitting process, eliminating the need for a demanding upgrade. The schematic representation of MCFC CC unit with LNG as fuel and semi-permeable membrane to separate H2 and CO2 before cryogenic liquification is shown in below diagram figure 6.4.

Figure 6.4 Schematic of the MCFC and semipermeable membrane on board to cut CO2 emissions, adapted from Bosio et al., 2023



6.6 Ship based Carbon Capture system with Calcium Hydroxide

One potential approach for capturing CO2 is through CO2 bonding, which involves the creation of insoluble carbonate salts. This can be achieved by carbonating a caustic solution that absorbs CO2. The utilisation of an aqueous solution of Ca(OH)2 as a solvent for the absorption of CO2 is highly successful due to its numerous favourable characteristics (Han et al., 2011). To begin with, calcium (Ca) possesses the advantageous qualities of being cost-effective, widely available, and lacking in harmful properties. The precipitation of calcium carbonate (CaCO3) resulting from the carbonation process of an aqueous solution of calcium hydroxide (Ca(OH)2) is a well-known and widely seen reaction in the natural world. Furthermore, there are options for reclamation and regeneration in order to properly dispose of the generated CaCO3.

The practise of closed reclamation within a confined region has emerged as a sustainable and enduring method for storage. The economic viability of direct reclamation of CaCO3 may surpass that of traditional CO2 sequestration due to the lack of additional expenses associated with CO2 liquefaction and shipping (Han et al., 2011).

Calcium oxide, scientifically referred to as CaO, is a solid substance that is often known as lime or quicklime. It is typically observed as a white or greyish white compound and is generated on a massive scale through the process of heating calcium carbonate to eliminate carbon dioxide. Under ambient conditions, calcium oxide (CaO) exhibits the propensity to undergo a spontaneous process of carbon dioxide (CO2) absorption from the surrounding environment, thereby causing the reaction to proceed in the opposite direction. Additionally, it has the capacity to undergo water absorption, resulting in the conversion of the substance into calcium hydroxide $Ca(OH)_2$ and the liberation of thermal energy. The reaction is shown in equation (2) below. The generation of bubbles that accompanies the chemical reaction is the origin of its designation as "quick," or vital, lime. The exothermic reaction between quicklime and water is occasionally employed in portable heat sources. Quicklime, which is considered one of the most ancient outcomes of a chemical reaction, finds widespread application as a construction material (Encyclopaedia Britannica. 2019).

$$CaO+H_2O \rightarrow Ca(OH)_2 \quad (2)$$

In this chemical reaction, calcium oxide (CaO) and water (H_2O) undergo a reaction to produce calcium hydroxide ($Ca(OH)_2$) along with the release of heat. The aforementioned reaction can be conducted through the combination of a slurry of calcium oxide (CaO) with water or by introducing water to powdered calcium oxide (CaO).

Carbon capture systems utilise a mechanism wherein they collect carbon dioxide (CO_2) from flue gases, which are emissions originating from power plants, industrial activities, and ship engines. This absorption process involves a chemical reaction with calcium hydroxide ($Ca(OH)_2$), resulting in the conversion of CO_2 into calcium carbonate ($CaCO_3$). This reaction can be represented by Equation (3):

$$CO_2+Ca(OH)_2 \rightarrow CaCO_3+H_2O \quad (3)$$

The calcium carbonate can thereafter be discarded or utilised for other uses. Calcium carbonate ($CaCO_3$) is widely recognised as the primary calcium compound of utmost significance. It serves as a principal constituent in various geological formations such as limestone, marble, chalk, oyster shells, and corals. Calcium carbonate, derived from its natural sources, serves as a filler in a diverse range of products, including ceramics, glass, plastics, and paint. The utilisation of synthetic calcium carbonate, known as "precipitated" calcium carbonate, is necessary in situations where a high level of purity is desired. This is particularly evident in the field of medicine, where it is used in the production of antacids and dietary calcium supplements. Additionally, it finds application in the food industry, specifically in the production of baking powder. Furthermore, it is utilised for laboratory reasons (Encyclopaedia Britannica. 2019).

6.6.1 Ship Based Carbon Capture with Ca(OH)2- Process Description

The initial step involves the routing of engine-generated exhaust gases to a wet electrostatic precipitator. This device serves to reduce the presence of dust and SO3, which, if left uncontrolled, might accelerate the degradation of the wet solution. Subsequently, the exhaust gases are routed onto a SO2 scrubber. Approximately 25% of the emitted exhaust gases, which consist of carbon dioxide (CO2) among other substances, and subsequently channelled into the bottom compartment of the carbon dioxide scrubber. This process operates within a closed loop system. Arranging stack of CO2 scrubber units in parallel then can accommodate whole flow of exhaust gas stream from ship’s ICEs.

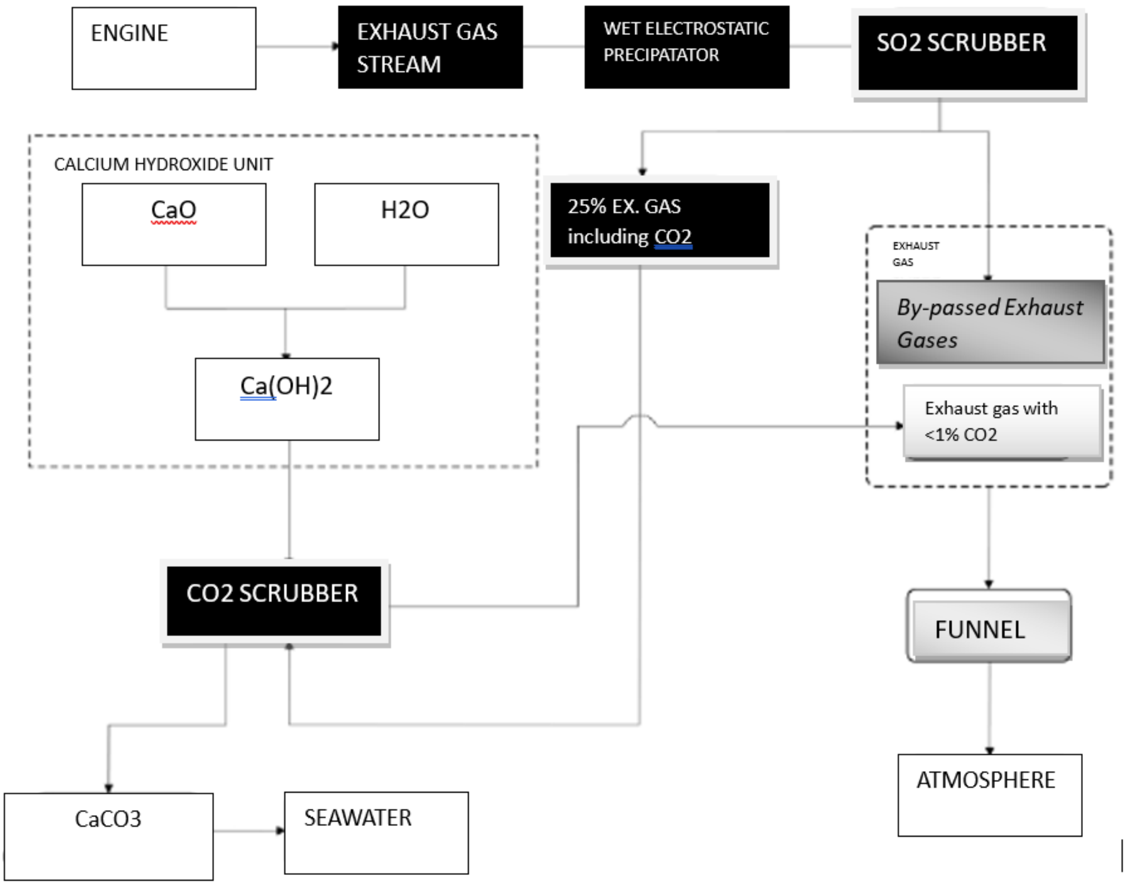
The calcium oxide (CaO) that is stored in a dedicated tank on board as a solid bulk powder is drawn out and undergoes a reaction with water (H2O) when mixed, resulting in the formation of calcium hydroxide (Ca(OH)2).

The calcium hydroxide (Ca(OH)2) is introduced into the upper portion of the carbon dioxide (CO2) scrubber by injection. The lower portion of the scrubber is where the exhaust gases are introduced, and they flow in a direction opposite to the calcium hydroxide solution. As a result, the exhaust gases undergo a process of being washed through contact with a suspension of calcium hydroxide. The reaction between calcium hydroxide and carbon dioxide results in the formation of calcium carbonate (CaCO3) and water (H2O), as represented by Equation (3).

The resulting output of the CO2 Scrubber will consist of the following components:

The exhaust gas, containing a carbon dioxide (CO2) content of less than 1%, will be discharged into the atmosphere through a funnel, along with the untreated exhaust gas. Additionally, small particles of calcium carbonate (CaCO3), a somewhat soluble and environmentally benign substance, may be directly released into the water or collected for shore disposal for other uses. Bortuzzo et al., (2023) proposed a schematic design of a SBCC arrangement using Ca(OH)2 as capturing medium in following diagram.

Figure 6.5 Schematic of the SBCC with Ca(OH)2 to cut CO2 emissions, adapted from Bortuzzo et al., 2023



This researcher understands that stack of CO2 scrubber units if arranged in parallel to divide exhaust gas stream among themselves then total reduction of CO2 emissions from ship's engines could be substantially attained.

Nevertheless, the aqueous solution of Ca(OH)2 has not attracted much research interest in the field of CO2 collection due to two inherent constraints. The primary source of Ca(OH)2 (or CaO) has predominantly been derived from natural limestone. However, the extraction process involved in obtaining these compounds is highly energy-intensive, resulting in a significant rise in CO2 emissions. The subsequent concern is to the appropriate management of the substantial quantities of CaCO3 and water mixture that are generated. Consequently, the majority of research conducted on the carbonation of Ca(OH)2 has focused exclusively on the synthesis of precipitated CaCO3 (Han et al., 2011) .

Nevertheless, a plethora of cutting-edge technologies have emerged in recent times to tackle these challenges. Numerous scholarly articles have been dedicated to investigating alternative sources of calcium, such as the extraction of calcium from wollastonite (CaSiO3) and from calcium silicate (Ca2SiO4) found in different industrial byproducts, including municipal solid waste incinerator, ash, and steel slag (Sakita, et al., 2017). Furthermore, numerous recent research have provided reports on the formation of CaO through the thermal dissociation of CaCO3, a process commonly referred to as Ca looping (Anthony, 2011).

Despite the presence of various obstacles arising from the overall energy intensity and temperature demands associated with the calcination process, there exists significant potential for its application. This is primarily due to the ability to efficiently utilise high-temperature waste heat, such as that generated by solid oxide fuel cells or molten carbonate fuel cells, as well as concentrated solar energy, for the purpose of Ca(OH)2 generation (Han et al., 2011).

The well to wake (WtW) concept for calculation of emitted CO2 as per IMO latest requirements or future integration of WtW in emmission calculation will have impact on utilising this process for SBCC system as CaO extraction is still a CO2 contributor for GHG unless CaO is produced through greener process.

