NATIONAL TECHNICAL UNIVERSITY OF ATHENS
DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

THESIS

Ioannis Marios Beltsidis

Concept assessment of a marine carbon capture system for vessel regulatory lifetime extension

Supervisor:

G. Dimopoulos, associate professor

Examination committee:

N.Themelis, assistant professor

G.Papalabrou, assistant professor

Athens, July 2023

Contents

List of Tables

List of Figures

Acknowledgements

Reaching the end of my studies, I would like to express my sincere gratitude and appreciation to National Technical University of Athens and the department of Naval Architecture and Marine Engineering for the invaluable assets given. I would also like to thank DNV, specifically the Research, Development and Advisory Unit for their support throughout my internship and the guidance provided for the work on this thesis. Their guidance, expertise, and commitment to excellence have been instrumental in shaping the research and contributing to its completion. I am particularly grateful to my supervisor George Dimopoulos and Dr. Chara Georgopoulou, Head of R&D and Advisory, DNV Piraeus, for their remarkable assistance, support, and willingness to share their extensive knowledge. Their insightful feedback and constructive suggestions have greatly enriched this thesis. I would also like to extend my heartfelt thanks to my family, friends and girlfriend for their constant encouragement, understanding, and patience during this endeavor. Their unwavering support has been a source of strength and motivation throughout the entire process.

Abstract

Anthropogenic Greenhouse gas emissions increase rapidly throughout years, forcing International Maritime Organization (IMO) to set strict targets on reducing emission in shipping. Carbon capture (CC) could be one of the solutions within the decarbonization spectrum, given its potential for significant emission reduction. The shipping community is already exploring CC solutions through concept studies, joint development projects and pilot demonstrations. However, no clear window for CC inclusion in Carbon intensity index (CII) calculations has been provided by IMO, at the time this thesis is written. The objective of this study is to explore, on a concept design level, the capacity of a CC system to improve the CII of a VLCC tanker vessel, to ensure regulatory compliance throughout her life expectancy. The vessel's annual operating profile and the benefits of tight heat integration are accounted. To calculate the CC performance, a process model is developed of a conventional amine-based carbon capture system integrated to the ship machinery, with waste heat recovery (WHR) for CC heat supply. At design conditions all features of CCS and WHR components are determined. At operating conditions, estimates of pumping and compression requirements, reboiler duty and WHR production capacity are evaluated and accounted for in the total footprint of the ship. The results are annualized and compared to base line no CCS conditions. The associated increase in fuel consumption due to CC use is estimated, along with the CC system's capital and operational costs. Net present value of costs is accounted to investigate the optimum carbon capacity of the CCS system.

Nomenclature

A	Area [m^2]
ACAPEX	Annualized CAPEX
AE	Auxiliary Engine
A_{ev}	Area of evaporator [m^2]
A_{pr}	Area of preheater [m^2]
$\dot{b}$	Fuel consumption of reboiler [tn/hr]
C	Parameter estimated through regression fits,CII
C_f	Conversion factor of IMO from FO to CO_2
C_{str}	Capacity of the stripper [kJ/kg]
CAPEX	Capitalized Expenditure
$CaCO_3$	Calcium Carbonate
CaO	Calcium oxide
$Capr$	Capture rate
$CalV_{HFO}$	Calorific Value of HFO [MJ/kg]
CC	Carbon capture
CCS	Carbon Capture& Storage
CCUS	Carbon Capture Utilization and Storage
CII	Carbon Intensity Index [gr/(tn·nm)]
CII_{ref}	Reference CII [gr/(tn·nm)]
CO_2	Carbon dioxide
Cp_{MEA}	Heat capacity of MEA [kJ/(kg·K)]
Cp_g	Heat capacity of gas [kJ/(kg·K)]
Cp_{g1}	Heat capacity of gas, condition 1 [kJ/(kg·K)]
Cp_{g2}	Heat capacity of gas, condition 2 [kJ/(kg·K)]
Cp_{g3}	Heat capacity of gas, condition 3 [kJ/(kg·K)]
Cp_{gev}	Heat capacity of gas in the evaporator [kJ/(kg·K)]
Cp_{gpr}	Heat capacity of gas in the preheater [kJ/(kg·K)]
Cp_{liq}	Heat capacity of liquid solution [kJ/(kg·K)]
Cp_{liq1}	Heat capacity of liquid solution, condition 1 [kJ/(kg·K)]
Cp_{liq2}	Heat capacity of liquid solution, condition 2 [kJ/(kg·K)]
Cp_w	Heat capacity of water [kJ/(kg·K)]
CRF	Capital Recovery Factor
con	function of %w/w CO_2 with variation on ME load
dg	Density of gas [kg/m^3]
dw	Density of water [kg/m^3]
DG	Diesel Generator
DWT	Deadweight [t]
FF	Friction Factor
FO	Fuel Oil
g	Acceleration due gravity [m/s^2]
GA	General Arrangement
G_m	Molar gas flow rate per unit cross-sectional area
H	Head [m]
H_L	Head of liquid [m]
H_{ov}	Head overall [m]
H_{ov1}	Head overall, condition 1 [m]
H_{ov2}	Head overall, condition 2 [m]

HEX	Heat Exchanger
HSE	Health safety and environment
h_{inl}	Enthalpy of liquid, inlet stream [kJ/kg]
h_p	Enthalpy at the pump [kJ/kg]
h_{p1}	Enthalpy at the pump, condition 1 [kJ/kg]
h'_p	Enthalpy of saturated water at the pump [kJ/kg]
h'_{p1}	Enthalpy of saturated water, condition 1 [kJ/kg]
h''_{p1}	Enthalpy of saturated steam, condition 1 [kJ/kg]
i	Interest rate
kn	Knots
KPI	Key Performance Indicator
kWh	Kilowatt-hours
IEA	International Energy Agency
IMO	International Maritime Organisation
L	Load of main engine [%]
L %	Loading [%]
$LeanLoad$	CO_2 loading of lean solution [mol/mol]
L_m	Molar liquid flow rate per unit cross-sectional area
$LMTD$	Logarithmic mean temperature difference [K]
$LMTD_{ev}$	Logarithmic mean temperature difference at the evaporator [K]
$LMTD_{pr}$	Logarithmic mean temperature difference at the preheater [K]
$\frac{L}{D}$	Length to diameter ratio
L/G	Liquid to gas ratio
M	Total mass of CO_2, CII [gr]
ME	Main Engine
MEA	Monomethylamine
Mtpa	Million tons per annum
$\dot{m}_{CO2}$	Mass flow rate of CO2 [kg/s]
$\dot{m}_{CO2-GtL}$	Mass flow rate of CO2 that is going from gas to liquid phase [kg/s]
$\dot{m}_g$	Mass flow rate of gas [kg/s]
$\dot{m}_{gas}$	Mass flow rate of gas [kg/s]
$\dot{m}_{in,w}$	Mass flow rate of water, inlet stream [kg/s]
$\dot{m}_{ing}$	Mass flow rate of gas, inlet stream [kg/s]
$\dot{m}_{inliq}$	Mass flow rate of liquid solution, inlet stream [kg/s]
$\dot{m}_{out,exg}$	Mass flow rate of exhaust gas, outlet stream [kg/s]
$\dot{m}_{outg}$	Mass flow rate of gas, outlet stream [kg/s]
$\dot{m}_{outr}$	Mass flow rate of rich solution, outlet stream [kg/s]
$\dot{m}_{st}$	Mass flow rate of steam [kg/s]
NH3	Ammonia
N_{OG}	Number of stages
NOx	Nitrogen Oxides
NPV	Net Present Value
n	years of investment
OPEX	Operational Expenditure
P	Pinch [K]
P_{ev}	Pinch of evaporator [K]
PZ	Piperazine
Q_{hbl}	Hydraulic power of blower [kW]

Q_{hp}	Hydraulic power of pump [kW]
Q_{HEX}	Heat exchange of HEX [kW]
Q_{bl}	Power of blower [kW]
Q_{ev}	Heat exchange of evaporator [kW]
Q_p	Power of pump [kW]
Q_{pr}	Heat exchange of preheater [kW]
Q_{reb}	Heat of reboiler [kW]
$RichLoad$	CO_2 Loading of rich solution [mol/mol]
SEEMP	Ship Energy Efficiency Management Plan
$SFOC$	Specific Fuel Oil Consumption [gr/kWh]
$SFOC_{DG}$	SFOC of DG [gr/kWh]
$SFOC_{ME}$	SFOC of ME [gr/kWh]
SOA	State of Art
T	Temperature [K]
T_{ev}	Temperature at evaporator [K]
T_{inbl}	Temperature at blower, inlet stream [K]
T_{ing}	Temperature of gas, inlet stream [K]
T_{inl}	Temperature of liquid solution, inlet stream [K]
T_{inliq}	Temperature of liquid solution, inlet stream [K]
T_{inpr}	Temperature at preheater, inlet stream [K]
T_{instr}	Temperature at stripper, inlet stream [K]
$T_{in,w}$	Temperature of water, inlet stream [K]
T_{outr}	Temperature of rich solution, outlet stream [K]
$T_{out,w}$	Temperature of water, outlet stream [K]
T_{outg}	Temperature of gas, outlet stream [K]
$T_{out,exg}$	Temperature of exhaust gas, outlet stream [K]
T_{prout}	Temperature at preheater, outlet stream [K]
TAC	Total Annual Cost
TRL	Technology Readiness Level
U_{ev}	Heat transfer coefficient of evaporator [$kw/m^2 \cdot K$]
U_{pr}	Heat transfer coefficient of preheater [$kw/m^2 \cdot K$]
u_g	Velocity of gas [m/s]
u_w	Velocity of water [m/s]
$\dot{V}g$	Volumetric flow rate of gas [m^3/s]
$\dot{V}w$	Volumetric flow rate of water [m^3/s]
VLCC	Very Large Crude Carrier
VOPEX	Variable Operational expenditure
W	Total transport work, CII [tn·nm]
WHR	Waste Heat Recovery
x	Mass fraction of MEA or weight percent MEA
a	parameter estimated through regression fits, CII
ΔT_{in}	Temperature difference, inlet stream [K]
ΔT_{out}	Temperature difference, outlet stream [K]
η_b	Efficiency of reboiler
η_{m1}	Mechanical efficiency, condition 1
η_{m2}	Mechanical efficiency, condition 2
η_{p1}	Efficiency, condition 1
η_{p2}	Efficiency, condition 2
%w/w	Weight percent weight by weight

%wt	Weight percent
$\%w/wCO_2$	Weight percent weight by weight of CO2

1 Introduction

1.1 Motivation

With the increasing concern over climate change and the need to reduce greenhouse gas emissions and extend the regulatory life of vessels, there has been growing interest in carbon capture technologies as a means of mitigating the environmental impact of various industries. In the shipping industry, vessel emissions are a significant contributor to carbon dioxide emissions, making the development of a carbon capture system for vessels an important area of research. This thesis aims to evaluate the technical and economic feasibility of implementing a marine carbon capture system, as well as the potential environmental benefits and regulatory implications. By examining these factors, this research can provide insights into the practicality and potential of such a system, and assist the development of policies and regulations to encourage its adoption in the shipping industry.

1.2 Regulatory framework

The Carbon Intensity Index (CII) is a regulatory framework developed by the International Maritime Organization (IMO) to measure and reduce the carbon intensity of shipping. The CII system measures the amount of carbon dioxide (CO_2) emissions per unit of transport work, taking into account factors of ship size, distance travelled, and cargo capacity. The CII regulatory framework provides a standard for measuring and reporting carbon emissions, and encourages the adoption of measures to reduce emissions. Operational changes such as reducing the speed of vessels or optimizing the routing of ships could be a short-term solution. Technological solutions such as using alternative fuels, improving energy efficiency through design changes or a CCS system may result in a significant reduction of CII. According to the IMO, the goal is to reduce the CII of international shipping by at least 40% by 2030 compared to 2008 levels, and to reduce the total annual greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008 levels [1]. A stricter scenario involves a CII reduction of 100% by 2050 (zero-50 scenario), which will be investigated as well. These targets require significant efforts from the shipping industry, and the implementation of effective regulatory measures to incentivize and enforce emissions reduction. The success of the CII regulatory framework in achieving these goals will depend on a range of factors, including technological and economic feasibility, regulatory effectiveness, and international cooperation. Figure 1.1 illustrates the CII goal of 40% CII reduction for a random ship case. Letters A, B, C, D, E represent the rating of the vessel regarding their emissions, while SEEMP refers to the Ship Energy Efficiency Management Plan.

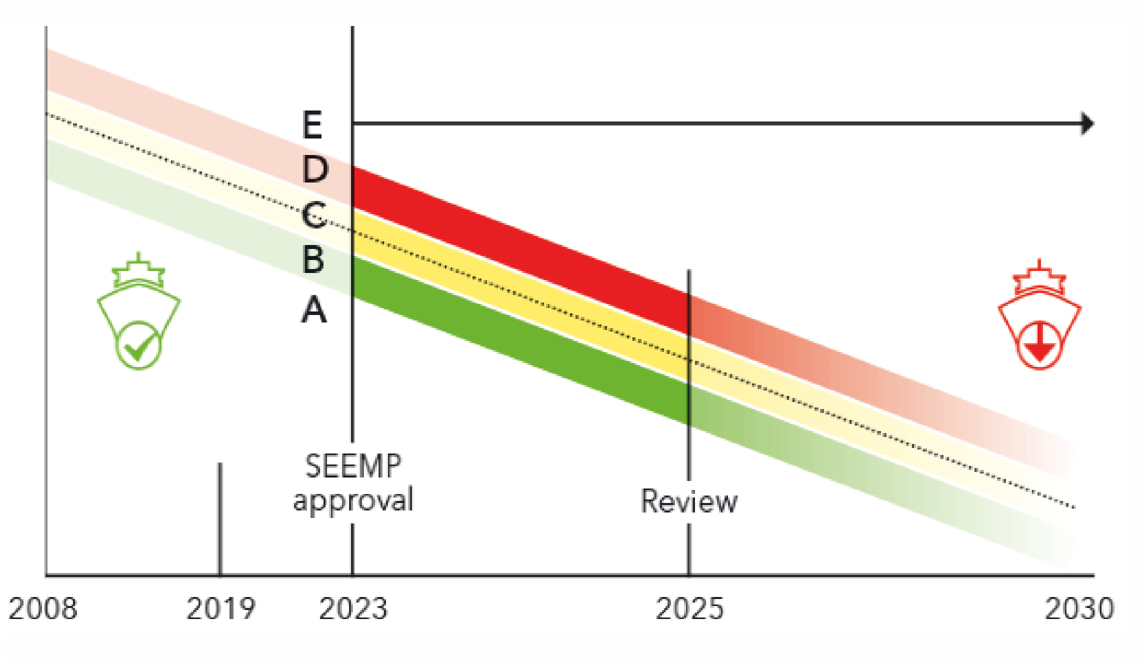

Figure 1.1: Required annual operational CII (DNV, 2023) [2].

1.3 CCS market overview

CCS systems are already used in land-based facilities to reduce the amount of CO_2 emissions released into the atmosphere. This process enables the permanent removal of CO_2 that would otherwise be released into the atmosphere. CCS systems are increasingly recognized as a critical tool for reducing greenhouse gas emissions and achieving climate targets, and their use is encouraged by governments and international organizations around the world. While the implementation of CCS systems can be challenging, it offers significant benefits in terms of reducing carbon emissions and mitigating the impacts of climate change. As Global CCS Institute implies [3], the installed CCS capacity must increase from 40 Mtpa (Million tons per annum) today to 5600 Mtpa by 2050 to limit global warming to 2°C. The capacity of projects in development increased by 48% from the end of 2020 till September of 2021, making the CC technology timelier than ever. It is estimated that 70-100 facilities must be built every year to reach international goals, while there are only 27 operating facilities (figure 1.2) and 106 facilities are in construction, advanced or early development combined. As carbon capture facilities increase, there is a bigger diversity in the scale of facilities. Carbon can be captured through direct air capture, cement production, iron and steel production, waste to energy, power generation (natural gas-coal), hydrogen production, chemical production, ethanol production, fertiliser production natural gas processing. Figure 1.3 illustrates CCS projects by sector and scale (Metric Tonnes per Annum Mtpa) over time. International Energy Agency (IEA) [4] estimated that 800 Mtpa CO_2 will be captured globally by 2030 and 6000 Mtpa by 2050. DNV considers this scenario optimistic, as its own estimation is rather smaller. DNV's scenario of 175 Mtpa by 2030 and 2100 Mtpa by 2050 is considered closer to reality [4].

Regarding the utilization of CO2, fertilizer and oil and gas industry are the main utilizers of CO_2. Among with food and beverage production, mineral carbonation, metal fabrication, chemicals manufacturing, water treatment and healthcare, they result in more than 230 Mtpa of CO_2. Estimates for 2030 are promising as they range from 1000 Mtpa to 7000Mtpa. The sustainable development scenario 2020-2070 of IEA [4] estimates that 92% of cumulative captured CO_2 will be destined for permanent storage and the other 8% for utilization, most of which for feedstock for synthetic fuel production. Figure 1.4 demonstrates suitable storage regions for CO_2.

Given the maturity of land-based CCS systems, there is a growing need to explore the potential of maritime CCS technology to reduce carbon emissions from shipping. While technological solutions such as improved energy efficiency and the use of alternative fuels can contribute to reducing the CII in shipping, they may not be sufficient to meet the ambitious targets set by the IMO to reduce carbon emissions from the shipping industry. As such, maritime CCS systems represent a promising solution that can be further investigated and developed to address this challenge. While research and development are required to identify and address technical and economic barriers to the widespread adoption of maritime CCS, such systems have the potential to significantly contribute to reducing carbon emissions from the shipping industry. By investing in the development of maritime CCS technology, stakeholders can work towards achieving the goals of the IMO and the Paris Agreement while providing an effective solution for reducing carbon emissions from shipping.

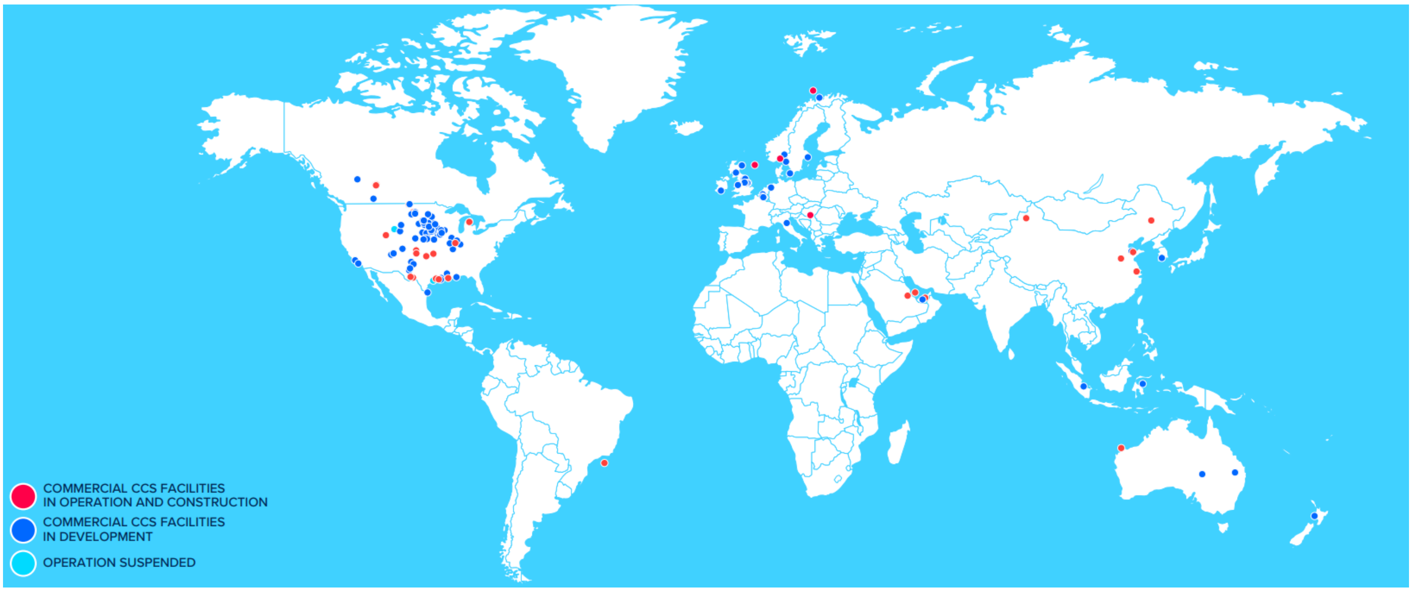

Figure 1.2: World map of CCS facilities at various stages of development (Global CCS Institute, 2021) [3].

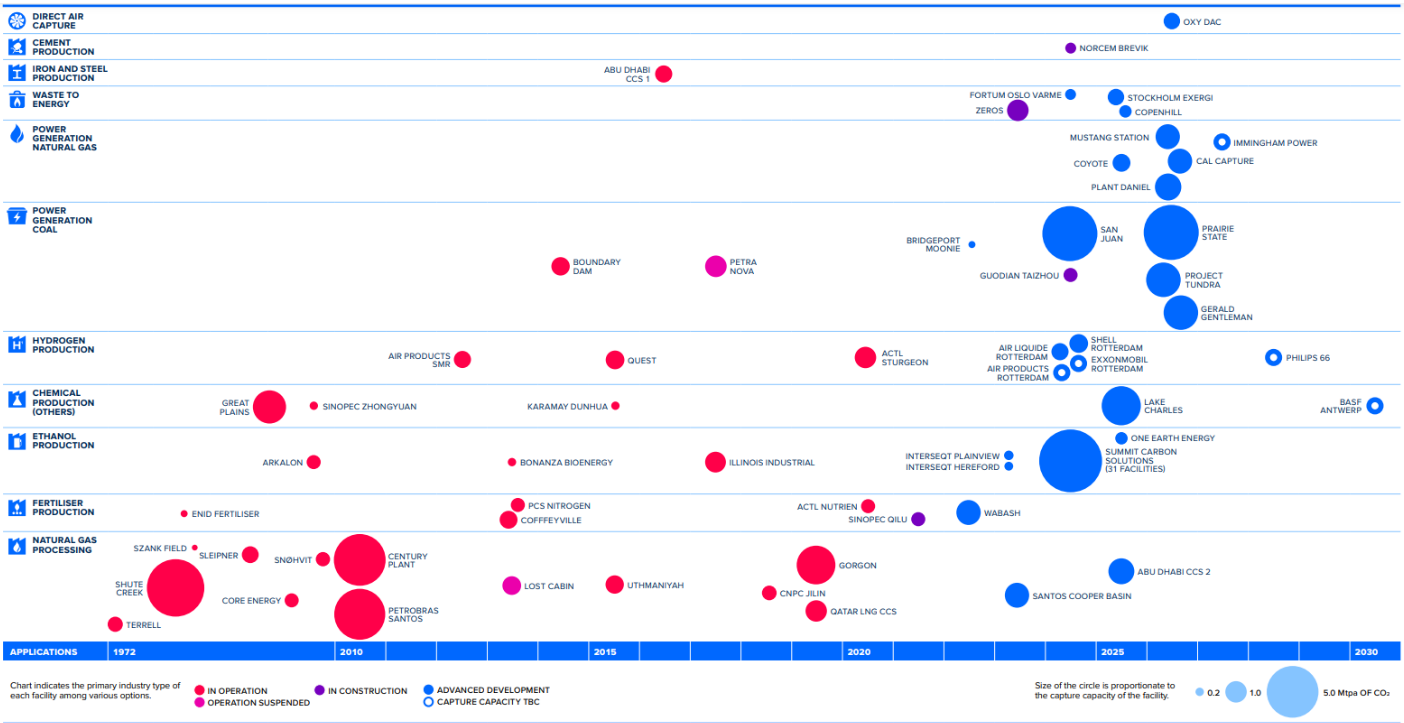

Figure 1.3: CCS projects by sector and scale over time (Global CCS Institute, 2021) [3].

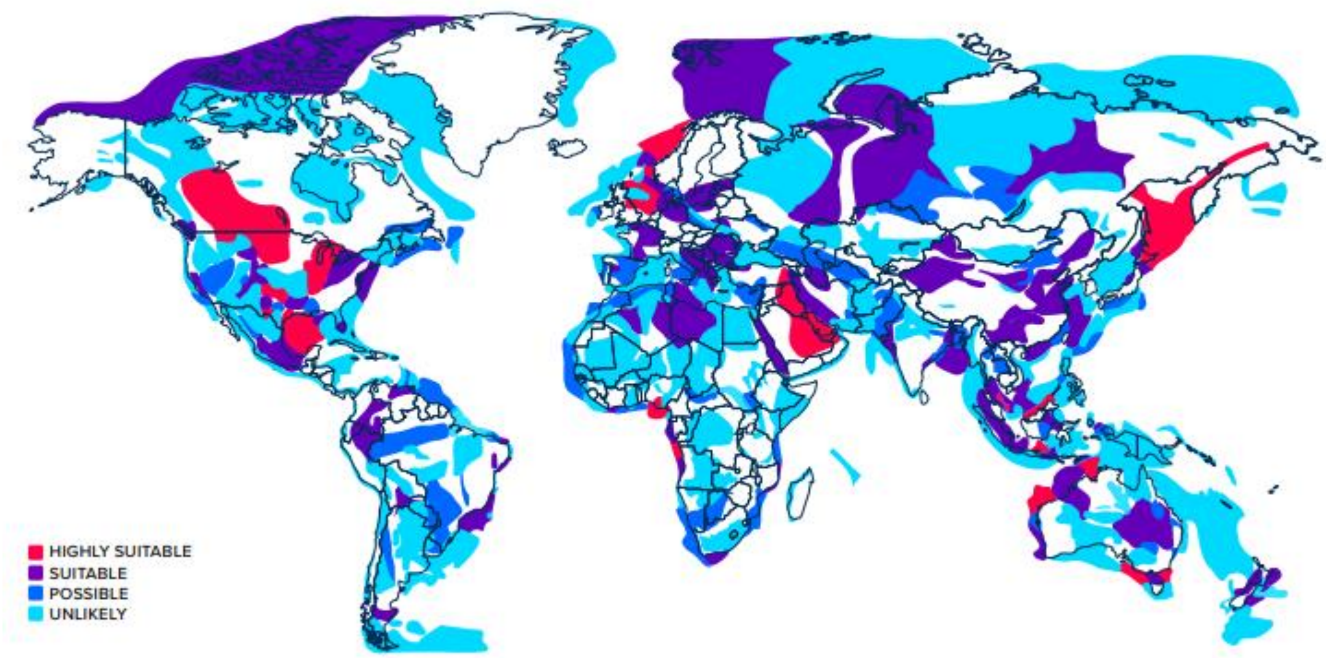

Figure 1.4: Suitable storage regions of the world based on the global CCS institute's storage basin assessment database (Global CCS Institute, 2021) [3].

1.4 Target of this thesis

The aim of this thesis was to develop a simplified model of a solvent-based CCS system that could be applied to any given vessel based on its basic technical specifications given. The research questions that will be addressed in this thesis include:

- Determining the required thermal and electric energy demand for the CCS system

- Determining the required thermal and electric energy demand for the CCS system.
- Applying a WHR (waste heat recovery) system for energy saving.
- Evaluating the effect of energy demand on fuel oil (FO) consumption.
- Assessing how the results align with the operational profile of the ship.
- Examining how the implementation of the CCS system will reduce the overall CII.
- Analysing the costs associated with the CCS system.
- Estimating the investment required for a given time period, along with a sensitivity analysis, to meet the IMO scenarios.
- Concluding which carbon capacity option is best and how many years it will extend the regulatory life of the vessel.
- Evaluating the space impact of the CCS system.

Through this analysis, the thesis aims to provide insights into the implementation of CCS systems on ships and contribute to reducing carbon emissions in the maritime industry. It is worth mentioning that the main part of this thesis was conducted as an internship in DNV R&D and Advisory Unit.

1.5 Summary of contents

In section 2, the focus will be on CCS technology where approaches and technologies of carbon capture are illustrated, while maritime applications and current SOA (state of art) in shipping is analysed. Section 3 contains the analysis of the CCS methodology where the aim, approach, features and requirements of the model are described. Furthermore, the case ship is given with her necessary data for the evaluation of the CCS system. The detailed development of the model with all the sub-systems considered (pre-processing, carbon capture, liquefaction) is described in section 4. Section 5 explores the CCS energy demand and the impact of WHR system, describes the technoeconomic model while metrics and CII calculations are the last parts of this section. An application study for a specific carbon capture capacity and a comparison regarding the basic results and the economic aspects of each examined capacity are illustrated in section 6. Last but not least, a sensitivity analysis which takes into consideration possible biofuel prices is made so as to converge to the conclusions of this thesis.

1.6 Publication

The work of this thesis provided the basis for the following conference peer-reviewed paper: *Concept Assessment of a Marine Carbon Capture System for Vessel Regulatory Lifetime Extension*. I. Beltsidis, C. Georgopoulou, G. Dimopoulos, L. Koukoulopoulos.

The paper was presented at 7 of March, 2023 during the 8th International Symposium on Ship Operations, Management and Economics (SOME) in Athens, at the Eugenides Foundation Conference Centre Auditorium.

2 The CCS technology

2.1 Approaches and technologies

There are multiple methods to capture CO2 from the use of fossil fuels and/or biomass. One of these approaches is post-combustion capture, which involves separating CO_2 from flue gases produced by burning fossil fuels. After treatment, most of the CO_2 is separated and stored in a tank, while the rest of the gases are released into the atmosphere.

In an oxy-fuel combustion engine, combustion occurs using nearly pure oxygen, resulting in flue gases composed mainly of CO_2. Capturing the emitted CO_2 is necessary to moderate the excessively high flame temperature.

Another approach is pre-combustion capture, which involves reacting a fuel with oxygen or air and/or steam to create a "synthesis gas" consisting mainly of carbon monoxide and hydrogen. The carbon monoxide is then reacted with steam in a catalytic reactor to produce CO2 and more hydrogen, which can be separated using physical or chemical absorption processes to obtain hydrogen-rich fuel for various applications.

Various carbon capture technologies are already being effectively used in onshore projects, including chemical absorption, physical separation, membrane separation, oxy-fuel separation, calcium looping, chemical looping, and direct separation. These technologies could serve as a foundation for designing a ship-based Carbon Capture System.

In matter of technologies there is a wide range that are already in use effectively in onshore carbon capture projects [5]:

- Chemical absorption – The most common purification technology. The CO2 contacts with a chemical in an absorption column.
- Physical separation – The main capture method used in natural gas processing. Most plants use proprietary solvents
- Membrane separation – Separation of CO_2 from the gas mixture by polymer membrane. Low-cost technology.
- Oxy-fuel separation – Same method described as above
- Calcium Looping – CO2 is captured at high temperatures by the use of two main reactors. In the first reactor CaO sorbent captures CO_2 from gas stream to form $CaCO_3$
- Chemical looping – Chemical looping is similar two-reactor technology. In the first reactor, small particles of metal are used to bind oxygen from the air to form a metal outside, which is then transported to the second reactor where it reacts with fuel, producing energy and a concentrated stream of CO_2, regenerating the reduced form of the metal.
- Direct separation – It is used in cement production. The limestone is heated indirectly by a special calciner. CO_2 is stripped directly from the limestone resulting in low energy costs.

Carbon capture technologies are already used in onshore industry plants, providing an adequate pillar to design a ship-based Carbon Capture System.