CHAPTER SEVEN

7.0 Ship-based Carbon Capture Projects

7.1 CO2ASTS project

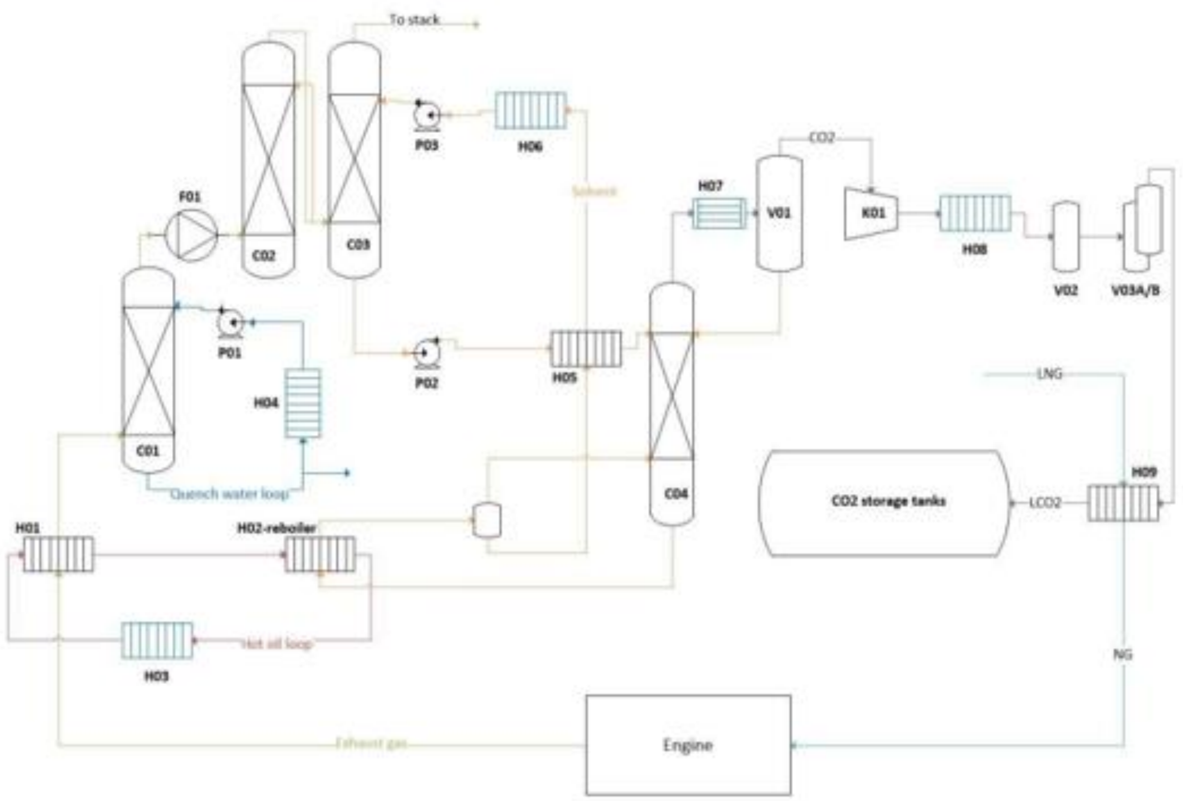
In the year 2020, there was a significant development in the field of carbon capture known as CO2ASTS. The Storage and Transfer in Shipping project examined potential shipping situations that could utilise Carbon Capture and Storage (CCS) technology.

The CO2ASTS technology is designed to specifically target the capture and storage of carbon dioxide emissions generated by liquefied natural gas (LNG) powered ships. This encompasses the process of carbon dioxide (CO2) absorption by an aqueous solution containing 30% monoethanolamine (MEA), a chemically reactive amine. Additionally, it involves the subsequent steps of liquefaction and on-board storage. The liquefied carbon dioxide (CO2) might thereafter be transported to the port and marketed to prospective consumers, particularly for the purpose of manufacturing sustainable fuels known as E-Fuels (Monteiro, 2020). Currently, there is a lack of a globally accessible system of similar nature for the purpose of shipping.

The project facilitates the transition towards a more sustainable and environmentally friendly shipping industry by promoting cross-border cooperation. This initiative aligns with the environmental and transport policy objectives of Germany, the Netherlands, and the European Union in the maritime sector. Furthermore, it contributes to the climate goals outlined in the Paris Agreement of 2015 (Monteiro, 2020).

The objects illustrated in Figure 7.1 exemplify the overarching notion of the CO2 capture unit used in the project.

Figure 7.1 Schematic of CO_2 capture in post-combustion approach (Monteiro, 2020)



The flue gas is delivered into an absorber column within a CO2 capture unit that utilises amine-based technology. In this process, the amine compound known as MEA undergoes a chemical reaction with CO2, resulting in the formation of chemical compounds. The reboiler of a stripper column employs heat to facilitate the regeneration of these substances, resulting in the conversion of amine and pure CO2 to their respective free forms. The freed amine is reintroduced into the absorber column, and the process is repeated. The condenser located at the top of the stripper column generates free CO2 with a purity level of around 98%. The presence of water is considered to be the most prominent contaminant. Carbon dioxide (CO2) is subjected to compression at a pressure of 7 bar, followed by a drying process, and subsequently transformed into a liquid state at a temperature of around -50ºC.

The process equipment (columns, heat exchangers, compressors pumps and valves, etc.) is standard and thus readily available on the market. Tanks are employed for the purpose of containing and preserving liquid carbon dioxide (CO2). LNG-fuelled ships integrate perfectly with carbon capture and liquefaction because the heat of the exhaust gas and the cold of LNG vaporisation can be used in the process, significantly lowering the process's operational costs. Heat is used in the solvent regeneration step, and cold is used in the CO2 liquefaction step (Monteiro, 2020).

CO2ASTS project used three distinctive ship cases for concept carbon capture technology (Monteiro, 2020). Among three cases, 1st case concept is highlighted below.

7.1.1 1st Ship case

The sea-river vessel which is used in the 1st case is powered by a modular LNG-electric propulsion system, with three Sandfirden GLA 821C gas generator sets fitted into a single 20-foot ISO container providing both propulsion and auxiliary power. The maximum total output is 1050 kW (Monteiro, 2020).

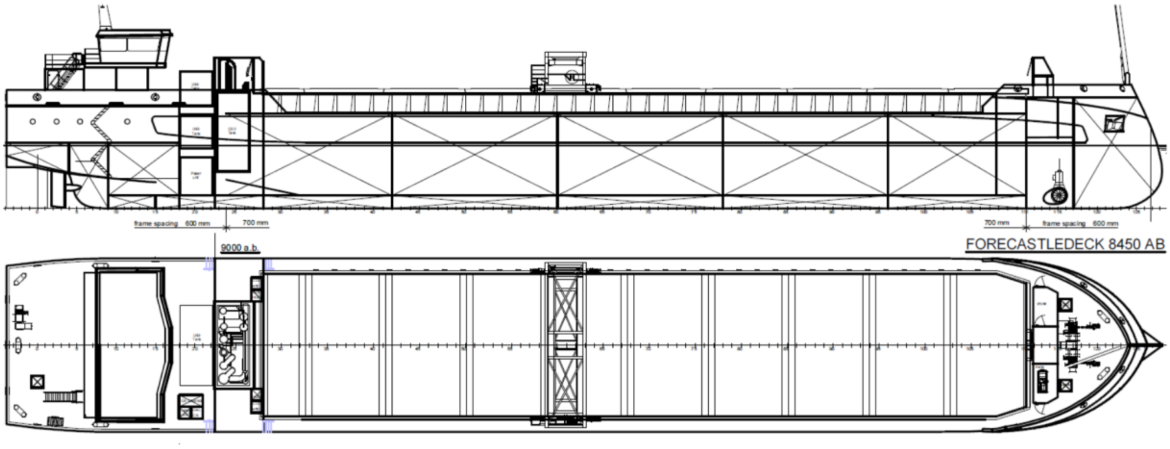
One or more tank containers hold fuel. Fuel capacity can thus be adjusted in response to demand. As a result, the capture and storage systems will be built on a 20-foot ISO container footprint; if additional fuel capacity is required on occasion, the capture plant and/or CO2 storage tanks can be replaced by fuel containers (Monteiro, 2020).

In this particular instance, the primary dimensions and onboard power requirement of the vessel adhere to the standard characteristics observed in sea-river vessels. Due to the similarity in total installed power with that of large inland freighters, the technology created for this specific use case holds potential for employing to a diverse array of vessels operating throughout European waterways.

7.1.2 Vessel Design

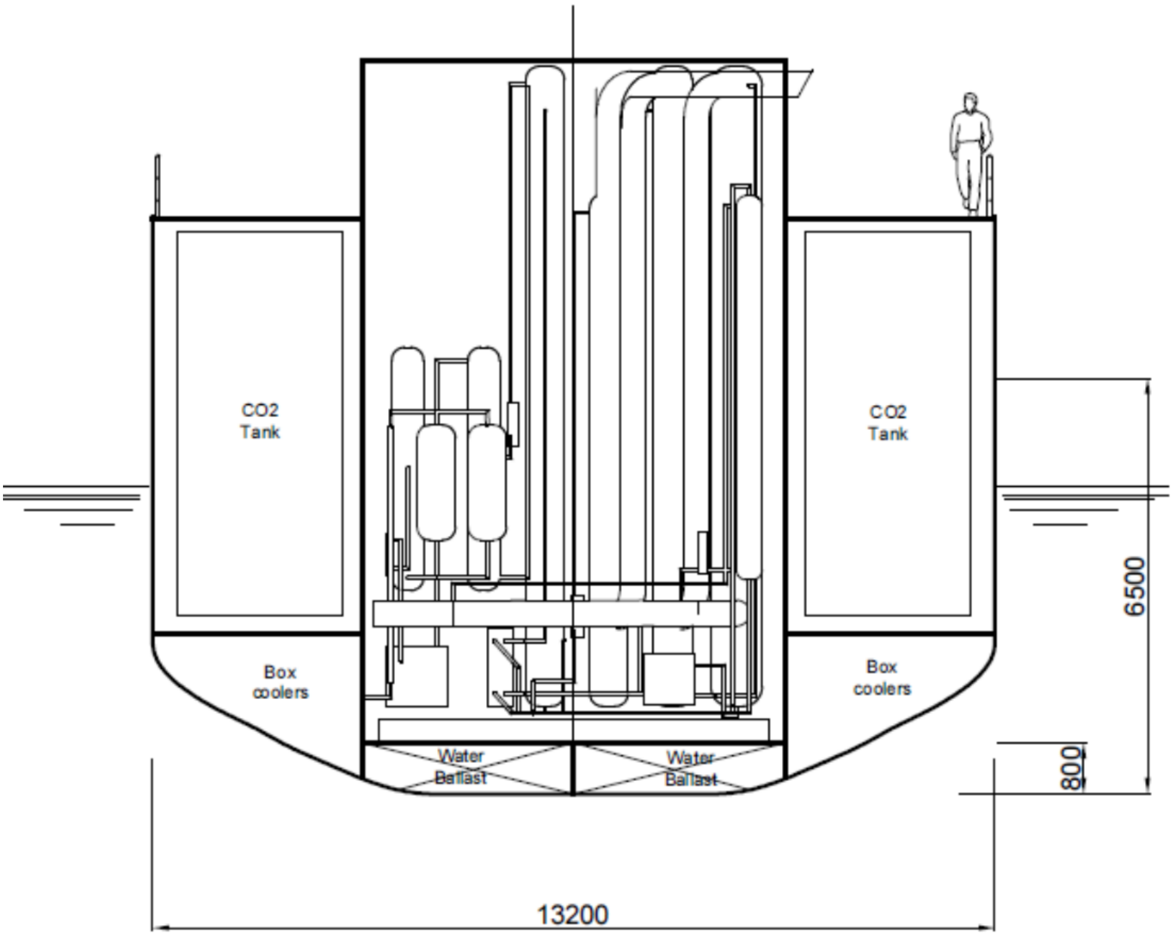
A conceptual arrangement of a capture module is devised, drawing inspiration from the planned CO2 capture liquefaction and storage facility. The capture system, like the fuel tanks and power plant, has a 20-foot container footprint, and the CO2 storage tanks are likewise 20-foot tank containers. Although the system has a modest footprint, it requires quite a bit of height: the top of the quench tower, as well as the absorber and stripper columns, is 10.5 metres above the skid's base (Monteiro, 2020).

Figure 7.2 Vessel General Arrangement(GA) Plan for sea-river vessel with CC system (Conoship International, 2020)



The stability analysis reveals that the heightened hold and the increased weight of the capture system and storage tanks do not exert a substantial influence on the stability of the vessel. There has been minimal alteration in the trim of the vessel as well (Monteiro, 2020).