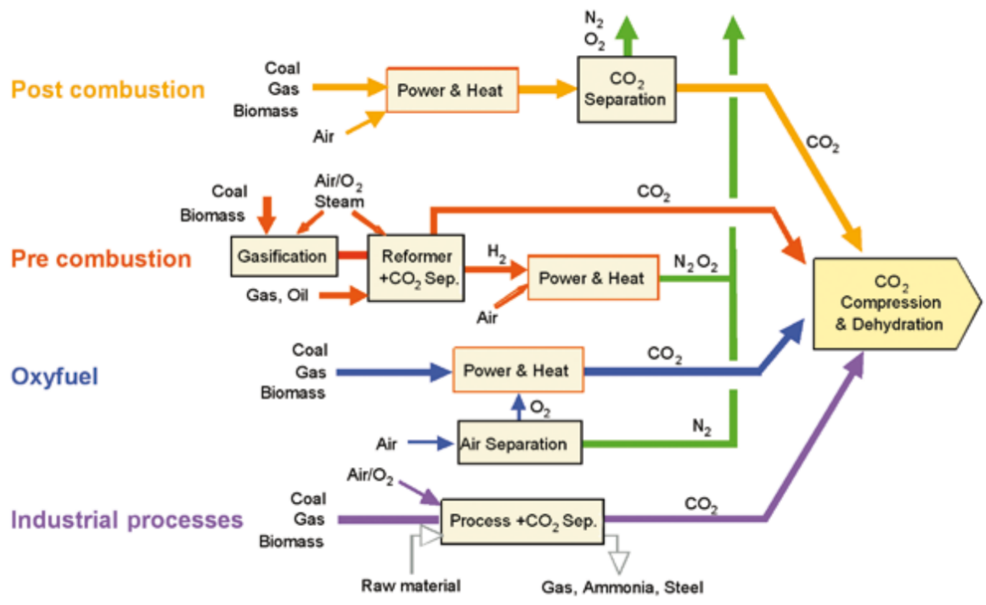

Figure 2.1: CO_2 capture systems [5].

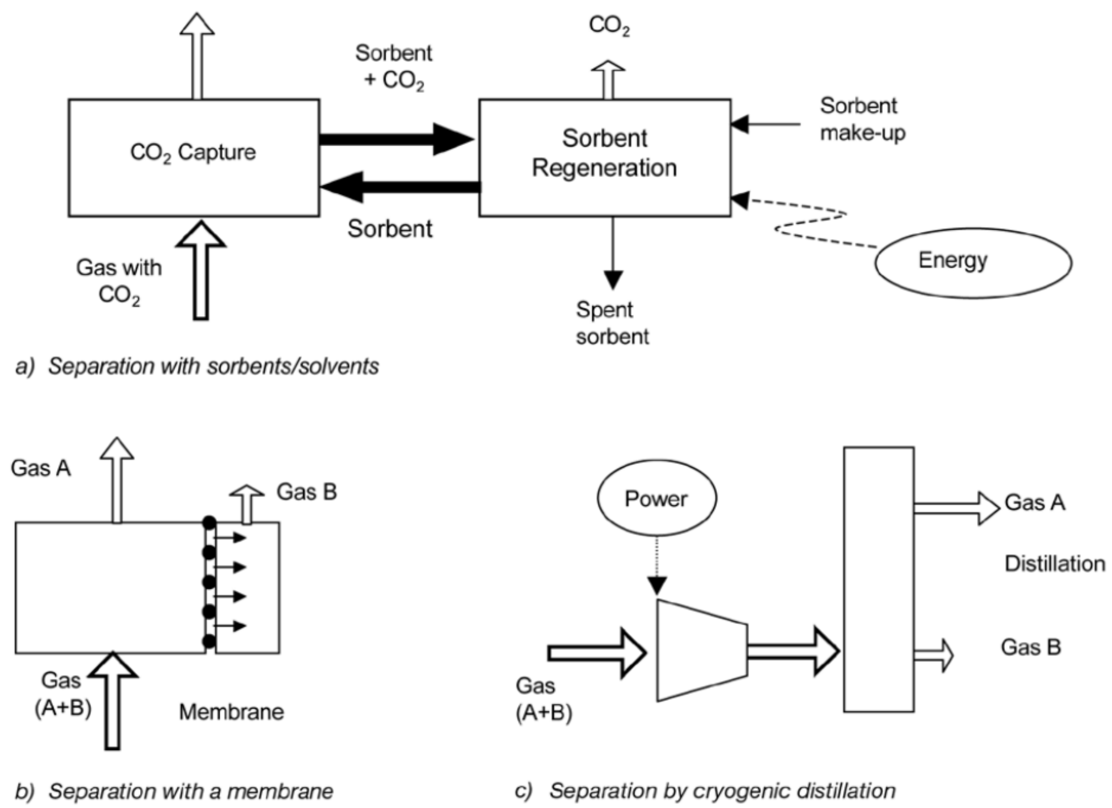

Figure 2.2: Operation of carbon capture technologies (a: Chemical absorption, b:membrane separation, c: Oxy-fuel separation [5].

2.2 Maritime CCS

Onboard carbon capture and storage is an innovative and highly promising solution for decarbonizing the maritime sector, as such systems may be established to non-technological advanced and pollutant vessels with no complicated intervention to the methanological parts of the them. The feasibility of this approach has been established through successful implementation of a range of CCS technologies, including chemical absorption using amine or ammonia scrubber and thermal stripper systems, high-gravity rotating packed beds, temperature swing chemical adsorption, membrane separation, cryogenic separation, and CO2 mineralization. Previous studies [14-16, 23, 29, 30, 34, 40, 41] have shown that CCS systems perform well in matters of capture rate and overall CO2 reduction, as this thesis will explore. Furthermore, no significant changes are expected in trim & stability and DWT aspects. The cargo space is not reduced, as CCS systems are usually established at the main deck of the vessel. However, the cost of onboard carbon capture remains relatively high and is expected to decrease with increasing Technology Readiness Level (TRL) and economies of scale, similar to other novel maritime decarbonization technologies. Figure 2.1 illustrates the TRLs as European Union implies. The challenges about the effective and universal use in maritime industry are the following:

- Investment cost compared to other decarbonization solutions.
- Future framework and IMO regulations regarding CCS.
- Vessel (retro-)fitting potential.
- Satisfactory carbon storage formation or utilization of CO_2.
- Advanced efficiency to reduce cost per ton of CO2 captured and extend regulatory life of vessel .

Figure 2.3: TRL definition (TWI global) [6].

2.3 Commercial outlook

The implementation of Carbon Capture and Storage in maritime transport has become increasingly important in the context of reducing greenhouse gas emissions from the shipping industry. Currently, there are several CCS maritime projects that are in different stages of development. Regarding the offshore carbon capture, the liquid absorption technology which is a post-combustion process, has gained ground. Post-combustion technologies are the most popular as the intervention with the engine is minimized [4]. Mitsubishi Shipbuilding has already designed the world's first marine based CO_2 Capture system (small scale) which successfully separates and captures CO_2 from exhaust gas [7], while Ionada's Membrane Decarbonization system for marine use combines proven chemical absorption processes with porous ceramic tube membranes to remove CO_2 from flue gas without creating a throwaway sludge product as figure 2.2 demonstrates [8],[9]. Bildfinger and Compact Carbon Capture (3C) are also working on marine CCS concepts [4],[9].

In terms of the state-of-the-art CCS systems, several companies have developed different technologies for CO_2 capture, compression, transportation, and storage in the maritime industry. Aker Solutions has developed a subsea carbon storage concept that consists of a gas compression station, a subsea pipeline, and an offshore reservoir for CO2 storage [10]. On the other hand, Japanese shipbuilder Mitsubishi Shipbuilding, part of Mitsubishi Heavy Industries (MHI) Group, has launched world's 1st liquefied CO2 transportation demonstration test ship intended for carbon capture, utilization and storage (CCUS). ENAA, Kawasaki Kisen Kaisha (K LINE), NGL, and Ochanomizu University will accelerate their research and development of the LCO_2 transportation technology and contribute to the reduction of the cost of CCUS technology and realization of LCO_2 safe large-scale long-distance transportation [11]. The Porthos project in the Netherlands is a joint venture between the Port of Rotterdam, Gasunie, and EBN (figure 2.3), and is set to capture and store 2.5 million tonnes of CO_2 per year from 2024 onwards [12]. Another project is the Northern Lights project in Norway, which aims to develop an infrastructure for the transportation and storage of CO_2, with the potential to store up to 5 million tonnes per year. Phase one of the project will be completed in 2024 with a capacity up to 1.5 million tonnes of CO_2 per year [13].

Despite these developments, several challenges remain for the implementation of CCS in the maritime sector. These include the high costs of CCS technologies, the lack of infrastructure and regulatory frameworks, and the technical challenges associated with CO_2 transportation and storage at sea. Therefore, it is essential to continue research and development efforts towards the improvement and commercialization of CCS technologies in the maritime sector.

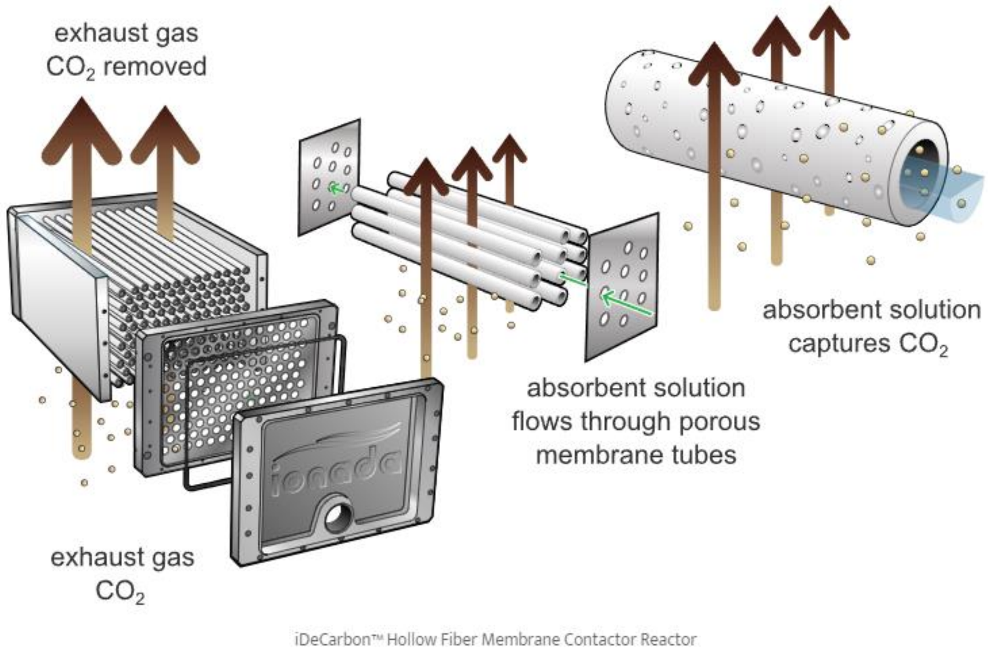

Figure 2.4: Ionada's Membrane Decarbonization system (Ionada,2023) [8].

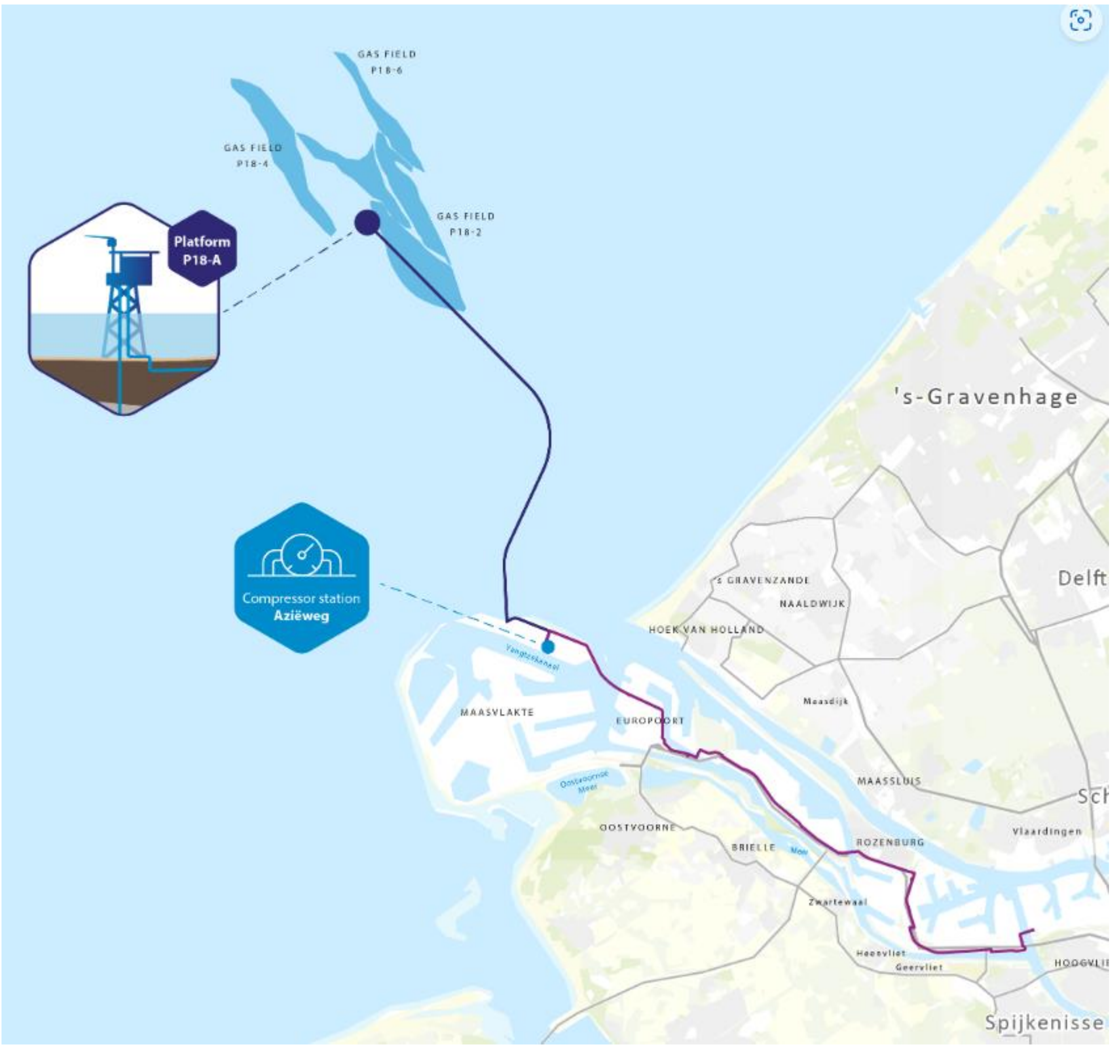

Figure 2.5: Porthos project (PorthosCO2, 2023) [12].

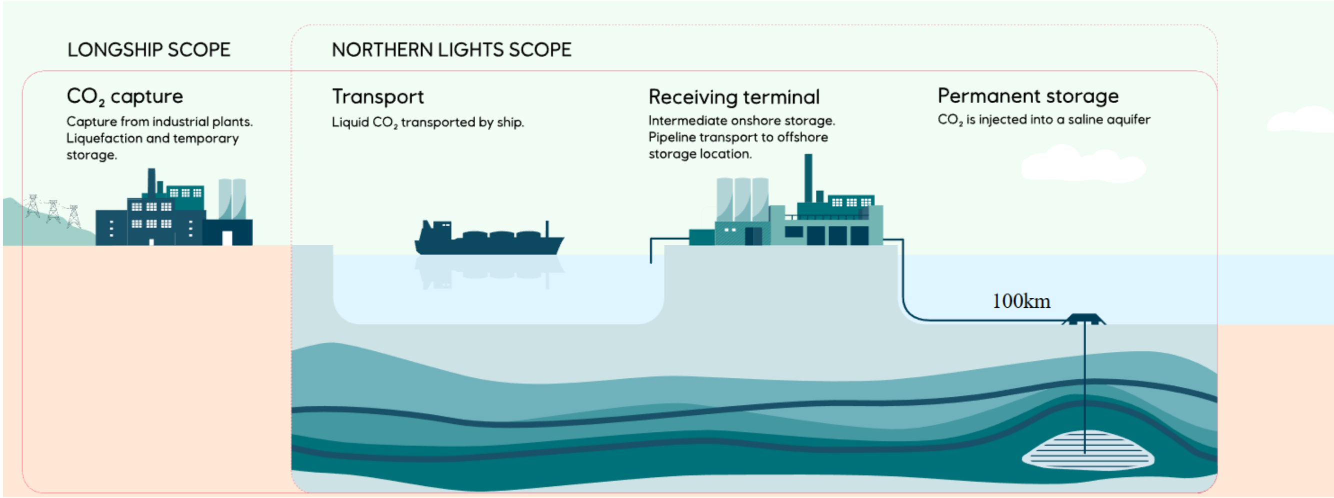

Figure 2.6:Northern lights scope [Equinor, 2023] [13].

3 Analysis methodology

3.1 Scope and approach

This study aims to apply a simplified solvent-based post-combustion carbon capture process which will be available for use for every given vessel. In order to evaluate the performance of the CCS system, a VLCC with a specific annual profile was chosen, while the data that were used are well known and easy to be found in every ship case. The goal is to explore the behaviour of the overall system for various CCS sub-system capacities. To serve this scope, the optimum CCS capacity is investigated, having as an objective the maximum overall CII reduction and thus the maximum regulatory life extension of the vessel. Despite the possible satisfying results on CII reduction for the optimum CCS capacity, a technoeconomic analysis is necessary, so as to account in all parameters. The energy penalty of the CCS system, the initial investment, the additional costs and the biofuels use so as to have a compliant vessel with IMO regulations throughout the lifetime of the investment are investigated in order to converge to the final result of this study.

3.2 Model specification

In previous works, scientific analyses of CCS onboard ships were conducted, focusing primarily on the assessment of the systems consumptions [14-16], rather than the intended effect of CCS on regulatory compliance and related carbon intensity metric, CII, which is the key element of our analysis.

To estimate performance, we follow a systems' engineering approach in the modelling and simulation of the system at various operating modes, as presented in [17] and [18]. Systems engineering is one of the key elements of the holistic ship design concept that is presented in [19] and [20].

The CCS process includes four individual sections:

- Pre-processing: Includes the pre-treatment of the gases before entering the carbon capture process.
- Carbon capture: The main process where the absorption of CO_2 takes part.
- Liquefaction: The CO2 captured is liquified and driven to storage tank.
- Waste heat recovery for energy efficiency improvement.

The system is designed to capture 99% of carbon processed. If exhaust gas flow exceeds the capacity of the CC system, the excess is assumed to bypass the system. If exhaust gas flow is lower than 20% of the capacity of the CCS system, the system is inactive to mitigate FO increase, as emissions are relatively low in this range of ME load. All necessary parameters for part load behaviour are evaluated concurrently with the design ME load. The contribution of WHR is analysed for varying loads to examine the best coverage of extra energy requirements imposed by CCS.

The CII of the baseline vessel without CCS is calculated to examine the impact of the CC system. The reference tanker operates in various conditions which depend on ballast sailing, laden sailing, and non-sailing modes and its respective speeds. Each condition is described by a unique set of parameters, consisting of: main engine (ME) power, electric power demand, boiler fuel oil flow and time in each specific condition / mode. The calculations performed with the model are coupled with the operational profile of the ship to examine the additional energy requirements for the operation of the CC system and finally evaluate the CII reduction.

Both exhaust gas flow and temperature of exhaust gas inputs come from International Maritime Organization (IMO) NOx technical file of the reference ship (testbed performance measurements), while the exhaust gas mass content in CO_2 (%w/w) is evaluated through fuel consumption of IMO NOx technical file along with IMO's conversion factor C_f, assuming conventional fuel operation.

In the WHR section, the important parameters are the overall heat transfer coefficient and the heat transfer area of evaporator and preheater, which are calculated so that the steam production is maximized. In that way, we achieve the best possible energy saving, as electricity is produced through a steam turbine generator. At part loads of ME operation, the steam flow is calculated by keeping the design characteristics of nominal load and by making the appropriate adjustments.

3.3 Case ship

A Very Large Crude Oil tanker (VLCC) will be the reference ship of this study. The case study vessel specifications, drawings and performance data were provided by Euronav Ship Management LTD. The vessel has one W7X82 Hyundai-Wartsila main engine with nominal rating of 33250 kW x 84 rpm. She also supplies 3 Hyundai-Himsen 9MELOAD1/32 auxiliary engines with a total output of 4590 kW x 900 rpm. The fuel consumed by the engines belongs to HFO. All data used in this study were gathered from her shop tests and the general arrangement (GA). Table 3.1 shows the main characteristics of the selected reference ship gathered from her general arrangement, while figure 3.1 illustrates the GA of the reference VLCC.

Table 3.1: Basic characteristics of case ship.

Deadweight	300000	*tones*
Length overall	333.08	*m*
Beam	60	*m*
Draft	20.5	*m*
Nominal rating ME	33250 x 84rpm	*kW*
Auxiliary power	4590 x 900rpm	*kW*

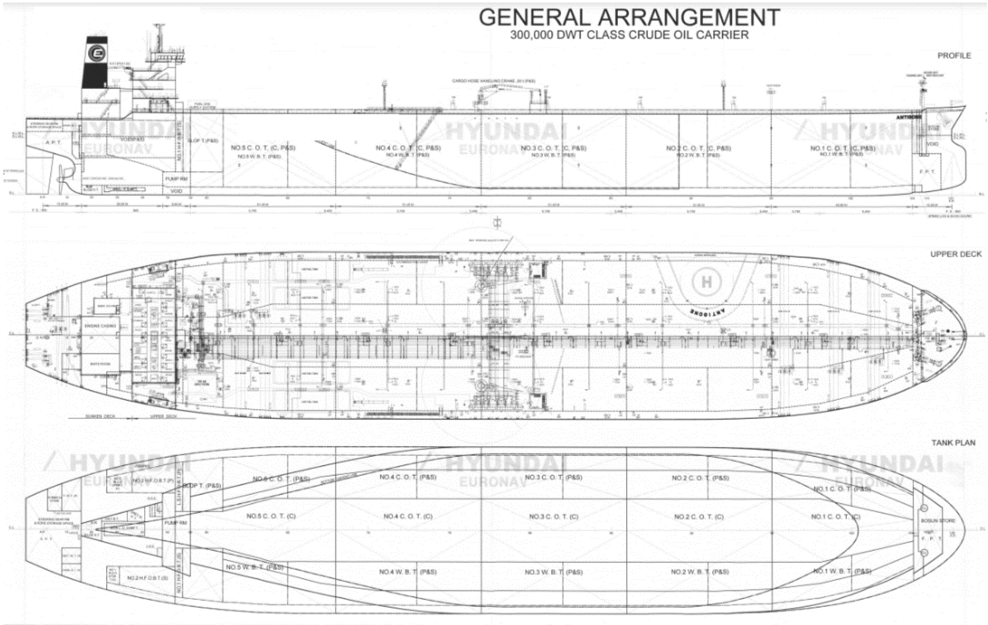

Figure 3.1: GA of the case study VLCC.

The year-round operational profile of the reference vessel will be matched up with the onboard integration that follows in the next section. The model that this study has developed will be able to screen the performance of the CCS system in each sailing condition for a chosen carbon capacity. The operational profile of the vessel was necessary so as to examine the overall result of the system, and the corresponding CII reduction. Figure 3.2 gives a generic view of the operation of the VLCC.

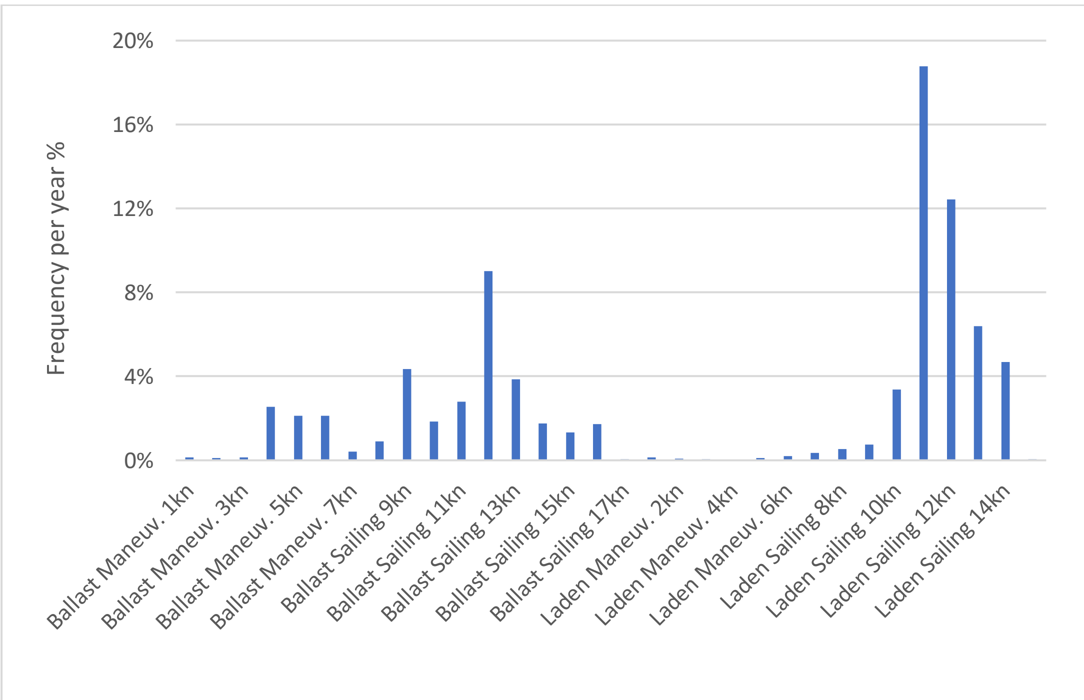

Figure 3.2: Vessel operational profile.

4 CCS model description

The selected onboard CCS system consists of three subsystems:

- Pre-processing
- Carbon Capture
- Liquefaction

Pre-processing

Following the combustion process in the main engine, flue gases are directed towards a pre-processing stage, while a portion is directed to the funnel (in instances where the ME load exceeds the design load of the CCS system). During the pre-processing stage, the exhaust gases are treated in preparation for the carbon capture process. Waste Heat Recovery (WHR) technology is utilized to recover the heat carried by the gases after combustion (this sub-system will be described later in this study), resulting in the cooling of the gases and the production of steam. Subsequently, the flue gases enter a cooling tower, wherein the temperature of the gases is significantly reduced, facilitating the absorption process. The temperature drop is accompanied by a corresponding pressure drop, which is mitigated using a blower. Water is circulated within the cooling tower, and the necessary water pump and cooler equipment ensure that the flue gases reach the appropriate temperature for absorption. Figure 4.1 demonstrates the stream of exhaust gas and water in the pre-processing section.

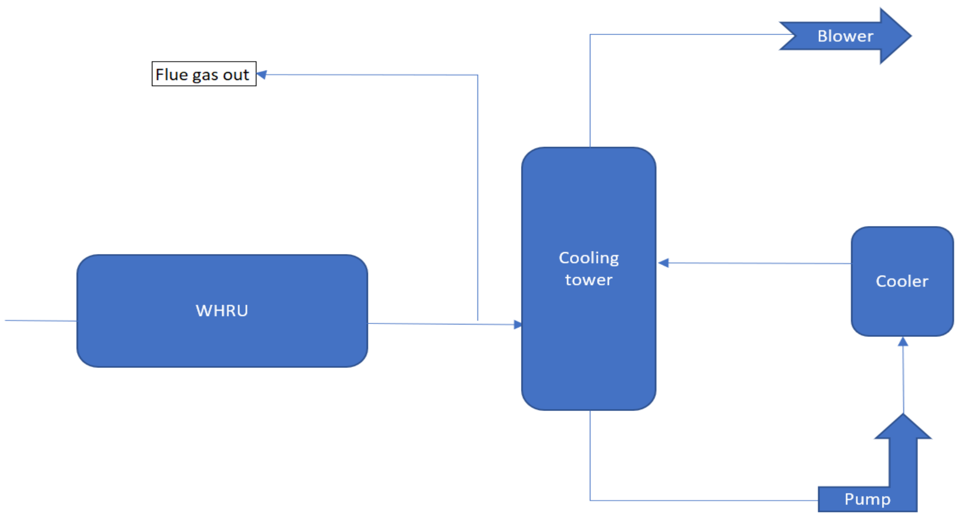

Figure 4.1: Pre-processing section design.

Cooling Tower

In direct-contact heat exchange, the hot and cold streams are brought into contact without any separating wall, and high rates of heat transfer are achieved. Water-cooling towers are a particular example of direct-contact heat exchange. To serve their scope, water circulation consists of a cooling tower, a pump and a cooler. Figure 4.2 demonstrates a typical direct-contact cooler [21].

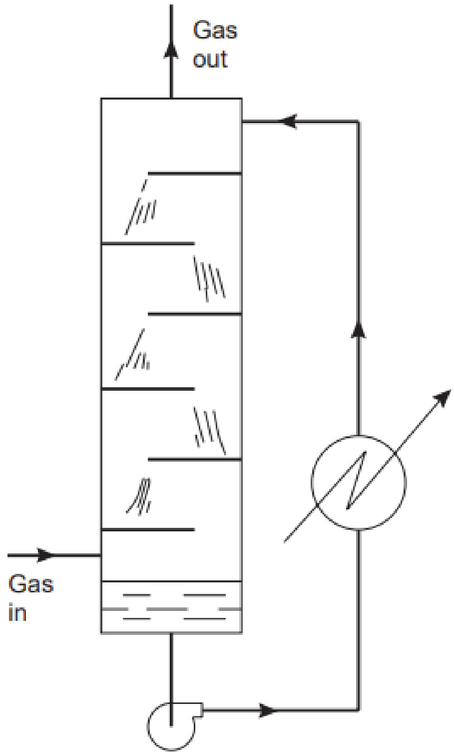

Figure 4.2: Typical design of a direct-contact cooler (Chemical Engineering Design,2008) [21].

Carbon Capture

The cooled flue gases enter the absorber where they react with MEA solution. CO_2 goes from gas to liquid, while pure gases (CO_2 removed) go to funnel. The rich solution of MEA now has CO_2, MEA and water. The pump drives the rich solution to the cross-heat exchanger (HEX), where the rich solution gets heat so as to reach the stripper at proper temperature. Stripper distillates CO_2 from rich solution. CO_2 stream is ready for liquefaction section. Rich solution, after the distillation of $CO_{2,}$ turns into lean solution, as part of CO_2 remains. The percentage of CO_2 in the lean solution depends from the cyclic capacity of MEA. The lean solution is heated and gets regenerated. Then it is driven back to cross HEX, where it is cooled from the passing rich solution. The end of the cycle comes when it is cooled. Then it gets back into the absorber at the desired temperature. Figure 4.3 contains all the parts required for the carbon capture and illustrates the stream of the solutions as well.

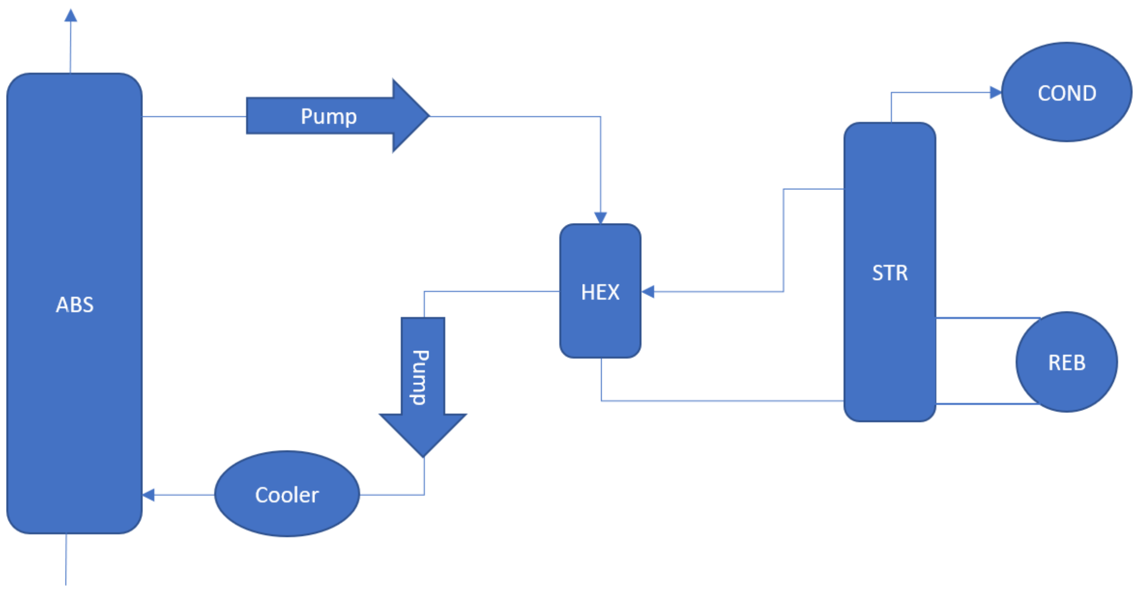

Figure 4.3: Carbon Capture section design.