Figure 7.3 Cross-sectional diagram (Transverse section in way of CC unit) ((Monteiro, 2020)



7.2 Other projects

7.2.1 K-Line project

Kawasaki Kisen Kaisha (K Line), a prominent Japanese shipping company, has successfully implemented a process to sequester and retain carbon dioxide (CO2) emissions derived from the exhaust gases emitted by the Corona Utility, a vessel mostly used for transporting coal.

The testing and installation of Carbon Capture on the Ocean (CC-Ocean) are components of a programme supported by the Maritime Bureau of the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), Japan (Mandra, 2020).

In collaboration with Mitsubishi Shipbuilding and the class society ClassNK, the aforementioned company has successfully built and conducted trials on a CO2 collection facility, which is said to be the first of its kind globally and intended for implementation on a vessel.

In early August 2021, Mitsubishi Shipbuilding deployed a small-scale CO2 capture plant on a vessel. Subsequently, a team of professionals from the company conducted operations, maintenance, and training activities for the ship's crew. These activities encompassed the operation of the plant, as well as the measurement, analysis, and evaluation of its performance.

The crew of the ship has been engaged in the operation, measurement, and maintenance of the plant since mid-September. The company persists on evaluating the safety and functionality of the CO2 capture plant to address pertinent problems and conduct research and development activities aimed at eventual commercialisation.

As per the statements provided by the firm, the captured carbon dioxide (CO2) exhibited a purity over 99.9% during the demonstration, aligning with the anticipated performance objectives.

7.2.2 DSME Project and ABS

In 2022, Daewoo Shipbuilding & Marine Engineering (DSME), a prominent South Korean company, undertook a verification test of their carbon capture and storage technology on an LNG carrier.

The onboard carbon capture and storage (OCCS) technology was developed through a collaborative effort with Hi Air Korea, a firm specialising in heating, ventilation, and air conditioning equipment. The firms has been engaged in the development of the technology since the year 2020 (Offshore-energy, 2022).

The methodology employs a solution containing ammonia water that serves to facilitate the process of dissolving carbon dioxide released by the engines of the ship (offshore-energy, 2022). The aforementioned procedure leads to the transformation of dissolved carbon dioxide into a mineralized state inside an aqueous solution comprising sodium hydroxide. Throughout the duration of the treatment, the absorbent material undergoes a process of regeneration, enabling it to be subsequently reused (Mandra, 2022).

The technology employed in this process effectively absorbs and securely stores carbon dioxide (CO2) as a supplementary output. Subsequently, the CO2 is transported to onshore facilities located at a designated port, where it is unloaded.

As mentioned earlier, the system exhibits a significantly lower energy consumption compared to alternative onboard carbon capture systems available in the market. Additionally, the amount of supplementary carbon dioxide generated during equipment operation is negligible (Offshore-energy, 2022).

The ship classification society ABS has also published their requirements for implementing onboard Carbon Capture and Storage (OCCS) in December 2022 (ABS, 2022) for post-combustion CC process. The primary aim is to mitigate potential hazards to the seafarer, ship, and the environment.

The document expands the scope of ABS standards pertaining to Exhaust Emission Abatement (EEA) equipment by include equipment that is installed for the purpose of eliminating, treating, and storing carbon dioxide (CO2) from exhaust emissions. The publication has been formulated to offer guidance pertaining to the design, development, installation, and survey of machinery and systems for the vessels and offshore units that incorporate Onboard Carbon Capture and Storage (OCCS) equipment (Offshore-energy, 2022). The technical focus of this guidance is on wet scrubbing post-combustion technologies.

The class society ABS acknowledges that the spectrum of OCCS technology is extensive and can be integrated with other EEA equipment. Consequently, the specific requirements for compliance will differ depending on the unique circumstances of each case. Nevertheless, the primary objective of the aforementioned publication was not to impede the implementation of any emerging technologies or systems that were not explicitly outlined in the specified requirements document (ABS, 2022). Systems specifically developed for the purpose of capturing either partial or complete amounts of carbon dioxide (CO2) will also be taken into consideration. Pre-combustion or fuel treatment technologies, which are capable of eliminating carbon before to combustion or utilisation in energy conversion systems like internal combustion engines, boilers, or fuel cells, may also be taken into account. In addition to solvent-based scrubbing systems, alternative approaches such as membrane-based or cryogenic distillation systems that facilitate the removal, processing, and storage of carbon in molecules other than carbon dioxide (CO2) will also be taken into account (ABS, 2022).

7.2.3 ROTOBOX Model

American Bureau of Shipping (ABS) announced in 2022 that they have provided New Technology Qualification (NTQ) to Rotobox (ABS, 2022). Rotoboost, a globally recognised Norwegian Hydrogen company, was granted a new certification by the ABS classification organisation for their pre-combustion carbon capture system. This system is founded on the thermocatalytic decomposition process.

The aforementioned method, considered a pioneering innovation, facilitates the ongoing production of hydrogen and the capture of carbon emissions on marine vessels. In the system, a liquid catalyst is employed to facilitate the conversion of LNG into H2 and solid carbon. The gas produced can be effectively employed in fuel cells, as well as in combustion engines or gas-fired boilers as a fuel mixture. Based on the findings of the ABS, the use of this method holds the capacity to significantly mitigate carbon emissions, with the potential to achieve a reduction of up to 100 percent, subject to the specific heating technology applied.

As mentioned earlier, the utilisation of hydrogen as an additive fuel holds promise in significantly reducing methane slip from combustion engines and mitigating the release of particulate matter emissions by sequestering carbon in a solid state prior to the combustion process.

The utilisation of a methane disintegration process to generate hydrogen and solid carbon is a strategic method for the integration of a carbon capture and storage (CCS) system within gas-powered maritime vessels. This technological advancement obviates the need for onboard storage, and the solid carbon may be repurposed and employed in the production of fuel cells and batteries. The aforementioned technology possesses the capability to expedite the process of transitioning to sustainable energy sources, while simultaneously aiding in the achievement of international goals for reducing carbon emissions.

CHAPTER EIGHT

8.0 Discussion and Conclusion

8.1 Discussions

The emission of greenhouse gases presents a substantial challenge for the worldwide shipping industry, necessitating the implementation of comprehensive solutions to address the emissions challenges and achieve the goals set by the world maritime body IMO in relation to greenhouse gas reduction. The 2023 IMO Strategy on Reduction of GHG Emissions from Ships, which includes heightened targets to address detrimental emissions, was adopted by the Marine Environment Protection Committee (MEPC 80) in July 2023. The new International Maritime Organisation (IMO) Greenhouse Gas (GHG) strategy incorporates an improved objective of achieving net-zero emissions from the global maritime industry by the designated goal year of 2050 (IMO, 2023). Additional, more ambitious objectives have been set for alternative measures pertaining to zero or near zero greenhouse gas (GHG) fuels for coming years. The European Union Emission Trading System (ETS) will be implemented in January 2024, encompassing all vessels of 5000 GT and over, regardless of their flag state.

In May 2022, the Japanese government put forth a fiscal stimulus package with the objective of promoting the reduction of carbon emissions within the shipping industry. The aforementioned project proposes the implementation of a worldwide carbon tax, whereby the shipping sector would be required to remit a sum of $56 per metric tonne of carbon dioxide emissions, commencing in the year 2025. The proposed plan by Japan entails a gradual increment in taxes at five-year intervals, ultimately culminating in a peak value of $637 per metric tonne of carbon dioxide by the year 2040. In addition, the plan posits that the carbon tax imposed on bunkers should be tripled, as each metric tonne of bunker fuel is estimated to generate around three metric tonnes of carbon dioxide. In greater depth, governmental entities and regulatory bodies, such as the International Maritime Organisation (IMO), the European Union (EU), and Ship Classification Societies, are currently adopting a novel taxation framework. This framework entails the inclusion of emissions considerations and adherence to specific tiers for each stage of the fuel logistic chain, namely production, distribution, and consumption.

Emission taxes in the maritime sector is a complex and evolving issue. It is conceivable that carbon taxes might be implemented in the future at different levels encompassing global, regional, or national contexts. On one hand, the implementation of penalties will compel shipowners to enhance their understanding of the significance of energy efficiency and promote the advancement and competitiveness of cleaner technologies. On the other hand, there remains a challenge in accurately forecasting the global availability of specific solutions, such as alternative fuels. The adoption of environmentally sustainable measures to mitigate atmospheric emissions has the potential to exempt shipowners from additional taxes. Few factors would be coming into consideration while deciding the possible CC approach such as revenue impact, vessel lifespan, retrofitting cost and operational cost. In the present context, various aspects assume significance in determining the viability of innovative technologies aimed at reducing CO2 emissions. These factors include the availability of the technology, the space necessary for its on-board installation, the ease of installation process, the technology readiness level (TRL), as well as the costs associated with its installation and subsequent maintenance. In the previous chapters, the author provided a comprehensive discussion of the potential CC systems implementable on ships.

The analysis and recommendation of potential CC systems on merchant ships has been based on the evaluations on the alternative system configurations and Technology Readiness Levels (TRL). The information presented in this study provides a foundation for future case studies that could provide significant technical and economic insights into the incorporation of onboard CCS systems.

The limited availability of time is becoming increasingly apparent, as evidenced by the shifting aims and the establishment of ambitious targets by organisations such as the International Maritime Organisation (IMO) and various regional and international entities, including governments. The examination of the Technology Readiness Level (TRL) served as a primary determinant in the assessment and suitability of the Carbon Capture (CC) systems within the framework of this research. Another element that contributed to the suggestions was the complexity of the systems and components of the proposed systems, as well as the potential implications of their integration into existing machineries on board.

8.1.1 1st Recommendation

The initial technology exhibiting promise in terms of Technology Readiness Level (TRL) is the Carbon Capture System with amine such as ammonia or MEA. Nevertheless, these systems are accompanied by substantial expenses and certain technological obstacles that must be addressed. There is a need for increased onboard room to accommodate both system allocation and CO2 storage which is discussed below in details.

Amine-based absorption techniques have achieved Technology Readiness Level (TRL) 9 in the context of onshore industrial applications. The quantity of scholarly works examining the implementation of this technology on maritime vessels is significantly greater, indicating that current research on carbon capture (CC) application mostly centres upon post-combustion absorption methods.

Secondly, the benefit of employing NH3 solvents in the absorption process is the reduced operating expenses (OPEX) resulting from the diminished energy requirements and chemical expenditures. NH3 is beneficial than MEA in this respect. According to Awoyomi et al. (2020), the thermal energy needed for regenerating the solvent can be effectively supplied by harnessing the waste heat generated by the engine. However, it is imperative to approach this premise with a critical perspective. Frequently, research investigations make the assumption that the entirety of waste heat may be utilised for the purpose of regenerating the solvent, resulting in the attainment of elevated energy efficiency and reduced operational expenditures (Awoyomi et al., 2020; Feenstra et al., 2019). However, it should be noted that the utilisation of waste heat from the engine's exhaust are used in engine turbo chargers for supply of air scavenging air at first then in waste heat boiler and other onboard heating system.

Thirdly, as said before, the post-combustion absorption process is the technology with the largest space demands among the technologies considered in the assessment. The technology's significant spatial requirements have been acknowledged by its low rating. The large space requirement may serve as a limiting factor for numerous shipowners. The utilisation of absorption technology may not be a viable option, particularly for smaller vessels, due to the constraints imposed by limited space and increased weight. These factors would significantly diminish the transport capacity of the vessel to a greater extent compared to larger vessels.

Fourthly, another contributing aspect that supports the implementation of carbon capture (CC) technology in larger carbon dioxide (CO2) sources, such as larger vessels, is the concept of economies of scale. According to the study conducted by Feenstra et al. (2019), it was observed that there is a decrease in the average expenses associated with capturing one tonne of CO2 by 28% when the capture-rate is increased from 60% to 90%. However, it is important to note that the capital expenditures (CAPEX) tend to increase with a higher capture-rate. The expenses associated with the possible capture of more CO2 are consequently resulting in a decline in the cost per metric tonne of captured CO2. But the considerable expenditures associated with carbon capture for small vessels may render the adoption of renewable fuels a more economically viable option compared to the implementation of a carbon capture plant.