Packed Columns

Gas absorption is a unit operation in which soluble components of a gas mixture are dissolved in a liquid. The inverse operation, called stripping or desorption, is employed when it is desired to transfer volatile components from a liquid mixture into a gas. Both absorption and stripping make use of special equipment for bringing gas and liquid phases into intimate contact [22]. In this study two packed columns are used, absorber and stripper. A separate analysis will follow.

Cross Heat Exchanger

The cross HEX takes part in the biggest thermal exchange of the CC system. Cold stream (rich solution) and hot stream (lean solution) exchange heat to reach stripper and absorber correspondingly at the proper temperature. Considering all parameters, the model was built so as to solve the CC system by changing U-factor and A of the cross HEX.

Reboiler

Stripper's reboiler duty is to regenerate the MEA solution at the bottom of the stripper column. The heat reverts the carbamate formation reaction, thus regenerating the amine and freeing up CO_2. This heat comes from a burner of heavy fuel oil. The free CO_2 is produced at the top of the stripper column as a gas. The thermal demand is calculated through the gaseous CO_2 produced and the specific reboiler duty of the stripper.

Solvent Selection

A wide variety of solvents has been considered in studies, with the most common being solvent solutions of MEA [15,16] ,PZ [15] ,as well as NH_3 [23] . This study took into consideration a recent detailed analysis [14] which compares the main candidate-solvents (30 wt% MEA, 30-40 wt% PZ, 2-28 wt% NH_3) using Key Performance Indicators (KPI).

Despite PZ has better characteristics when coming to Heat Demand (74% compared to MEA) and twice the absorption capacity of MEA, its health safety and environment (HSE) KPIs are considered not acceptable. Toxicity in humans and low Biodegradability (Solvents with low biodegradability are not preferred as they will persist in the environment they have been emitted in) doesn't make the PZ the ideal solvent.

NH_3 needs 68% of heat demand for regeneration compared to MEA, while its Oxidative degradation is very low compared to MEA. However, its Ecotoxicity is not acceptable.

Taking into consideration the above, this study selected to use MEA solution. The appropriate concentration of MEA in the solution is 30 wt% , as used is most of the studies conducted on CO_2 absorption in a packed column [24-26] . In the study done by Setameteekul et al.(2008), the increase in MEA concentration at low temperature of 30°C resulted in low increment of mass transfer coefficient, which is due to low spreading ability in the packing surface [27] . Thus, this study will be conducted with 30 wt% MEA, as selected solvent.

CO_2 handling and storage

This section has not been modelized. A typical ship-based Liquefaction process contains a 1 or 2-stage compression (space limitations). Flash columns and dryer purify CO2 for condensation. CO_2 is stored near the triple point (-57°C , 6.5 bar) . The row for the liquefaction of CO_2 is shown in figure 4.4.

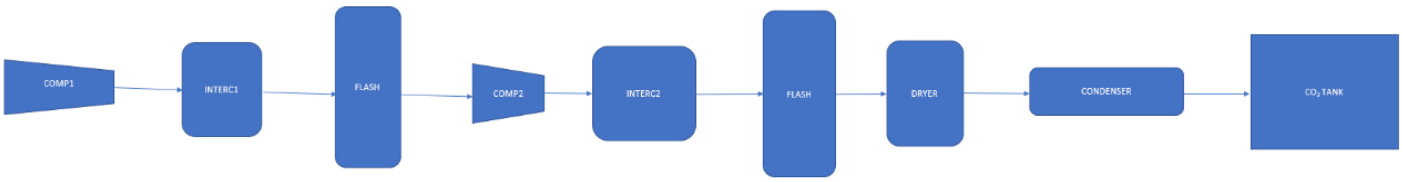

Figure 4.4: Liquefaction section design.

5 Onboard integration and vessel system

5.1 CCS energy demands

Cooling Tower and Blower Integration

The cooling tower cools the flue gas, so as to achieve the optimum absorption capacity. The tower treats the flue gas right after the WHR system, so the entry temperature is known, as well as the desirable exit temperature which is the same of the absorber entry gas temperature. Studies imply that the optimum gas entry temperature into the absorber in the range of 70-90 ^oC [14, 28-31].

The energy penalty of the cooling tower arises when the total output of the pump and the cooler is calculated. Industrial catalogues [53] were used to estimate the output of the coolers, taking into account the intended decrease of gas temperature and their inflow. The equations used for the pump and blower output calculation are illustrated below figure 5.1, where the position of the variables in the gas and water stream is given:

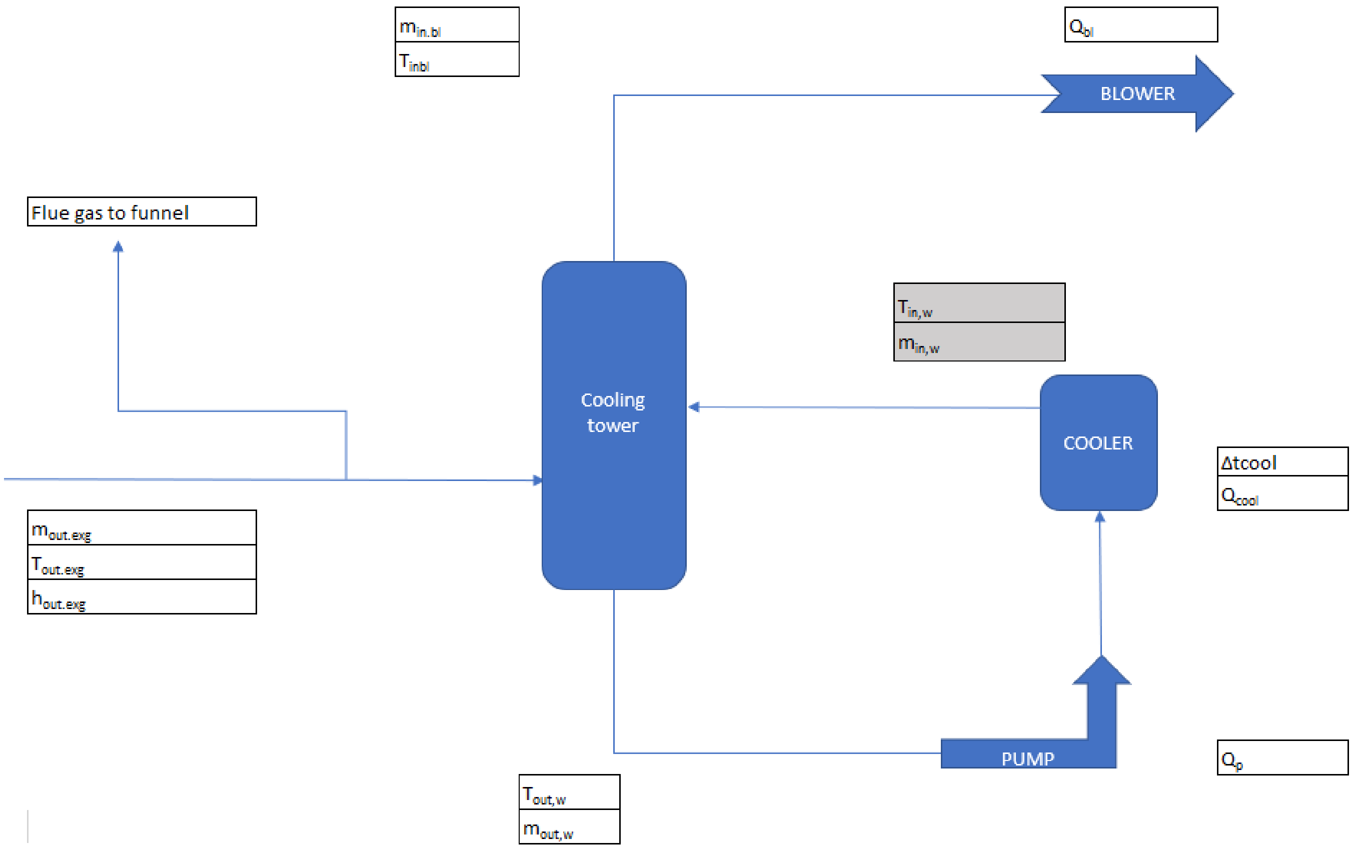

Figure 5. 1: Pre-processing system and variables.

The cell 'Flue gas to funnel' refers to bypass case, where ME load exceeds the design ME load. $T_{in,w}$ and $T_{in,bl}$ are design characteristics of the pre-processing system. Regarding liquid to gas (L/G) ratio, a study which analyzed a range between 0.75 and 2.25, implies that the optimum L/G ratio is in the range of 1.25 to 1.5, as figure 5.2 demonstrates [32].

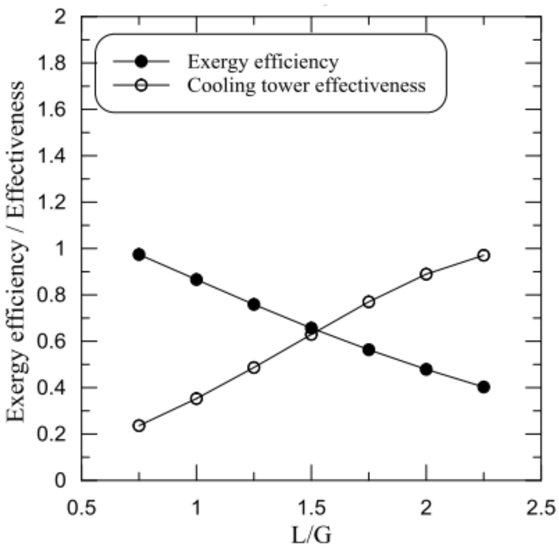

Figure 5.2: Effect of L/G ratio (Thermal and Exergy Analysis of Counter Flow Induced Draught Cooling Tower,2015) [32].

In this study a L/G ratio of 1.35 will be used. In terms of sizing, this study used the methods of Cornell and Onda, as illustrated in Chemical Engineering Design book [21]. Although these methods are mainly used for packed columns, Chen and Chia [33] mentions that direct-contact coolers between gas and liquid are designed along the same lines as gas absorbers. The widely used structured packing for absorption applications and cooling towers of Mellapak 250Y was selected [14, 15, 29, 34]. Taking into consideration both methods the diameter and the height was estimated for each ME load.

Absorber and Stripper

Absorber with a chemical reaction is a present-day commercial gas absorption process. MEA will be the solvent that is going to react to CO_2. Studies imply that the optimum temperature for the entering solution of MEA is 40°C, while gas enters absorber in the range of 70-90 °C.

Regarding the loading of lean and rich solution, this study took into account similar studies [29, 30, 34, 37-39] and used an average CO_2 loading of 0.45 mol/mol for rich solution and 0.26 mol/mol for the lean solution. The heat capacity of MEA was calculated through the below equation as [35,36] imply:

Where:

Heat capacity of MEA solution

Temperature in Celsius

mass fraction of MEA or weight percent MEA

CO_2 loading ($molCO_2/molMEA$)

The L/G ratio of exhaust gas and MEA solution system inside the absorber varies from 1.26 to 1.62. In all ME loads the ratio is above 1, which means that the amount of solvent is sufficient and bulge will not appear at the top of the absorption section [30]. Furthermore, the L/G ratio is well below 2 and thus the important increase of reboiler duty (with no corresponding results in CO_2 reduction) is avoided [40]. As for the efficient nominal MEA make-up, [41] implies that 1.5 kg is required for the absorption of 1 ton of CO2.

The efficiency of the absorber (carbon absorption) depends from the number of stages, mG_m/L_m factor and y_1/y_2:

- m = (mole fraction in vapor) / (mole fraction in liquid)
- G_m = molar gas flow rate per unit cross-sectional area
- L_m = molar liquid flow rate per unit cross-sectional area
- y_1 and y_2: the mol fractions of the solute in the gas at the bottom and top of the column, respectively

This study selected a carbon capture rate of 99% in the absorber. A percentage of 100% would not be feasible, as many N_{OG} (number of stages) are required (resulting in a very big absorber height). The optimum solution for the design problem of the absorber arises when mG_m/L_m is as high enough to favor stripper without significantly increasing the number of stages needed in the absorber.

The structured packing type of Mellapak 250Y was selected for the absorber as well. Following the same methods as for the cooling tower (Onda's and Cornell's), diameter and height was calculated.

Target pressure drop should lead to a satisfactory flooding at selected diameter. Pressure drop was verified with Robbin's and GPDC method from Perry [22] and Onda's method from Chemical engineering design [21] resulting in a result close enough to the target pressure drop.

As studies imply [17, 29, 30] the rich solution enters the stripper at about 120^{o}C. Stripper needs 2 less N_{OG} than absorber. The type of packing will be the same as the absorber while the same approach was applied for pressure drop and sizing.

Reboiler

Stripper's reboiler duty is to regenerate the MEA solution at the bottom of the stripper column. The heat needed comes from a burner of heavy fuel oil (HFO-calorific value 42.7 MJ/kg) with high efficiency (97%). The free CO_2 is produced at the top of the stripper column as a gas. The thermal demand is calculated through the gaseous CO_2 produced and the specific reboiler duty of the stripper. Considering that an advanced stripper will be used, its' duty is 2.9 $MJ_{th}/kgCO_2$ [54-57].

Carbon capture

The challenge in Carbon Capture integration was to calculate the design characteristics of the cross HEX, while achieving the intended conditions in terms of temperature, efficiencies and ratios. The model calculates the UA of the HEX through iteration to the target temperatures. The equations and all the variables that were used can be found below, as well as a figure which illustrates the position of the main variables. Regarding the Coolers' and Pumps' demand, the same equations as the pre-processing section were used. In figure 5.3 the position of the variables is given:

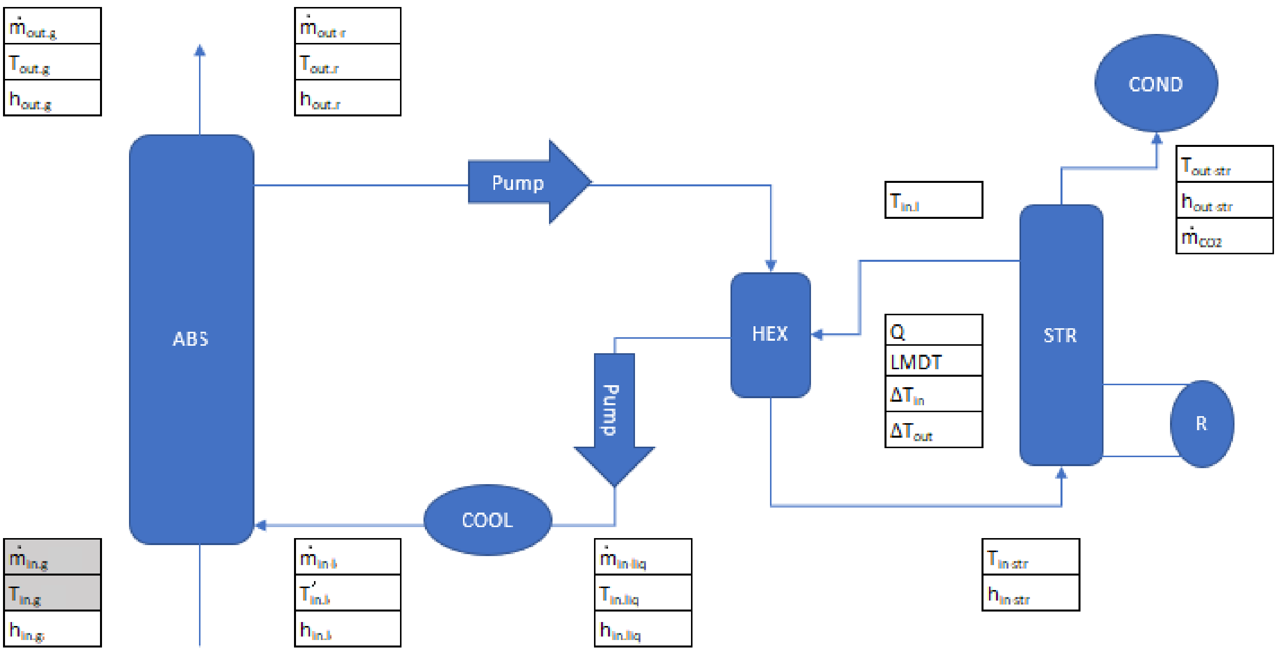

Figure 5.3: Carbon capture system and variables.