Furthermore, the disposal of carbon dioxide (CO2) has notable challenges with the selection and management of appropriate storage locations for its release. Indeed, conducting an availability study of both current and prospective geological sites is essential for evaluating the adequacy of site availability. At present, the range of accessible possibilities is restricted, as the majority of storage sites necessitate the injection of carbon dioxide (CO2) into subsurface geological formations, a process that presents considerable challenges and financial burdens.

Furthermore, the efficient implementation of transportation procedures is crucial. An extra complexity arises from the requirement of compressing CO2 to high pressures or converting it into a liquid state for transportation, resulting in additional expenses. However, this storage and disposal arrangement is ever challenging for any CCS technologies when captured CO2 has to be stored on board for onward delivery to shore facilities either in off-shore installation or port facility.

In general, the use of absorption with aqueous ammonia or other amine solvents for post-combustion capture may not be a viable option for small ships. However, its notable attributes such as its elevated energy efficiency and low operational expenditure (OPEX) render it the most auspicious choice for carbon capture (CC) implementation on board larger vessels like tankers, big container ships, bulk carriers etc.

8.1.2 2nd Recommendation

The Calcium Hydroxide carbon capture system is considered the most straightforward among the three options discussed in chapter six from a technological standpoint and offers the benefit of requiring minimal onboard space. This technology could be particularly suitable for vessels where storage of CaO in bulk may not pose serious concern in terms of safety, cargo space utilization and handling of bulk product. Some of the bigger ships that already possess the necessary infrastructure for storing the chemical reagent (CaO), have capability of a continuous supply of the reagent essential for the carbon capture process. Moreover, the Calcium Hydroxide technology eliminates the need for onboard CO2 storage space, as the resulting substance (CaCO3) could potentially be safely released into the marine environment without causing any harm or may be safely stored in vessel until it is disposed to shore installation. This technique is particularly intriguing in relation to CAPEX and OPEX.

While certain manufacturers of the CC system argue in favour of the direct release of CaCO3 into the ocean, it is crucial to do a comprehensive impact research before making any choices regarding the unrestricted discharge of CaCO3 particles into the marine environment. The process of ocean acidification resulting from the increased levels of carbon dioxide (CO2) is a naturally occurring phenomenon. The phenomenon of oceanic carbon dioxide absorption possesses the capacity to induce a decline in the pH level of saltwater, hence leading to an elevation in its acidity. The previously described phenomena possess the capacity to reduce the availability of calcium carbonate, an essential resource utilised by marine organisms for the formation of their shells and skeletons. The phenomenon being discussed is popularly known as ocean acidification, which has the potential to have negative impacts on the biodiversity of marine creatures and the overall functioning of ecosystems. It appears that the deposition of calcium carbonate (CaCO3) on the ocean floor may have beneficial outcomes for the marine ecosystem by mitigating the process of ocean acidification. However, further research and investigation are necessary to examine the impact of increased concentrations of CaCO3 in estuaries, ports, rivers, or confined waterways such as the Suez Canal.

As per Alexandra Navrotsky, from the University of California, calcium carbonate plays a crucial role as the principal long-term storage medium for atmospheric carbon dioxide. But the potential efficacy of releasing CaCO3 particles into the ocean for the purpose of mitigating greenhouse gas effects or reducing ocean acidification remains uncertain for SBCC with Ca(OH)2.

The mineral carbonation process, specifically employing calcium hydroxide (Ca(OH)2), has been classified as technique Readiness Level (TRL) 5 in the 2017 TRL list for industrial applications, as stated in the IEAGHG report. However, there is a dearth of research on the utilisation of this carbon capture technique for marine purposes, as well as a lack of practical demonstrations and commercial proposals in this domain. According to the researcher's comprehension, if the environmental consequences of CaCO3 disposal in the ocean are adequately elucidated, this carbon capture (CC) technology has the potential to emerge as the frontrunner in the carbon capture race within the shipping industry, hence exerting significant influence over forthcoming technical advancements in the maritime domain.

8.1.3 3rd Recommendation

The third proposal in this study is the implementation of a Carbon Capture System utilising Molten Carbonate Fuel Cells (MCFC).

Bosio et al. (2023) commended Molten carbonate fuel cells (MCFCs) have a high degree of compatibility with various ship types, owing to their capacity to efficiently extract carbon dioxide (CO2), even when present in low concentrations. These systems exhibit notably reduced operational expenses. Another noteworthy aspect is that MCFCs generate electricity while simultaneously capturing CO2, which enhances the power balance and energy efficiency of this carbon capture technology. Nevertheless, there are certain constraints also to the utilisation of fuel cells, mostly associated with spatial requirements and the intricate nature of the technology. Furthermore, given that these

MCFCs operate on hydrogen (H2) as their primary fuel source, it is imperative to ensure the adequate supply of this fuel in ports, as well as other alternative hydrogen sources such as liquefied natural gas (LNG), bio-LNG, ammonia, or syngas. Additionally, it is essential to have an efficient logistics and bunkering infrastructure to support the refuelling needs of these ships. In addition, the utilisation of alternative fuels for H2 production introduces a significant challenge, as it necessitates careful consideration of the intricacies associated with the reforming/cracking system. Finally, this CC system exhibits similar concerns pertaining to onboard storage, port disposal, transportation, and the long-term sequestration of CO2, as previously discussed in relation to amine-based carbon capture technology.

The MCFC, has been classified as technical Readiness Level (TRL) 7 in the 2017 TRL list for industrial applications, as stated in the IEAGHG report.

8.2 Implications for Sustainable Maritime Transportation

Supporting biodiversity and the ecosystem is a core principle of sustainable development (Owusu and Asumadu-Sarkodie, 2016). The environmental implications of CSS technology are to be dealt with considerable significance. The determination of this is frequently predicated on a consistent monitoring of atmospheric conditions, terrestrial ecosystems, aquatic environments, and the utilisation of natural resources. The deployment of carbon capture and storage (CCS) projects can have an impact on biodiversity, ecosystems, and land used for agricultural production. When transportation routes are constructed across agricultural fields, there is a potential decrease in food output. In certain projects, the necessity of relocation arises as a means to facilitate the development of secure and high-quality infrastructure. The destruction of sea life might render the ecosystem very susceptible, hence compromising its resilience. This phenomenon is frequently observed in both onshore and offshore operations. The potential consequences of this phenomenon include a decline in biodiversity due to its impact on ecosystems and habitats. When conducting a risk assessment for the implementation of carbon capture and storage (CCS), it is essential to take into account the potential harm that might be caused to both the CCS plant itself and the surrounding environment. Not only the storage of captured carbon but by-product such as $CaCO3$ dumping in sea or in estuaries to be thoroughly investigated for environmental impact. It is important to ascertain the environmental impact of the CC systems during onboard deployment. The issue of $CO2$ leakage is another concern associated with carbon capture and storage (CCS) technologies. The release of captured carbon dioxide ($CO2$) during transportation has the potential to adversely impact groundwater, plant life, and soil quality. Excessive exposure to elevated levels of carbon dioxide ($CO2$) has the potential to result in fatality. In the year 2012, a study was conducted in Scotland to examine the impact of carbon dioxide ($CO2$) leakage on maritime habitats. The experiment yielded findings indicating that certain species exhibited adverse reactions in response to an elevated concentration of carbon dioxide ($CO2$) (Shackley and Verma, 2008, Wilberforce et. al., 2019). It is well understood that $CO2$ leakages in shipboard environment might be more hazardous and requires good design consideration and safety process to mitigate the risk.

8.3 Conclusion

The implementation of carbon capture technology on ships is a promising avenue for mitigating the adverse effects of greenhouse gas emissions within the marine industry. Numerous studies and projects have been conducted to investigate various techniques and mechanisms for the capture, storage, and transportation of carbon dioxide (CO2) on merchant vessels. These include the use of CC with amines or NH3, use of fuel cell technology such as MCFCs, scrubbing with Ca(OH)2, all as post-combustion capture. Certain technologies purport to provide a reduction of up to 95% in carbon dioxide (CO2) emissions. Nevertheless, there are certain obstacles and impediments that must be addressed, including financial implications, safety concerns, regulatory considerations, and the logistics effectively. Hence, further investigation and advancement are required to render ship-based carbon capture both viable and efficacious in the extended duration.

Several significant challenges associated with ship-based carbon capture system include:

- The cost of installation and operation, which may vary depending on the type and size of the ship, the fuel used, the capture method and the storage system.
- The safety of handling and storing CO2 on board, which may require special equipment, regulations and procedures.
- The regulation of CO2 emissions from ships, which is currently fragmented and inconsistent across different regions and authorities.

- The scalability of the technology, which may depend on the availability and accessibility of CO2 storage or utilization facilities on shore.

This study concludes that three post-combustion carbon capture (CC) technologies have shown the most promising options for implementation and adaption with internal combustion engines on board. The technologies under examination include absorption using NH3 or other amines, CC with molten carbonate fuel cells, and scrubbing with Ca(OH)2. All of these options were determined to be promising for implementing onboard carbon capture systems. The utilisation of Ca(OH)2 for carbon capture is the most economically viable and straightforward approach to system integration. However, it currently lacks maturity and raises concerns over potential unknown environmental impacts associated with the disposal of captured CO2 as limestone. While the separation of MCFC systems is recognised as a technology that occupies minimal space and adds minimal weight, it requires extensive pretreatment of flue gases. This pretreatment process is also associated with a high energy demand, and the utilisation of sophisticated fuel cell technology, which may be unfamiliar to shipboard crew members due to its recent development. The technique of absorption using NH3 or amines was identified as the most spatially demanding method in the comparison. However, it demonstrates a low level of power consumption when NH3 is utilised and offers certain benefits in relation to sulphurous fuels. In present studies it shows the highest TRL achievement to date. This study examines three different technologies and concludes that using aqueous ammonia or amine solvent in the absorption process is the most advantageous choice for shipboard appliances for the time being, whether they are being installed in new ships or being retrofitted onto existing ones. However, if the potential environmental impact of releasing CaCO3 into the sea is investigated and proved to be beneficial, then the utilisation of Ca(OH)2 in carbon capture may emerge as a leading contender.

Overall, carbon capture is a viable option at present time for mitigating the carbon emissions associated with maritime industry. Given the substantial installation and storage requirements, carbon capture (CC) may be a more appealing option for bigger vessels. In the case of smaller vessels, the expenses associated with carbon capture (CC) may exceed those incurred by transitioning to renewable fuels. Just like in onshore applications, where batteries and zero-carbon fuels are designed for tiny emitters and carbon capture (CC) is being studied for large individual emitters, a similar combination of technologies could also be viable for the marine transportation industry.

However, the utilisation of carbon capture (CC) alongside fossil fuels can only serve as a temporary measure until sustainable propulsion alternatives are devised. This is due to the inherent limitations of CC technology, which make it impractical to absorb all emissions entirely. When renewable and greener fuels are utilised in conjunction with carbon capture (CC) technology implemented onboard ships, it has the potential to yield a net reduction in carbon dioxide (CO2) emissions.

It is important to note that this analysis was constrained by the data available in the existing literature, which was mostly incomparable due to variations in underlying assumptions. Further investigation into the implementation of CC aboard should be conducted using a consistent approach. In order to ascertain the most appropriate technology for the proposed vessel, it is necessary to take into account the available space and energy. This consideration is crucial when determining which technology can yield the maximum capture rate given specific circumstances. Regardless, it is imperative to evaluate the possibilities of many solutions, including but not limited to carbon capture (CC), in order to determine the most appropriate technology for reducing carbon emissions in an instance to achieve IMO 2050 goals.

Disclosure of Conflicting Interests

The author assert that he does not possess any identifiable conflicting financial interests or personal relationships that may have potentially influenced the findings presented in this research article.

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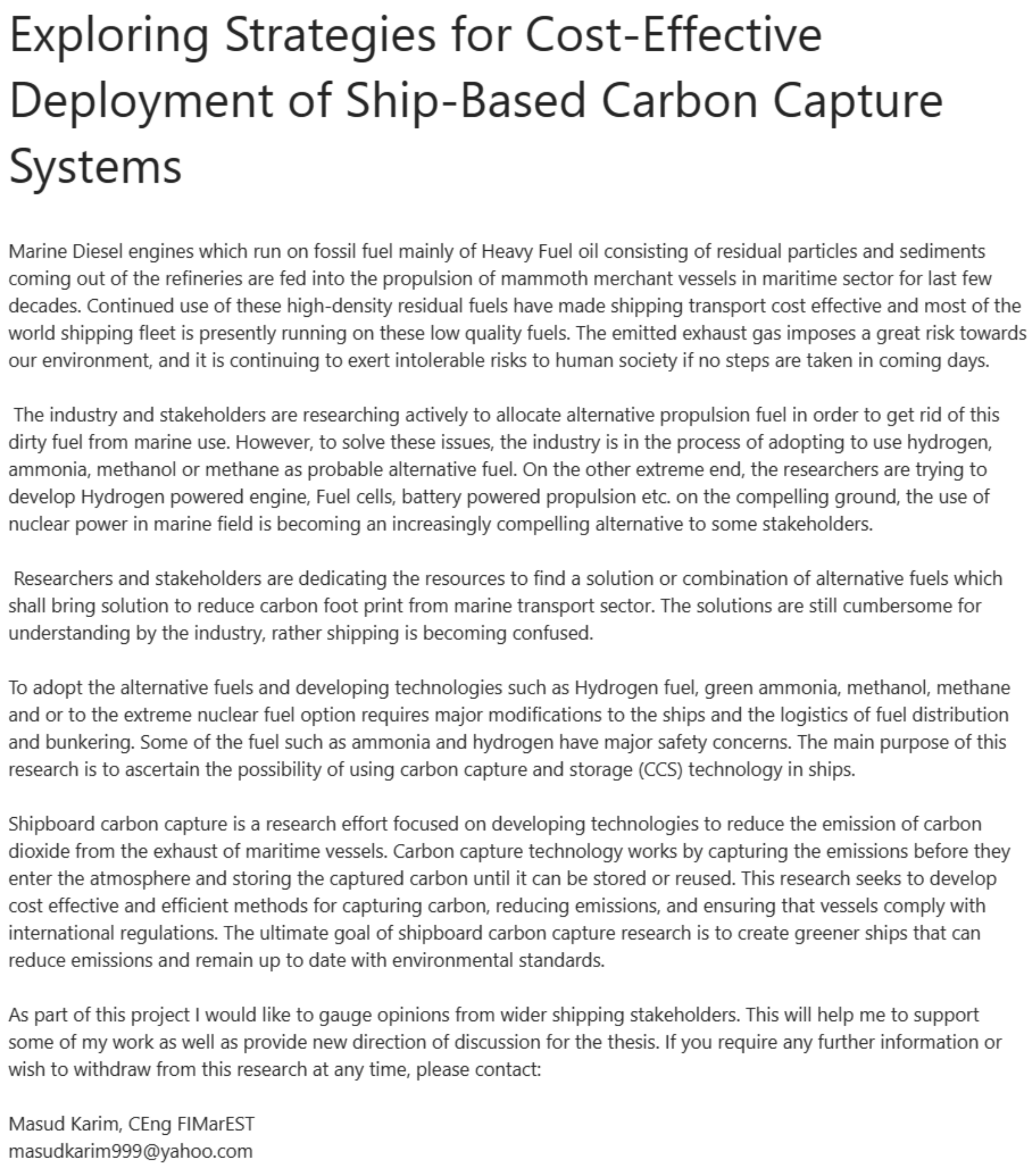
Appendix 1



Exploring Strategies for Cost-Effective Deployment of Ship-Based Carbon Capture Systems

Marine Diesel engines which run on fossil fuel mainly of Heavy Fuel oil consisting of residual particles and sediments coming out of the refineries are fed into the propulsion of mammoth merchant vessels in maritime sector for last few decades. Continued use of these high-density residual fuels have made shipping transport cost effective and most of the world shipping fleet is presently running on these low quality fuels. The emitted exhaust gas imposes a great risk towards our environment, and it is continuing to exert intolerable risks to human society if no steps are taken in coming days.

The industry and stakeholders are researching actively to allocate alternative propulsion fuel in order to get rid of this dirty fuel from marine use. However, to solve these issues, the industry is in the process of adopting to use hydrogen, ammonia, methanol or methane as probable alternative fuel. On the other extreme end, the researchers are trying to develop Hydrogen powered engine, Fuel cells, battery powered propulsion etc. on the compelling ground, the use of nuclear power in marine field is becoming an increasingly compelling alternative to some stakeholders.

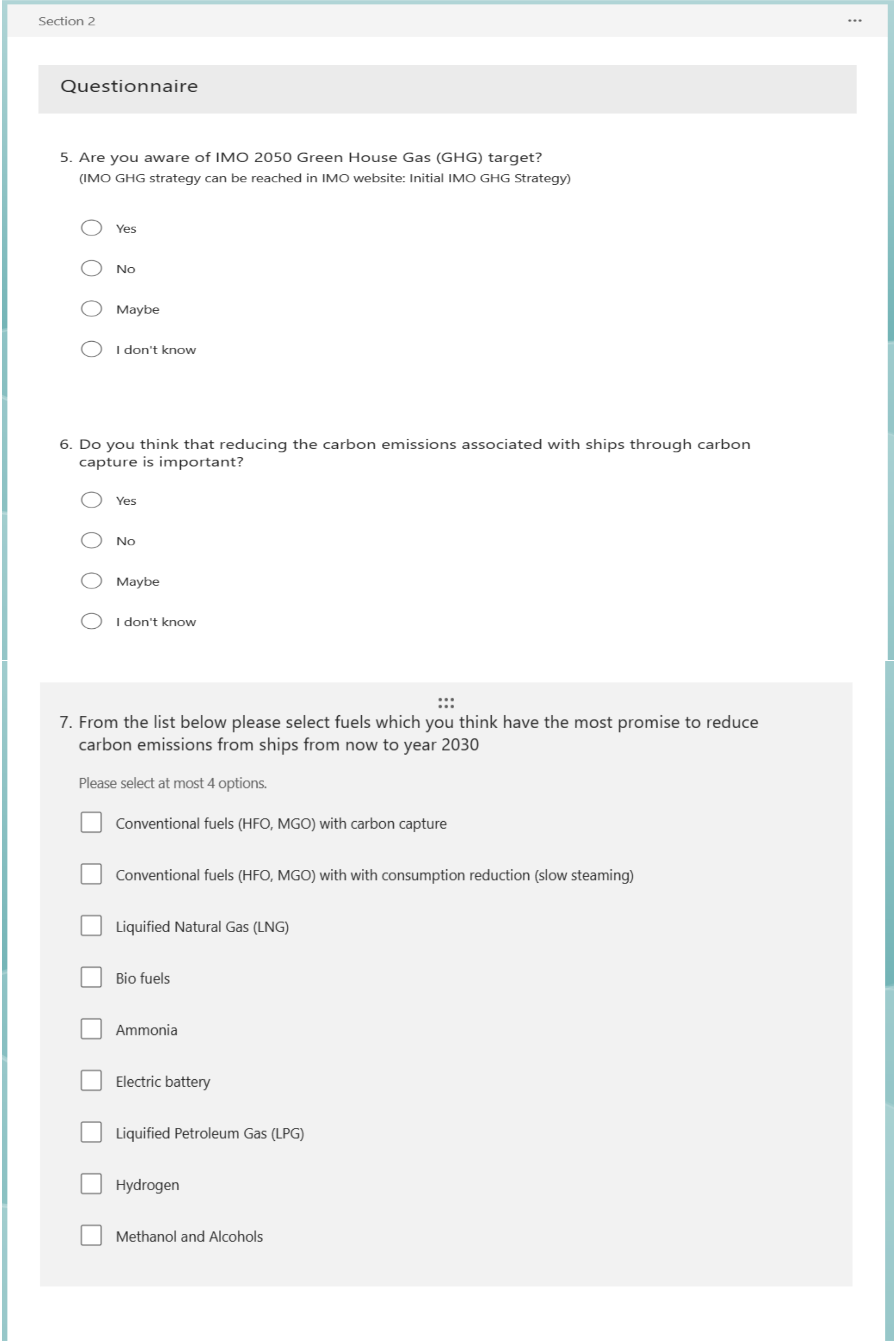
Researchers and stakeholders are dedicating the resources to find a solution or combination of alternative fuels which shall bring solution to reduce carbon foot print from marine transport sector. The solutions are still cumbersome for understanding by the industry, rather shipping is becoming confused.

To adopt the alternative fuels and developing technologies such as Hydrogen fuel, green ammonia, methanol, methane and or to the extreme nuclear fuel option requires major modifications to the ships and the logistics of fuel distribution and bunkering. Some of the fuel such as ammonia and hydrogen have major safety concerns. The main purpose of this research is to ascertain the possibility of using carbon capture and storage (CCS) technology in ships.

Shipboard carbon capture is a research effort focused on developing technologies to reduce the emission of carbon dioxide from the exhaust of maritime vessels. Carbon capture technology works by capturing the emissions before they enter the atmosphere and storing the captured carbon until it can be stored or reused. This research seeks to develop cost effective and efficient methods for capturing carbon, reducing emissions, and ensuring that vessels comply with international regulations. The ultimate goal of shipboard carbon capture research is to create greener ships that can reduce emissions and remain up to date with environmental standards.

As part of this project I would like to gauge opinions from wider shipping stakeholders. This will help me to support some of my work as well as provide new direction of discussion for the thesis. If you require any further information or wish to withdraw from this research at any time, please contact:

Masud Karim, CEng FIMarEST
masudkarim999@yahoo.com



Questionnaire

5. Are you aware of IMO 2050 Green House Gas (GHG) target?
(IMO GHG strategy can be reached in IMO website: Initial IMO GHG Strategy)

○ Yes
○ No
○ Maybe
○ I don't know

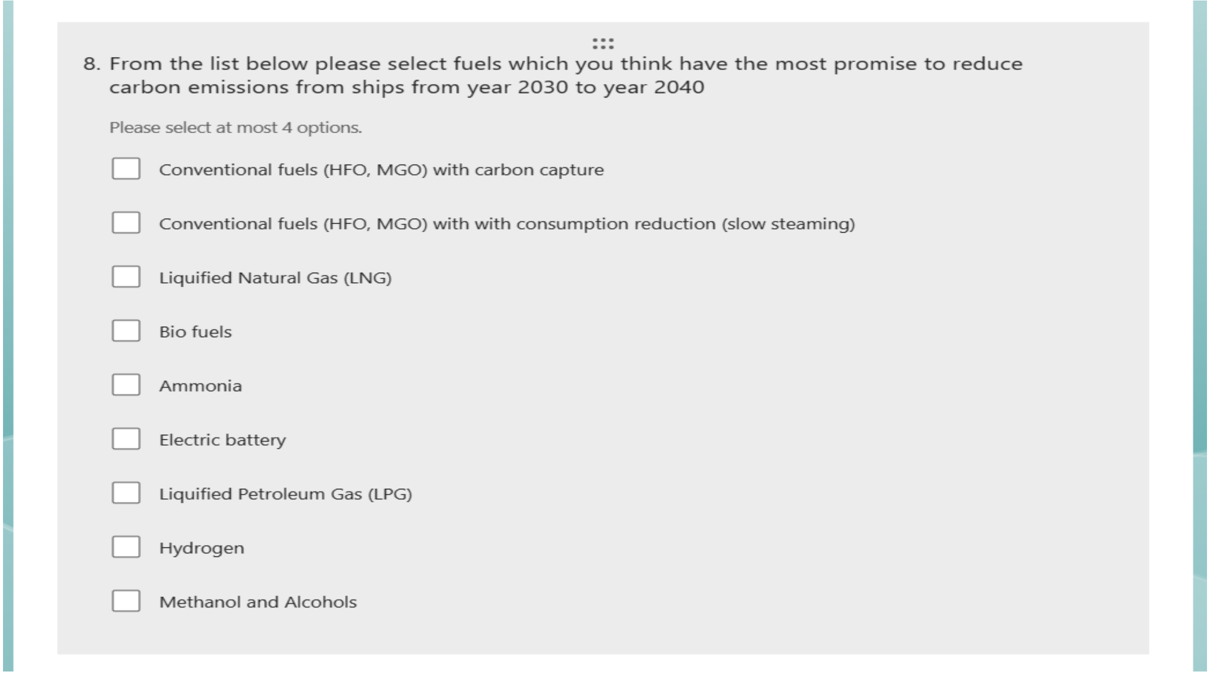
6. Do you think that reducing the carbon emissions associated with ships through carbon capture is important?