Liquefaction Integration

As mentioned above, the liquefaction section has not been modelized. Although, the energy penalty for the liquefaction of CO_2 is significant and thus is included in the calculations. A comparison of the energy consumption for CO_2 compression process alternatives implies that a 1-stage compression requires 130 kWh/tCO_2 for liquefaction [43]. This estimation was used in this study as space limitations will be a challenge in a marine based CCS system.

Integration results

In table 5.1, the results of the integration are illustrated. The results describe the performance of the system for different carbon capacities, supposing that the vessel is moving with a consistent ME load which will be her design load. As described in previous section, the design load is the load where the CCS system is capable of capturing maximum CO_2 possible for the given capacity, so no bypass and no part loads are taken into consideration. Figure 5.4 illustrates the electricity demand and reboiler duty with variation on design ME load, while figure 5.5 demonstrates CO_2 captured and total extra fuel with variation on design ME load.

Table 5.1: Integration results

Design ME load	75%	65%	60%	55%	50%	45%	30%	*%*
Output	18015	15613	14412	13211	12010	10809	7206	*kW*
Gas flow	144.3	130.8	123.9	116.7	109.4	101.9	78.4	*tn/hr*
CO_2 in exhaust	6.92%	6.73%	6.60%	6.45%	6.28%	6.09%	5.40%	*w/w*
CO_2 captured	9.89	8.71	8.09	7.45	6.80	6.14	4.19	*tn/hr*
Heat duty	4638.4	4087.7	3795.9	3496.2	3190.9	2894.8	1965.8	*kW*
Electricity demand	2661.6	2346.9	2185.7	2022.6	1858.8	1696.7	1,209.94	*kW*
Steam Generator	865.4	703.7	630.3	561.7	497.8	438.4	285.15	*kW*
Extra fuel-electricity	16.43	13.08	11.48	9.94	8.49	7.14	3.73	*tn/day*
Extra fuel-reboiler	9.68	8.53	7.92	7.29	6.66	6.04	4.1	*tn/day*
Total extra fuel	26.11	21.61	19.40	17.24	15.15	13.18	7.83	*tn/day*

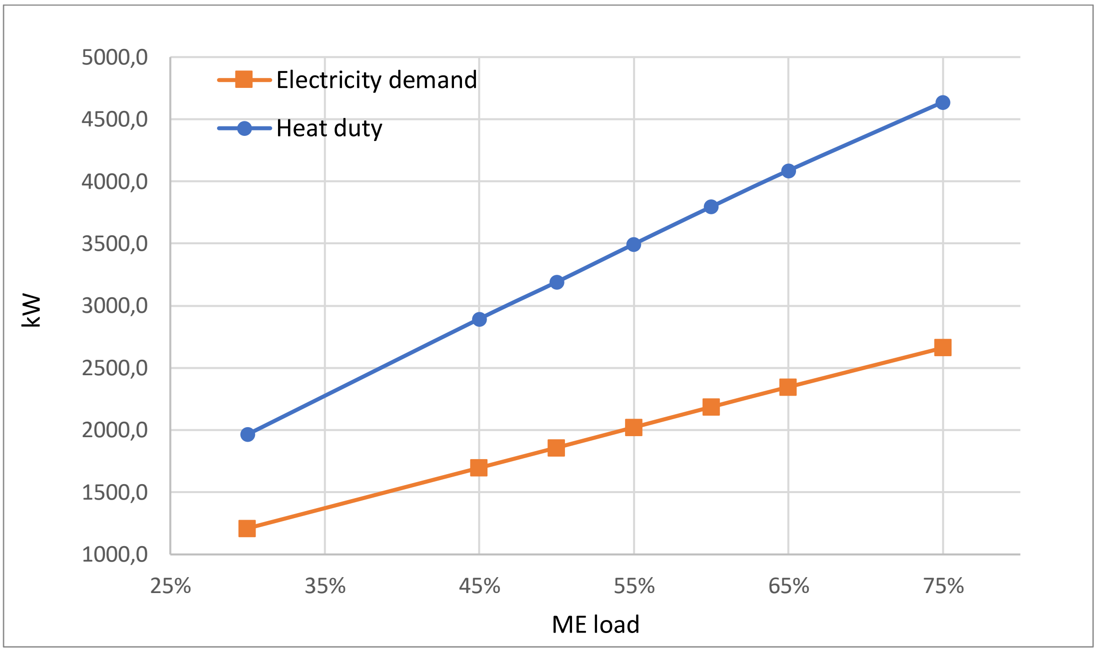

Figure 5.4: Electricity demand and reboiler duty with variation on design ME load.

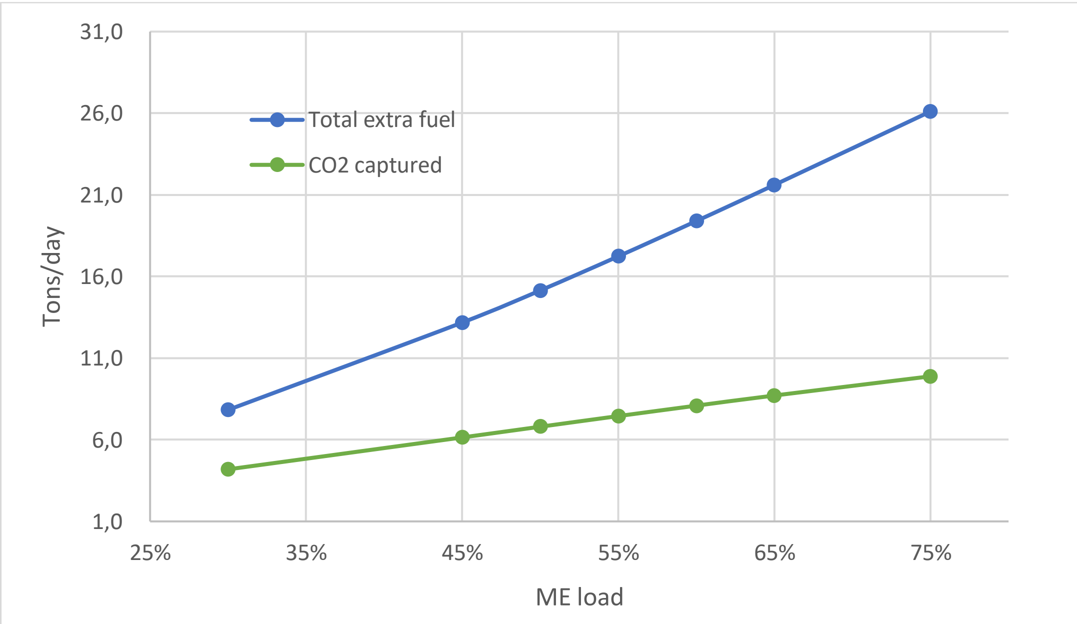

Figure 5.5: CO2 captured and total extra fuel with variation on design ME load.

5.2 ME, AE and reboiler

The CCS model uses seven technical specifications that have variation on ME load. Thus, for each ME load there is a unique set of technical data that will be used in the evaluation of the performance of the CCS model. The data regarding the ME and AE (except from CO_2 content %w/w which was calculated through IMO Cf=3.206) of ME loads of 25%,50% and 75% are taken from IMO NOx technical file of the reference ship while loads of 40% and 65% were calculated through iteration. The following equations describe each technical specification as a function of ME load:

Five different Loads (25%,40%,50%,65%,75%) with their main characteristics are illustrated in table 5.2. Main engine power % and output (kW), exhaust gas flow (), temperature of exhaust gas (), specific fuel oil consumption (SFOC) of diesel generators (DG) and ME, CO_2 content %w/w (con) in flue gas, uncorrected Fuel oil/day consumption can be found in Table 5.2, Figure 5.6 describes the SFOC of ME while figure 5.7 demonstrates the CO_2 content in the flue gas.

Table 5.2: Basic technical data for each ME load.

ME Power	75%	65%	50%	40%	25%	%
ME Output	18015	15613	12010	9608	6005	kW
Exhaust Gas Flow	40.08	36.35	30.39	26.19	19.52	kg/s
Temperature of Ex.Gas	467.80	464.74	460.65	458.25	455.15	K
SFOC - DG	245.00	247.00	250.00	257.00	265.00	gr/kWh
%w/w CO2	6.92%	6.68%	6.28%	5.93%	5.12%	%
SFOC - ME	163.1	164.83	168.3	171.19	176.4	gr/kWh
Fuel oil/day (ME)	70.50	61.83	48.51	39.40	25.42	tons

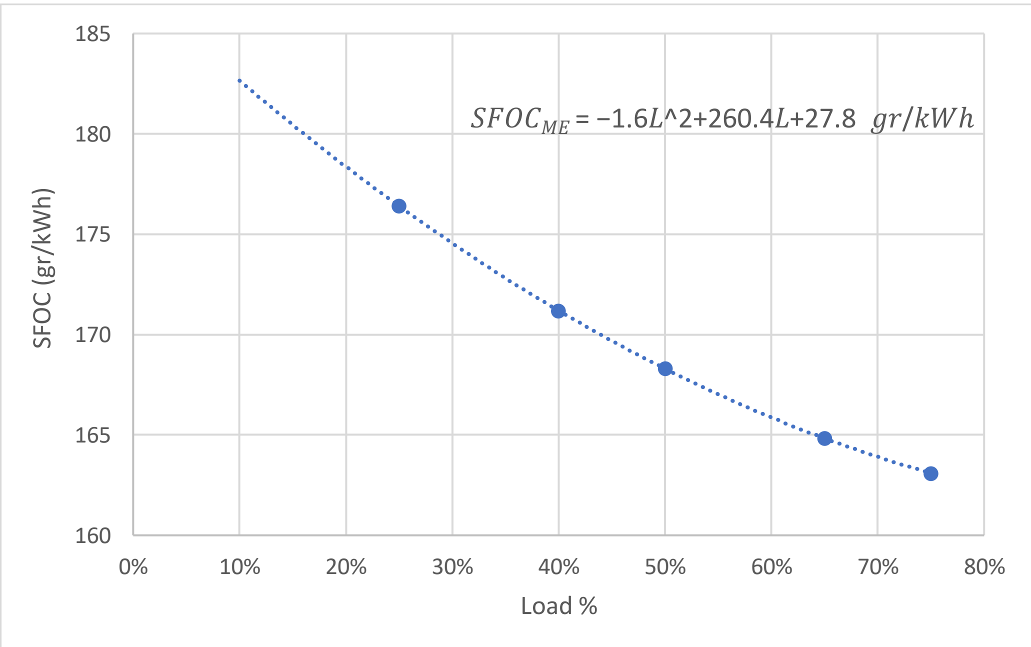

Figure 5.6: SFOC of ME with variation on ME load.

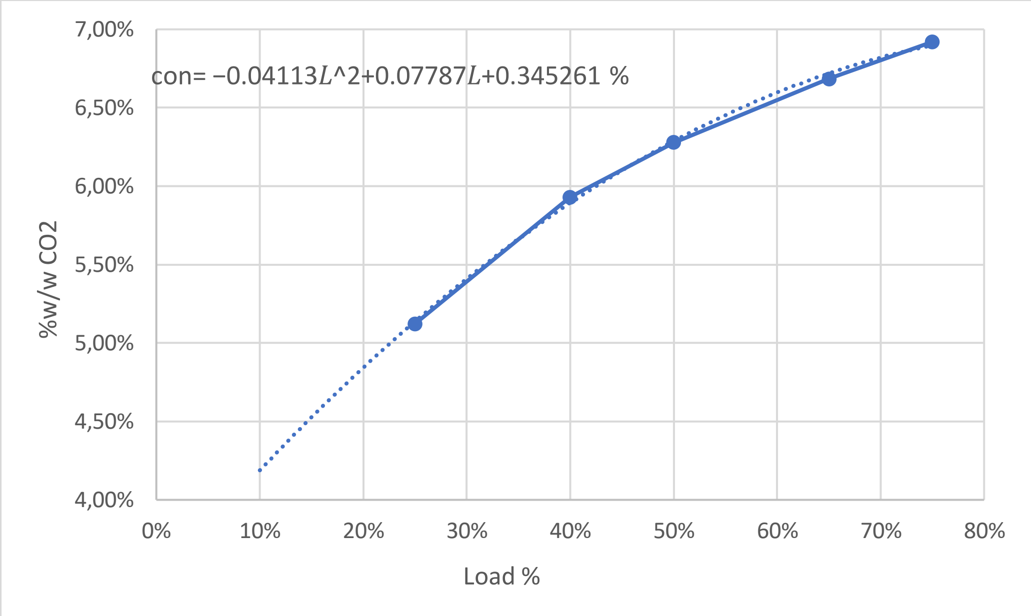

Figure 5.7: CO2 content %w/w with variation on ME load

5.3 WHR

Preheater

The preheater heats up the feed water close to saturated water temperature (below saturating temperature to avoid evaporation in preheaters' tubes) by gaining heat from the low-temperature flue gas. It is located in last part of WHR where the exhaust gas has the lowest temperature. The difference between the water exit temperature of the preheater (which is the same as the evaporator entry temperature) and the saturated water temperature is usually termed approach temperature difference. The pressure of water that gets in the preheater plays crucial role in m_{steam} production. Low pressure results in high steam production.

Evaporator

The evaporator further heats up the feedwater coming from the preheater up to the proper saturated water conditions and evaporates the entire mass flow to saturated steam, providing energy equal to the latent heat of the water. The gas temperature is higher than that of preheater. Gas enter evaporator with the temperature of the exhaust gas.

Steam generator

Evaporator delivers the steam to a steam generator for electricity production. The electricity gained from the heat of the exhaust gases eases the additional electricity need due to CCS system. Steam generator is considered to be advanced to achieve high efficiencies.

To examine the results of such an energy saving system, mathematical modeling is necessary. The equations and all the variables that were used can be found below, as well as figure 5.8 which illustrates the position of the main variables.

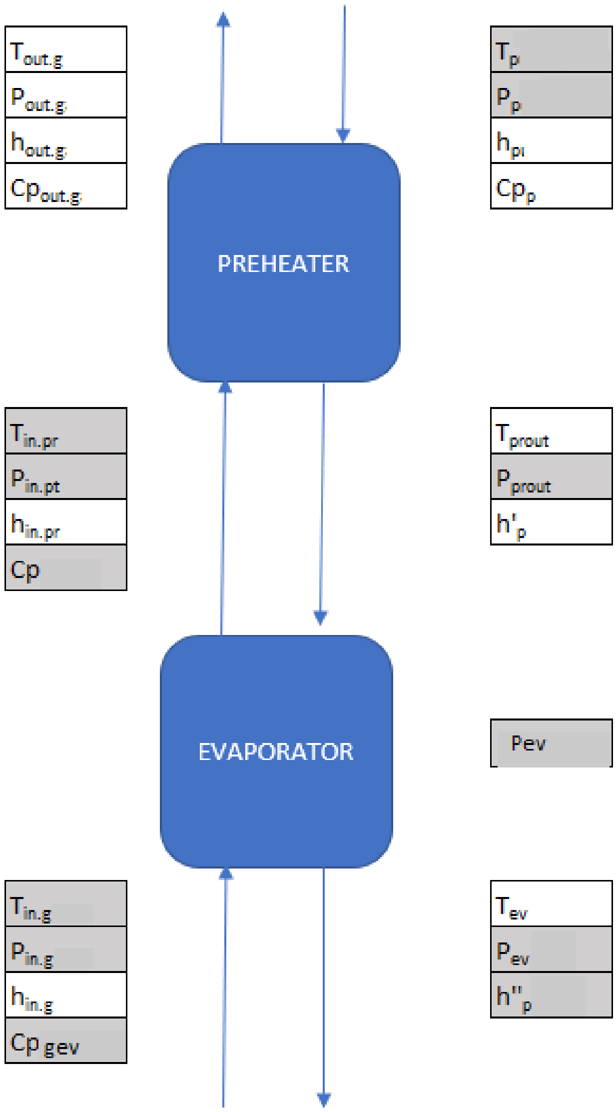

Figure 5.8: WHR system and variables.

Regarding the units, they are counted in metrics as table 5.3 defines:

Table 5.3: Units

Q (power)	
T (temperature)	
h(enthalpy)	
Cp(specific heat capacity)	
(mass flow)	
P(temperature difference)	

The model was based on degrees of freedom. We have 10 equations with 18 variables, so 8 inputs are needed to have the system solved. From the 8 inputs we already know 6 and the other 2 are given as design characteristics of the WHR system. The results of the modeling of WHR are pictured in figure 5.9. The gain of electricity is for the design ME load, meaning that for each carbon capacity the gain of electricity is for the matching design ME load.

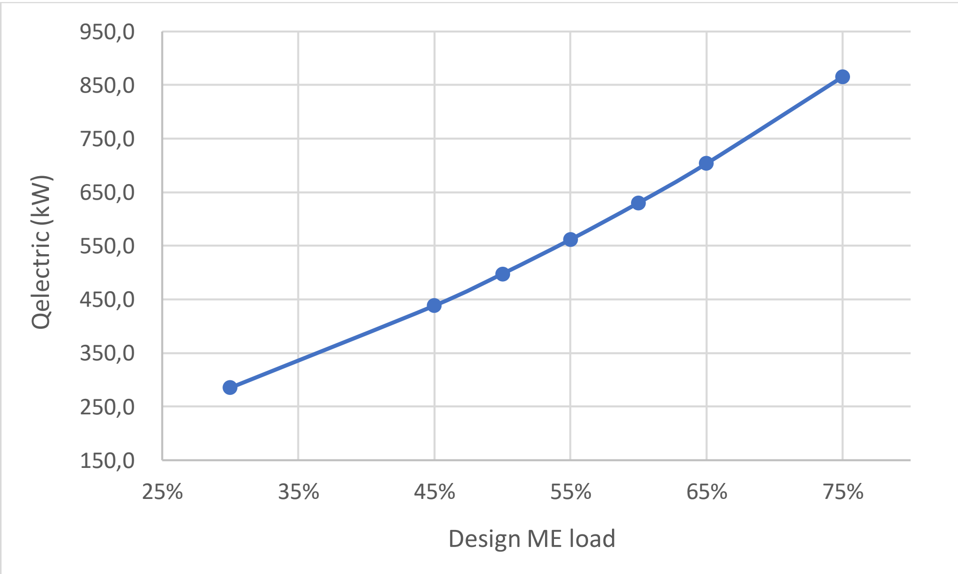

Figure 5.9: WHR performance with variation on ME load.

5.4 CII

To set the objective of CII reduction, the CII of the case vessel should be calculated, following the guidelines that IMO suggests [44]. For a defined group of ships the reference line is formulated as follows:

Where CII_{ref} is the reference value of 2019, *Capacity* is the DWT (deadweight) of the vessel, while *a* and *c* are parameters estimated through regression fits, taking the attained CC and the capacity of individual ships collected through IMO DCS in year 2019 as sample. All values used for the calculation of the CII and the CII itself are illustrated in table 5.4:

Table 5.4: Values used for CIIref calculation.

Ship type	*Capacity*	*a*	*C*	*CII_{ref}*
Tanker	300000	5247	0.610	2.39

The attained annual operational CII of individual ships is calculated as a ratio of the total mass of CO_2 (M) emitted to the total transport work (W) undertaken in a given calendar year, as follows [45] :

- M is calculated by multiplying the total mass of consumed fuel oil, HFO (heavy fuel oil) in our case, with IMO conversion factor C_F.
- W is calculated by multiplying the total distance travelled in a given calendar year with its DWT.
- No correction factors are applied.

All values used are illustrated in table 5.5:

Table 5.5: Values for attained CII calculation.

CF	*Nautical miles*	*M (tons)*	*W*	*attained CII*
3.206	*70523*	*43372.6*	*~2.12*10^12*	*2.05*

In maritime there are possible scenarios regarding the CII reduction over the years. The most well-known and prevalent are the annual CII reduction of 2% and the zero emission till 2050 scenario. This study will make its' estimations and the calculations taking into consideration the toughest to achieve. The different colored areas at figure 5.10 below represent the rating of the vessel compared to the required CII for zero 2050 scenario, as IMO suggests [46]. The red line pictures the current CII of the vessel, which will not be compliant with IMO regulations at 2027.

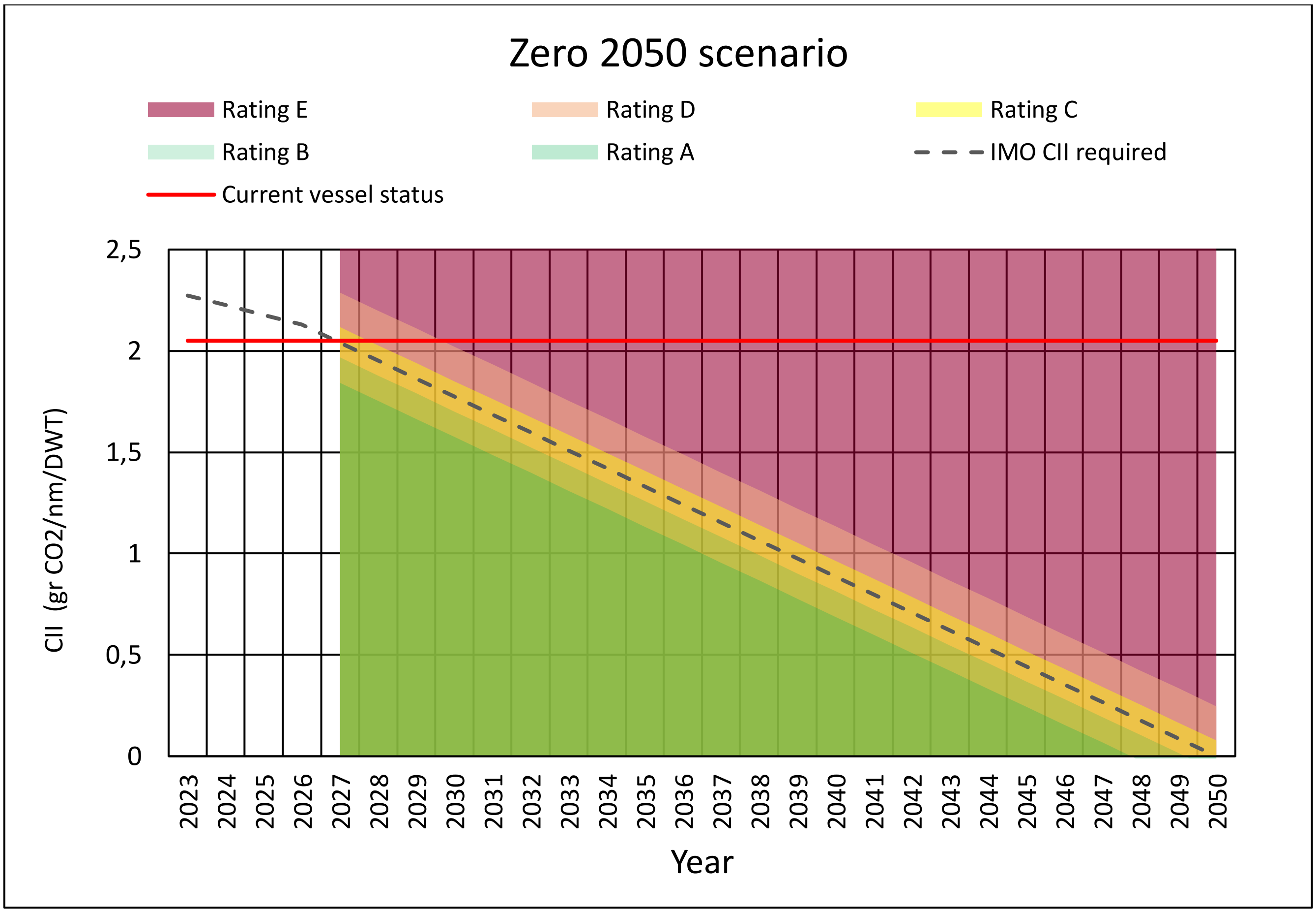

Figure 5.10: Current case ship CII and IMO CII reduction scenario of zero emissions till 2050.

5.5 Technoeconomic model

To evaluate the economic feasibility of carbon capture system, the total annual cost (TAC) is divided with the total CO_2 reduction in the year-round operational profile of the reference ship. TAC is calculated by annualized capital expenditure (ACAPEX), fixed operational expenditure (FOPEX), and variable operational expenditure (VOPEX) as equation below defines:

A preliminary cost estimation considering all machinery required for the CC system follows. Chemical engineering design [21] provides a function with its parameters for different equipment that calculates the cost of each part, having as an input its capacity. Multiplying the capital cost with the installation factors proposed by Hand, a total economic overview of the CC system is given. For the liquefaction process, rapid cost estimation has been applied, as this study doesn't estimate capacities for liquefaction machinery. This method was conducted considering similar liquefaction applications [47-51].

ACAPEX is calculated by multiplying CAPEX with capital recovery factor (CRF). CRF is a function of economic life of the plant and the interest rate. In this study we assume an economic life of 25 year and an interest rate of 8%.

FOPEX includes long term service agreement costs, overhead cost, operating and maintenance cost (O&M) and other costs fixed for the plant no matter if it is running at partial or full load or shutdown. FOPEX can be easily estimated as the 3% of the CAPEX.

VOPEX includes the cost of electricity consumption for pumps, blower, compressors, the cost of heat for solvent regeneration, the cost of cooling utilities and the cost of MEA solvent make-up. In previous section extra fuel requirements have been analysed for the 320-day operational profile of the ship. The current price of MDO is about 650$/ton. The current price of MEA is 2.3$/kg [52] while [41] implies that 1.5 kg of MEA is required for the absorption of 1 ton of CO_2. Table 5.6 illustrates the basic economic elements for the evaluation of the investment that will be done for each carbon capacity in the next section.

Table 5.6:Elements for economic evaluation

Interest rate	8%
Economic life of plant (years)	25
CRF	0.094
MDO ($/T)	650.00
kg MEA / ton CO2	1.5
MEA ($/kg)	2.3

6 CCS application study

6.1 Load dependent CCS performance

In this subsection the CCS performance for a given capacity will be investigated. The investigation will start from onboard integration detailed calculations in each stream section of the CCS system, and will conclude to the economic aspects of the selected carbon capacity. The carbon capacity that will be analysed belongs to design ME load of 65%.

WHR performance

In table 6.1 and figure 6.1, the performance of the WHR when having design ME load is given, while figure 6.2 illustrates a random part-load performance of 26% (0.4xDesign ME load), when the capture capacity is designed for ME load of 65%. All calculations have been done with the method described in section 5.3. The names of the variables remain the same.

Table 6. 1: Characteristics of heat exchangers – WHR design ME load.

	Q (kW)	*UA (kW/K)*	*LMTD (K)*
Preheater	157	4.8	32.57
Evaporator	1122	65.92	17.02

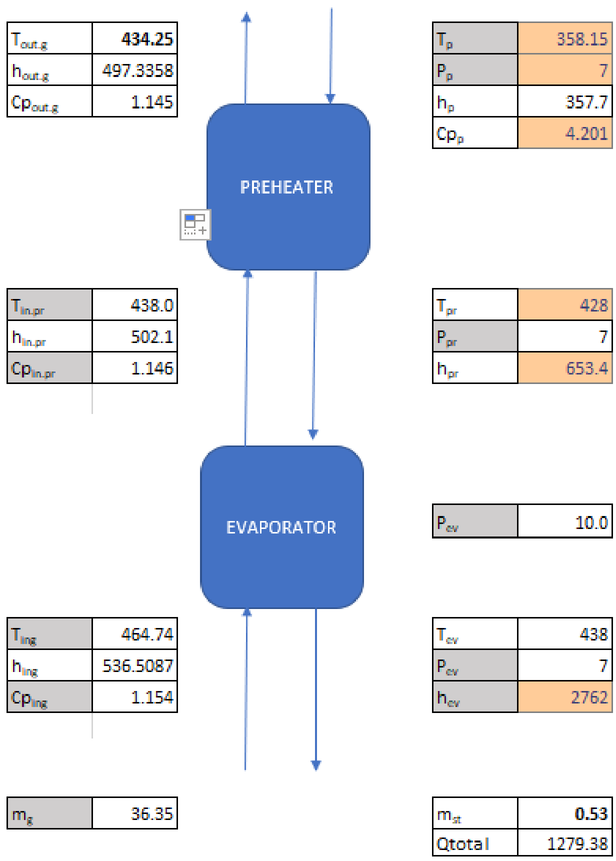

Figure 6.1: WHR performance for design ME load of 65%.

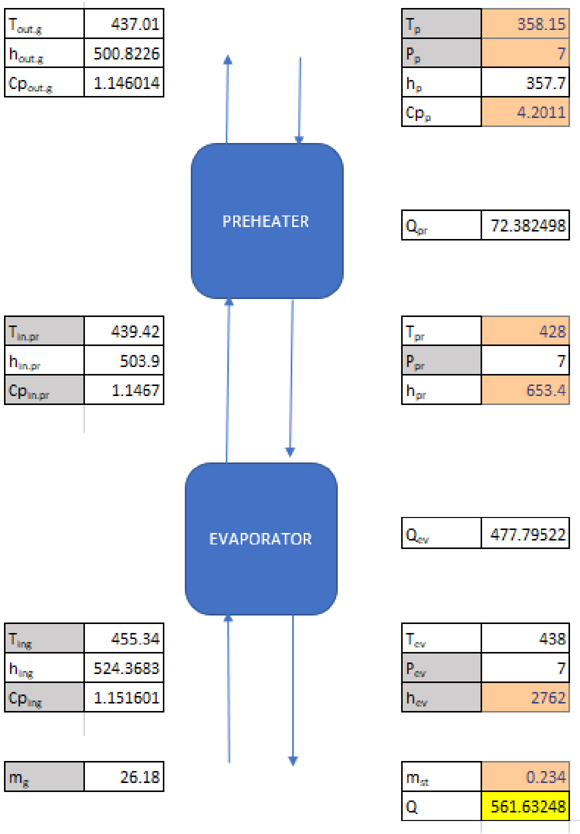

Figure 6.2: WHR performance for ME load of 26% for carbon capacity of 65%.

Pre-processing performance

The mathematic approach is described in section 5.1. Figure 6.3 illustrates the detailed numbers of pre-processing performance for the design ME load of 65%, while figure 6.4 is for the part-load of 26% of ME load.