○ Yes
○ No
○ Maybe
○ I don't know

7. From the list below please select fuels which you think have the most promise to reduce carbon emissions from ships from now to year 2030

Please select at most 4 options.

☐ Conventional fuels (HFO, MGO) with carbon capture
☐ Conventional fuels (HFO, MGO) with with consumption reduction (slow steaming)
☐ Liquified Natural Gas (LNG)
☐ Bio fuels
☐ Ammonia
☐ Electric battery
☐ Liquified Petroleum Gas (LPG)
☐ Hydrogen
☐ Methanol and Alcohols



8. From the list below please select fuels which you think have the most promise to reduce carbon emissions from ships from year 2030 to year 2040

Please select at most 4 options.

☐ Conventional fuels (HFO, MGO) with carbon capture

☐ Conventional fuels (HFO, MGO) with with consumption reduction (slow steaming)

☐ Liquified Natural Gas (LNG)

☐ Bio fuels

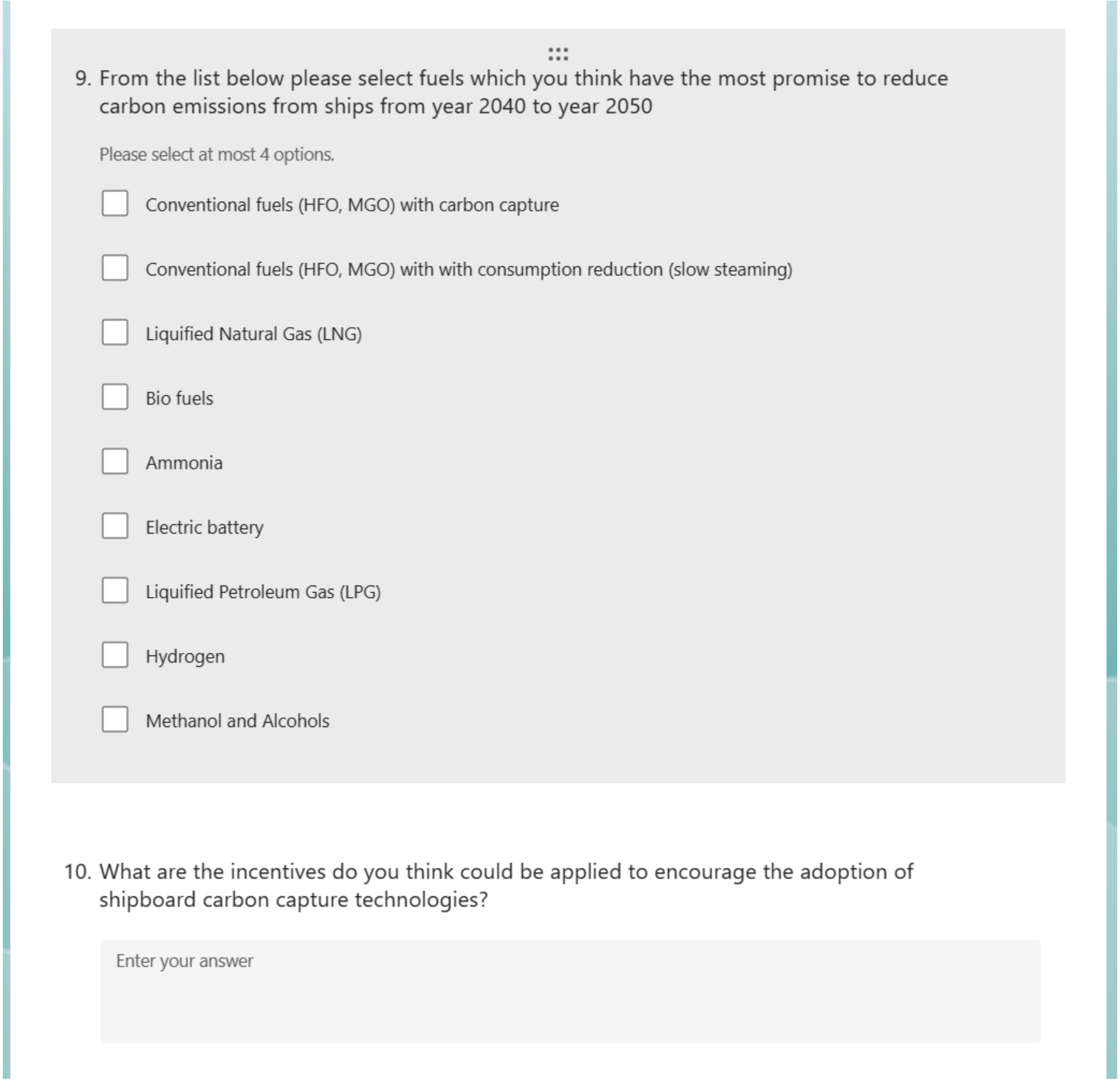
☐ Ammonia

☐ Electric battery

☐ Liquified Petroleum Gas (LPG)

☐ Hydrogen

☐ Methanol and Alcohols



9. From the list below please select fuels which you think have the most promise to reduce carbon emissions from ships from year 2040 to year 2050

Please select at most 4 options.

☐ Conventional fuels (HFO, MGO) with carbon capture

☐ Conventional fuels (HFO, MGO) with with consumption reduction (slow steaming)

☐ Liquified Natural Gas (LNG)

☐ Bio fuels

☐ Ammonia

☐ Electric battery

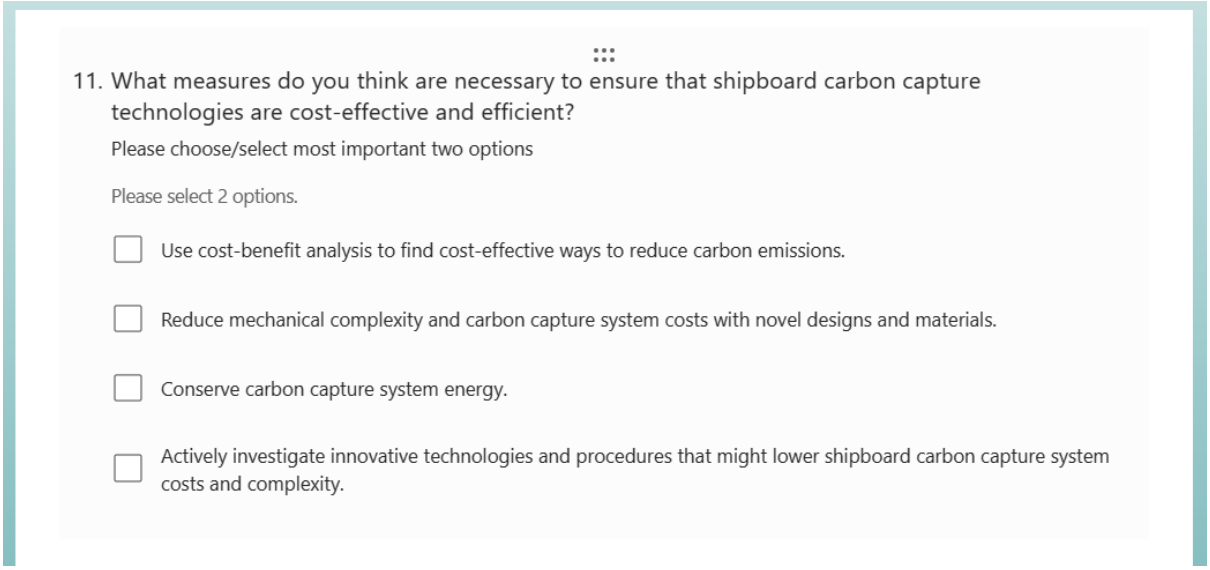
☐ Liquified Petroleum Gas (LPG)

☐ Hydrogen

☐ Methanol and Alcohols

10. What are the incentives do you think could be applied to encourage the adoption of shipboard carbon capture technologies?

Enter your answer



11. What measures do you think are necessary to ensure that shipboard carbon capture technologies are cost-effective and efficient?

Please choose/select most important two options

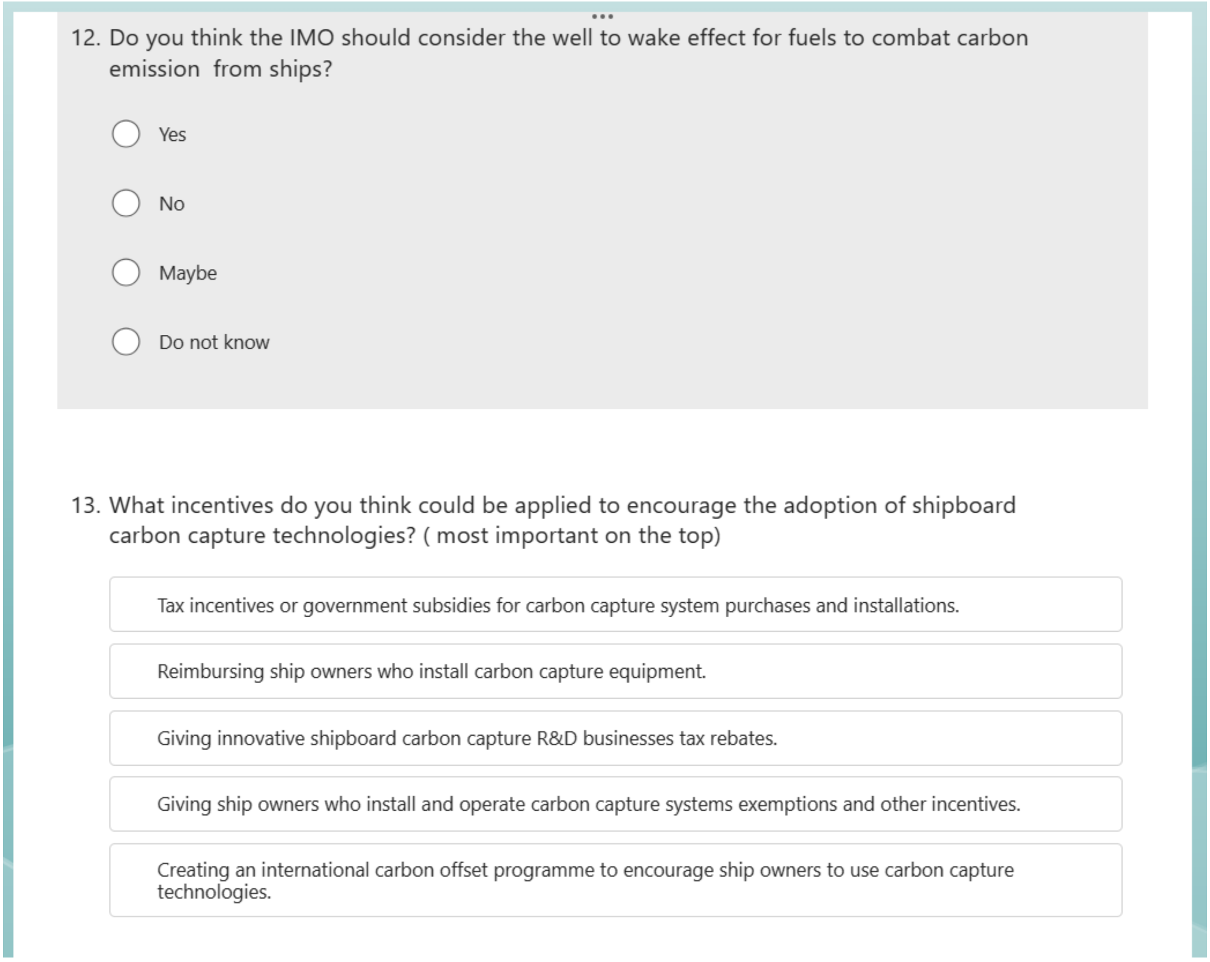
Please select 2 options.

☐ Use cost-benefit analysis to find cost-effective ways to reduce carbon emissions.

☐ Reduce mechanical complexity and carbon capture system costs with novel designs and materials.

☐ Conserve carbon capture system energy.

☐ Actively investigate innovative technologies and procedures that might lower shipboard carbon capture system costs and complexity.



12. Do you think the IMO should consider the well to wake effect for fuels to combat carbon emission from ships?

○ Yes

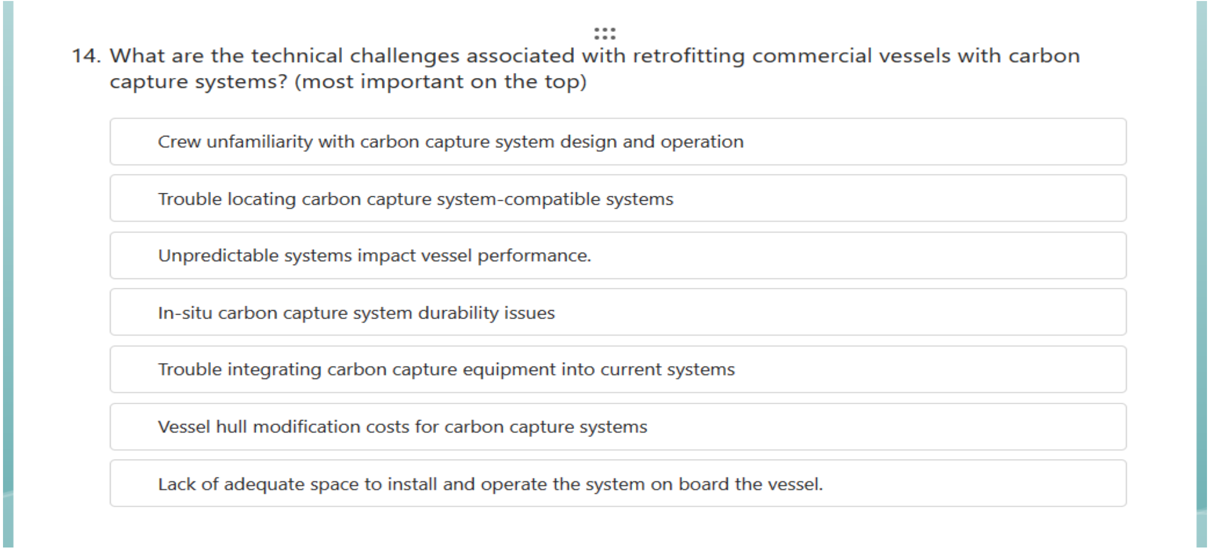
○ No

○ Maybe

○ Do not know

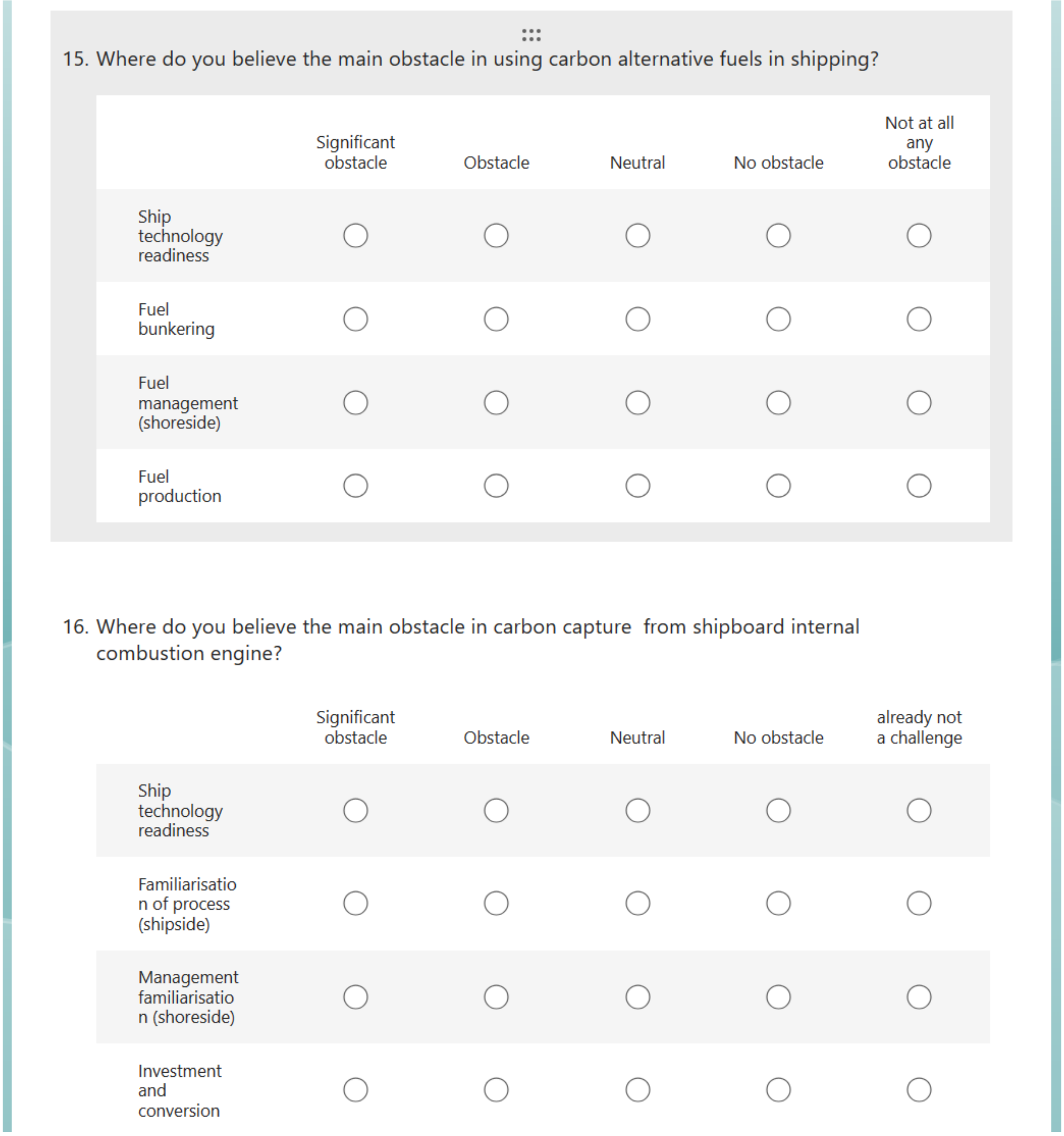
13. What incentives do you think could be applied to encourage the adoption of shipboard carbon capture technologies? (most important on the top)

- Tax incentives or government subsidies for carbon capture system purchases and installations.
- Reimbursing ship owners who install carbon capture equipment.
- Giving innovative shipboard carbon capture R&D businesses tax rebates.
- Giving ship owners who install and operate carbon capture systems exemptions and other incentives.
- Creating an international carbon offset programme to encourage ship owners to use carbon capture technologies.



14. What are the technical challenges associated with retrofitting commercial vessels with carbon capture systems? (most important on the top)

- Crew unfamiliarity with carbon capture system design and operation
- Trouble locating carbon capture system-compatible systems
- Unpredictable systems impact vessel performance.
- In-situ carbon capture system durability issues
- Trouble integrating carbon capture equipment into current systems
- Vessel hull modification costs for carbon capture systems
- Lack of adequate space to install and operate the system on board the vessel.



15. Where do you believe the main obstacle in using carbon alternative fuels in shipping?

	Significant obstacle	Obstacle	Neutral	No obstacle	Not at all any obstacle
Ship technology readiness	○	○	○	○	○
Fuel bunkering	○	○	○	○	○
Fuel management (shoreside)	○	○	○	○	○
Fuel production	○	○	○	○	○

16. Where do you believe the main obstacle in carbon capture from shipboard internal combustion engine?

	Significant obstacle	Obstacle	Neutral	No obstacle	already not a challenge
Ship technology readiness	○	○	○	○	○
Familiarisation of process (shipside)	○	○	○	○	○
Management familiarisation (shoreside)	○	○	○	○	○
Investment and conversion	○	○	○	○	○

17. What do you think are the primary challenges facing researchers and developers of shipboard carbon capture technology? (most important on the top)

Lack of flag regulations

Investment in research

Shipowner interest

Lack of class societies involvement

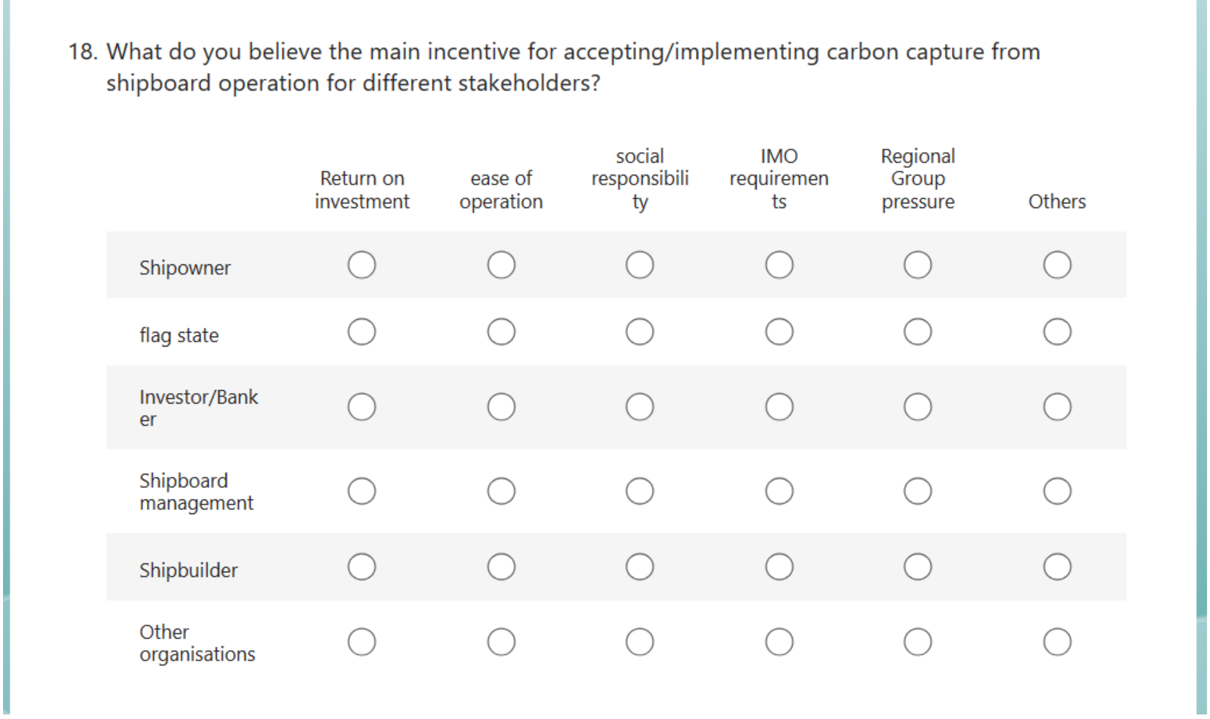
Technology rediness

Lack of international regulations

lack of IMO commitments/guidance

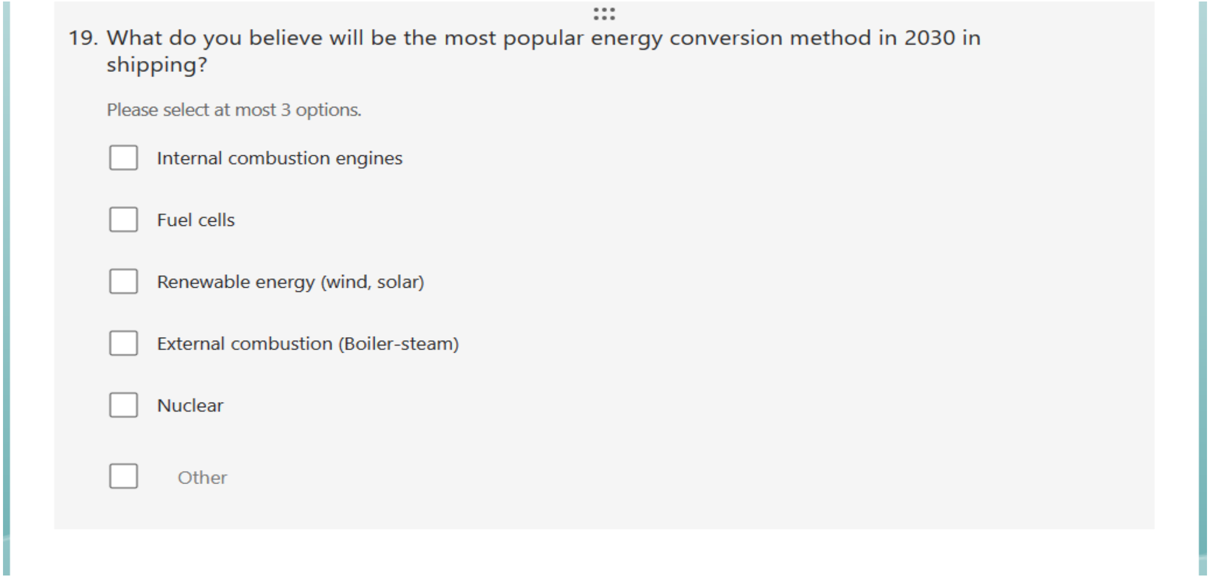
Pressure from alternative fuel developers

Others



18. What do you believe the main incentive for accepting/implementing carbon capture from shipboard operation for different stakeholders?

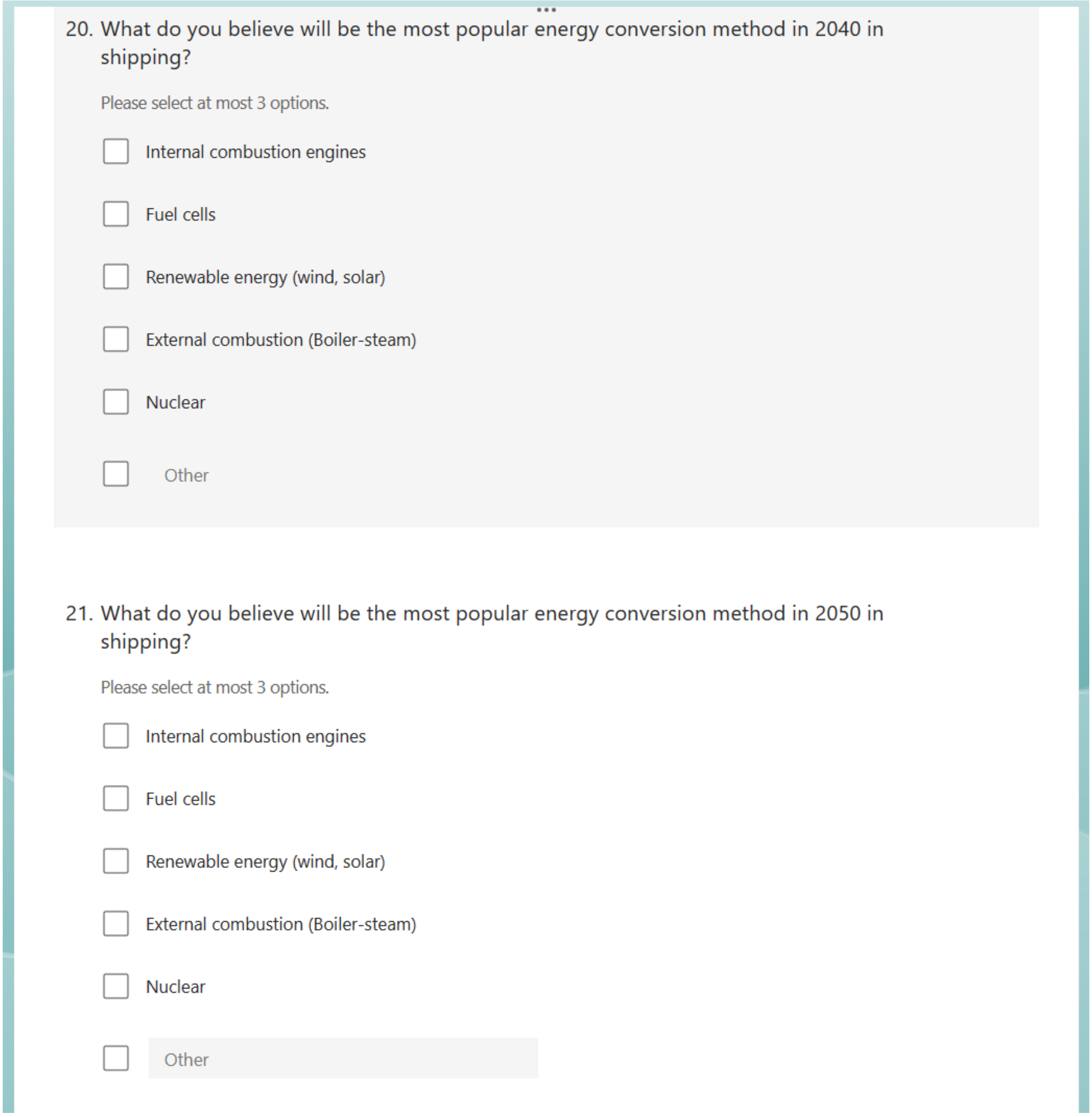
	Return on investment	ease of operation	social responsibility	IMO requirements	Regional Group pressure	Others
Shipowner	○	○	○	○	○	○
flag state	○	○	○	○	○	○
Investor/Banker	○	○	○	○	○	○
Shipboard management	○	○	○	○	○	○
Shipbuilder	○	○	○	○	○	○
Other organisations	○	○	○	○	○	○



19. What do you believe will be the most popular energy conversion method in 2030 in shipping?

Please select at most 3 options.

- ☐ Internal combustion engines
- ☐ Fuel cells
- ☐ Renewable energy (wind, solar)
- ☐ External combustion (Boiler-steam)
- ☐ Nuclear
- ☐ Other



20. What do you believe will be the most popular energy conversion method in 2040 in shipping?

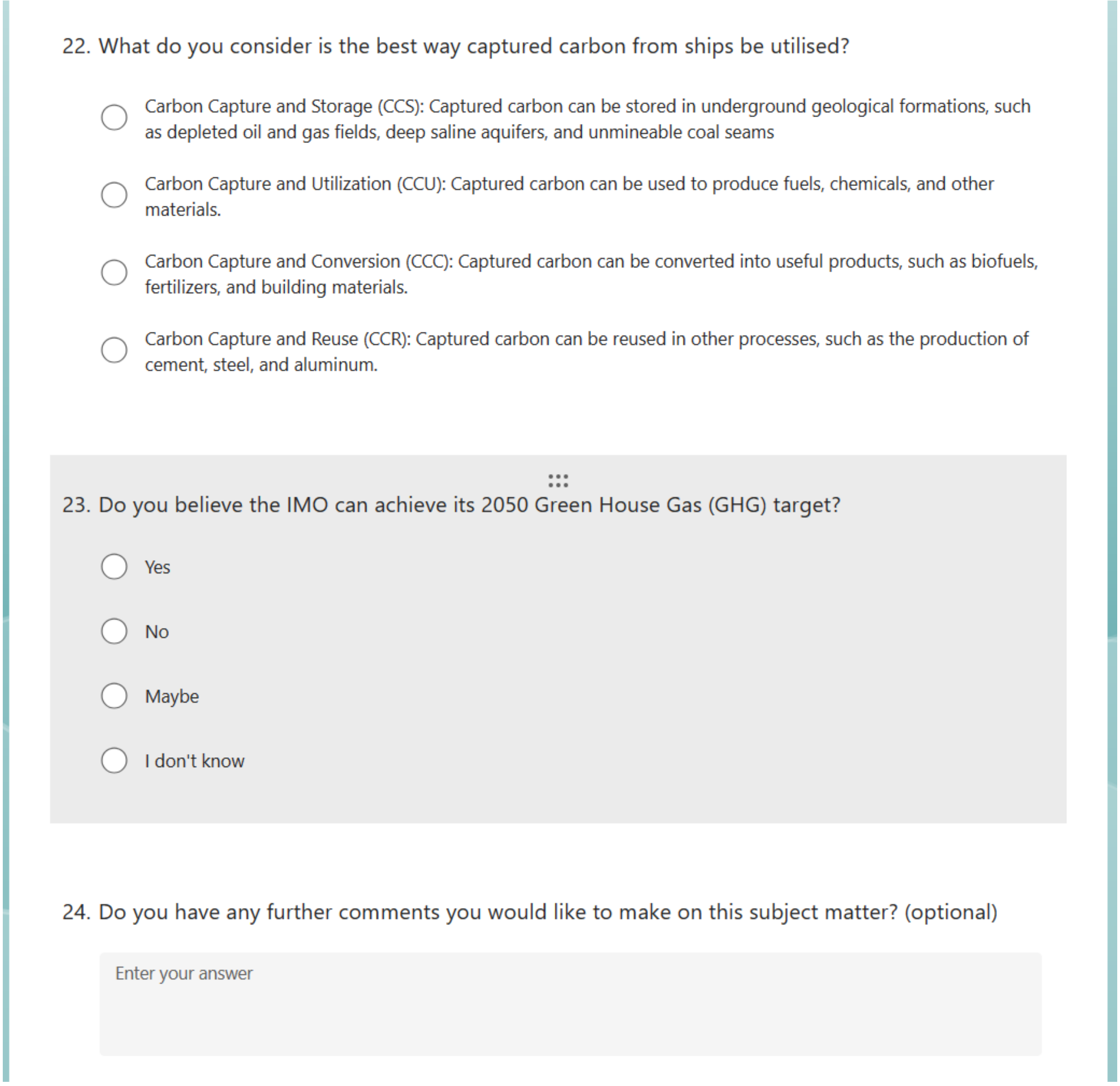
Please select at most 3 options.

- ☐ Internal combustion engines
- ☐ Fuel cells
- ☐ Renewable energy (wind, solar)
- ☐ External combustion (Boiler-steam)
- ☐ Nuclear
- ☐ Other

21. What do you believe will be the most popular energy conversion method in 2050 in shipping?

Please select at most 3 options.

- ☐ Internal combustion engines
- ☐ Fuel cells
- ☐ Renewable energy (wind, solar)
- ☐ External combustion (Boiler-steam)
- ☐ Nuclear
- ☐ Other



22. What do you consider is the best way captured carbon from ships be utilised?

○ Carbon Capture and Storage (CCS): Captured carbon can be stored in underground geological formations, such as depleted oil and gas fields, deep saline aquifers, and unmineable coal seams

○ Carbon Capture and Utilization (CCU): Captured carbon can be used to produce fuels, chemicals, and other materials.

○ Carbon Capture and Conversion (CCC): Captured carbon can be converted into useful products, such as biofuels, fertilizers, and building materials.

○ Carbon Capture and Reuse (CCR): Captured carbon can be reused in other processes, such as the production of cement, steel, and aluminum.

23. Do you believe the IMO can achieve its 2050 Green House Gas (GHG) target?

○ Yes

○ No

○ Maybe

○ I don't know

24. Do you have any further comments you would like to make on this subject matter? (optional)

Enter your answer

Acknowledgement and Dedication

I would like to extend my sincere thanks to the supervisor, academic staff, and administration of Selinus University of Sciences and Literature for their support and guidance during this research. This work is dedicated to Serajul Huq, my father, Motiara Begum, my mother, and Begum Tajkera, my beloved wife. The individuals who have continually demonstrated unwavering belief in my talents, offering guidance that has consistently propelled me forward in the vast ocean of knowledge, providing support and enabling me to perform at my highest potential, have remained a steadfast presence throughout my academic endeavours.