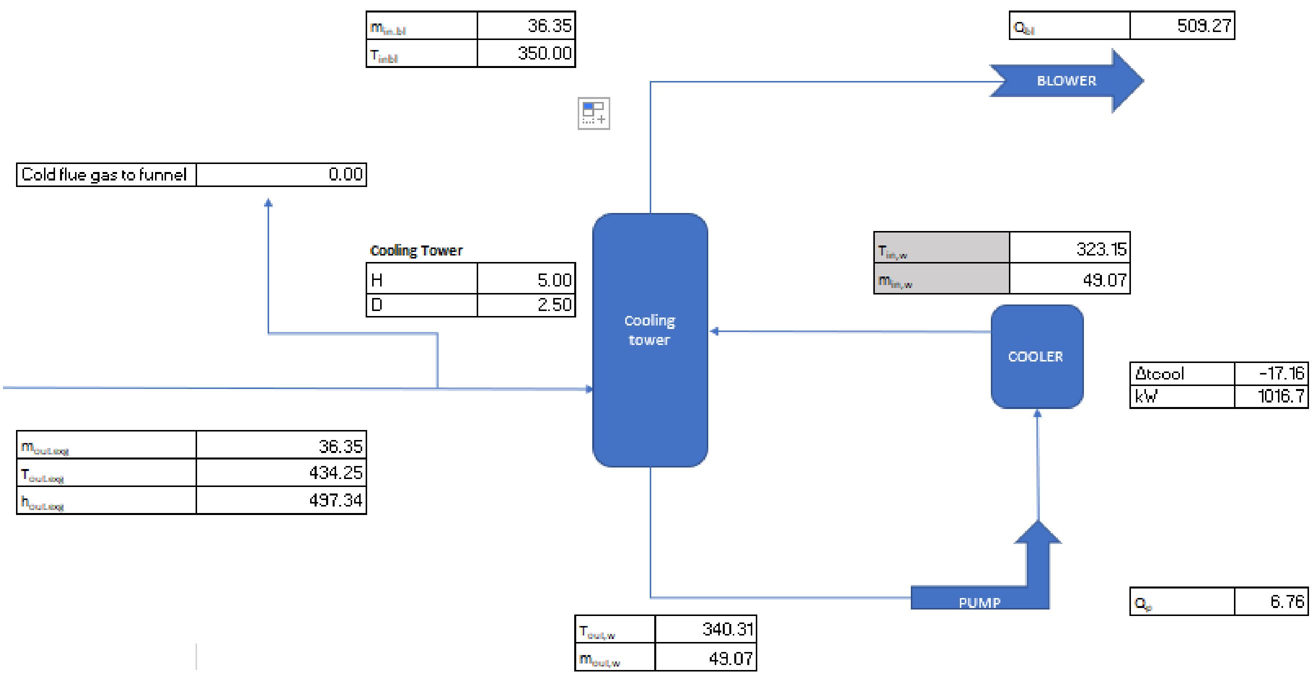

Figure 6.3: Pre-processing performance at design ME load of 65%.

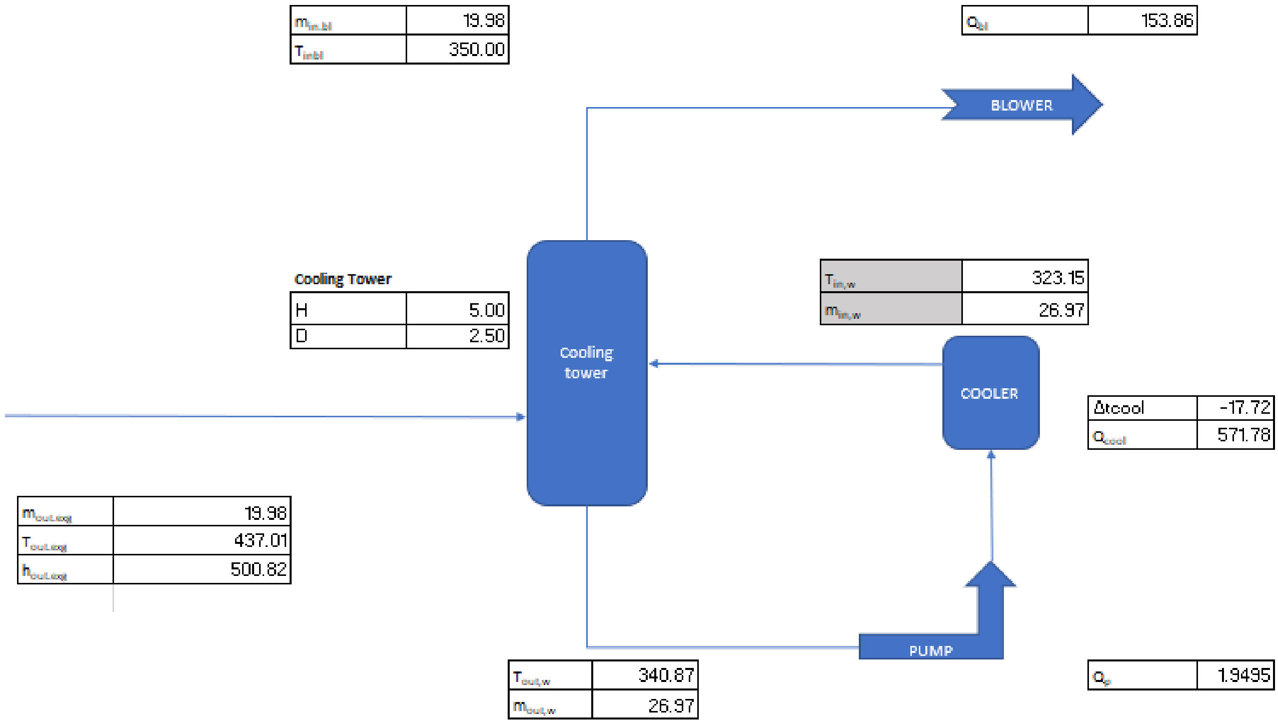

Figure 6.4: Pre-processing performance at part load of 26% with carbon capacity design of 65%.

Carbon capture performance

The mathematic approach is described in section 5.1 as well. Figure 6.5 illustrates the detailed numbers of carbon capture performance for the design ME load of 65%, while figure 6.6 is for the part-load of 26% of ME load.

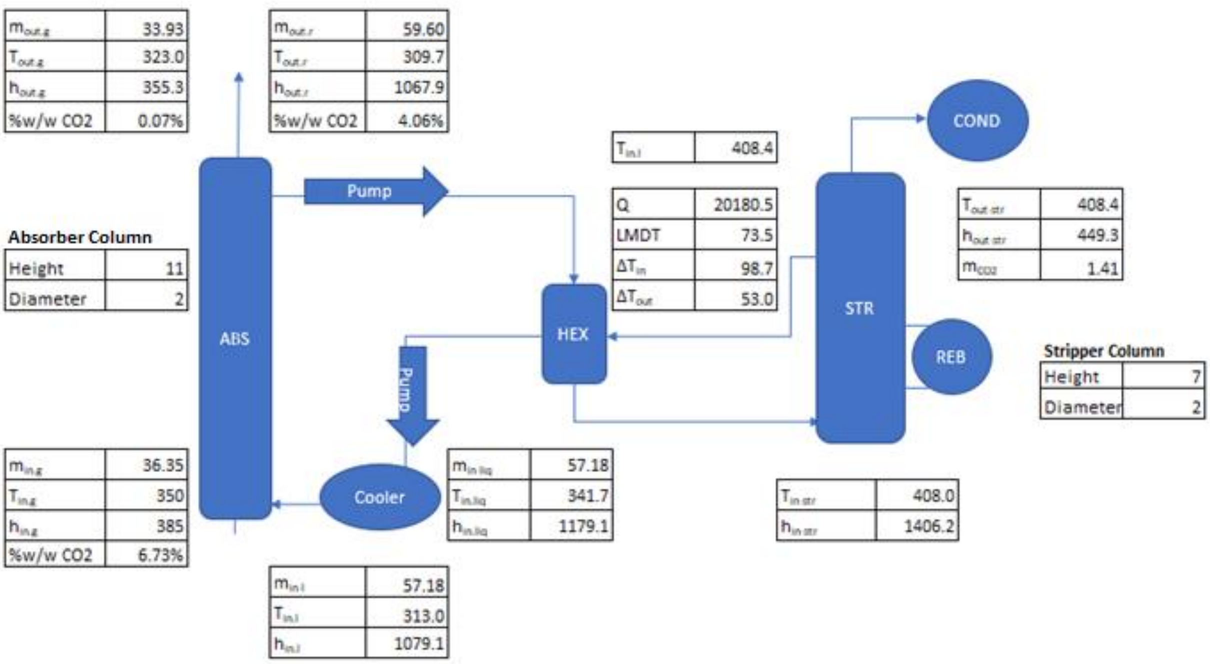

Figure 6.5: Carbon capture performance at design ME load of 65%.

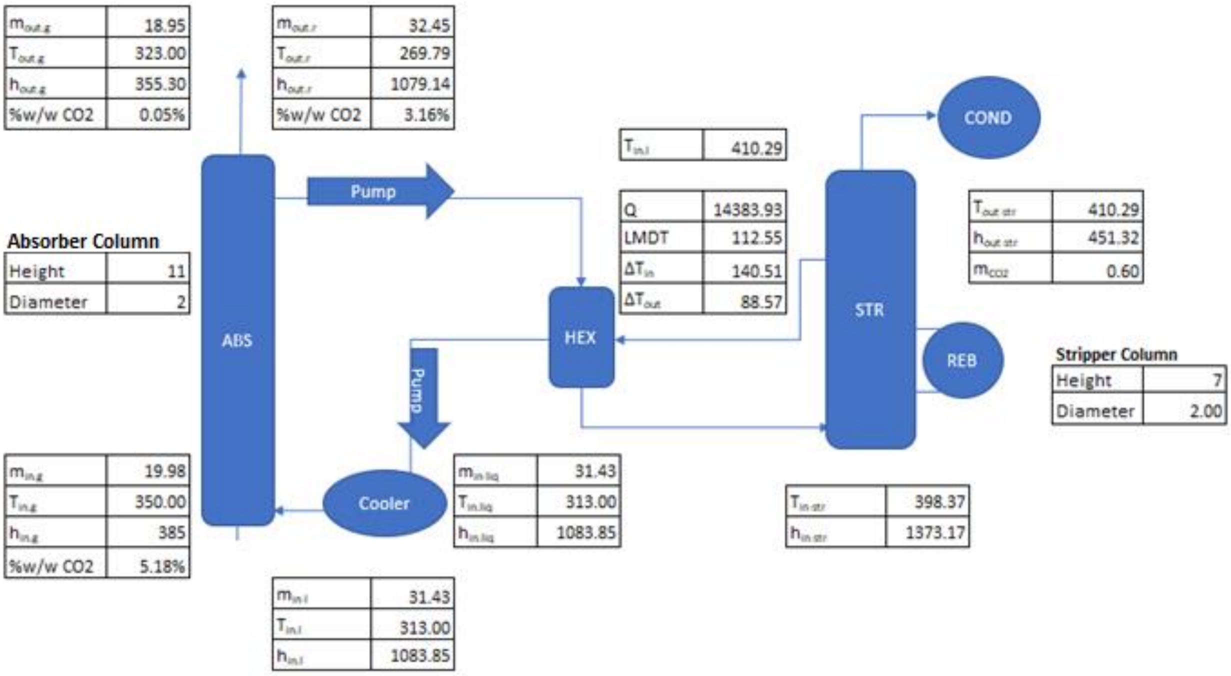

Figure 6.6: Carbon capture performance at part load of 26% with carbon capacity design of 65%.

Capex estimation

The methodology for the Capex calculation is described at section 5.5. Table 6.2 contains analytic cost estimation as Chemical engineering design proposes [21]. Variables , , n and installation factor () are different for each mechanic part of the CCS system, while S stands for the main design characteristic of the part. The formula for the cost calculation is defined below:

Table 6.2: Analytic CAPEX estimation.

	Equipment	No	S		a	b	n	Installation Factor	C	
Preprocessing&Capture	Evaporator	1	329.62	m2	17000	13500	0.6	3.5	$	1,548,829
	Preheater	1	23.99		10000	88	1	3.5	$	17,388
	Cooling Tower	1	49.06656	L/s	61000	650	0.9	4	$	147,433
	Absorber	1	34.5576	m3	0	3200	1	4	$	442,337
	Stripper	1	21.9912	m3	0	3200	1	4	$	281,487
	Coolers	2	1825.8533	kW	4900	720	0.9	2.5	$	1,555,829
	Cross HEX	1	1173.51	m2	10000	88	1	3.5	$	371,442
	Blower	1	124613.49	m3/h	4200	27	0.8	2.5	$	809,126
	Pumps	3	165.84288	L/s	3300	48	1.2	4	$	91,799
	Boiler	1	5400	kg/h steam	4600	62	0.8	2	$	124,643
	Tank	1	1581	m3	53000	2400	0.6	3	$	650,987
	Stream Turbine	1	1279.38	kW	Cost Estimation Through Diagram			3	$	426,342
Liquefaction	Dryer	1	Rapid Cost Estimation						$	2,298,347
	Condenser	1								
	Flash	2								
	Compressors	2								
	Intercoolers	2								
								Capex	$	8,765,987

6.2 Annualization

In order to evaluate the best performance, the operational profile of the vessel will be matched-up with the CC system. Different capacities will be evaluated so as to converge to the optimum design. Below, the operational profile of the case ship is given (table 6.3). This table contains various parameters related to the operation of a ship in different modes (sailing, manoeuvring, harbour, loading, unloading). The data includes the condition of the ship (Ballast or Laden), the mode of operation, the condition of the port (Harbour or At Sea), the log speed (in knots), average main engine power (in kW), average electrical power (in kW), average main engine load (as a percentage), average fuel oil flow for auxiliary boiler (in kg/h), and percentage of time spent in a specific sailing mode. For example, the first row describes the ship when it is in Ballast condition, sailing in Port, in Harbour condition, with log speed of 0 knots, and with no main engine power or load. However, there is some electrical power consumption of 689.1 kW, and some fuel oil flow for the auxiliary boiler of 0.04 kg/h. Additionally, the ship spent 3.75% of the time in this specific sailing mode.

Table 6. 3: Detailed operational profile of case ship.

	Condition B/L	Sailing mode	Condition port	LOG Speed(kn)	Average of ME Power (kW)	Average of Elec power (kw)	Average of ME Load %	Average of boiler FO Flow (kg/h)	%Time in specific sailing mode
1	Ballast	Port	Harbour	0	0.0	689.1	0%	0.04	3.75%
2	Ballast	Port	Loading	0	1.6	896.6	0%	244.53	1.42%
3	Ballast	Manoeuvering	At Sea	1	1807.7	887.3	8%	0.08	0.13%
4	Ballast	Manoeuvering	At Sea	2	3826.9	837.5	16%	15.54	0.11%
5	Ballast	Manoeuvering	At Sea	3	6112.7	751.9	25%	0.35	0.15%
6	Ballast	Manoeuvering	At Sea	4	1226.6	769.1	5%	0.92	2.56%
7	Ballast	Manoeuvering	At Sea	5	1401.1	774.5	6%	0.73	2.11%
8	Ballast	Manoeuvering	At Sea	6	1958.6	830.2	8%	0.02	2.11%
9	Ballast	Manoeuvering	At Sea	7	3892.7	852.6	16%	8.25	0.40%
10	Ballast	Sailing	At Sea	8	4948.8	847.5	21%	1.28	0.89%
11	Ballast	Sailing	At Sea	9	4910.8	843.2	20%	0.20	4.35%
12	Ballast	Sailing	At Sea	10	6745.8	899.8	28%	3.02	1.86%
13	Ballast	Sailing	At Sea	11	8506.9	861.7	35%	7.52	2.78%
14	Ballast	Sailing	At Sea	12	10324.4	807.6	43%	28.67	9.03%
15	Ballast	Sailing	At Sea	13	11147.1	765.1	46%	28.42	3.85%
16	Ballast	Sailing	At Sea	14	13448.1	805.3	56%	67.53	1.76%
17	Ballast	Sailing	At Sea	15	15218.0	848.8	63%	0.00	1.34%

	Condition B/L	Sailing mode	Condition port	LOG Speed(kn)	Average of ME Power (kW)	Average of Elec power (kw)	Average of ME Load %	Average of boiler FO Flow (kg/h)	%Time in specific sailing mode
18	Ballast	Sailing	At Sea	16	17458.5	829.1	73%	0.00	1.72%
19	Ballast	Sailing	At Sea	17	18027.3	859.7	75%	0.00	0.06%
20	Laden	Port	Harbour	0	0.5	816.4	0%	4.77	10.97%
21	Laden	Port	Unloading	0	0.0	1095.9	0%	1900.90	0.77%
22	Laden	Manoeuvering	At Sea	1	3462.8	871.4	14%	12.87	0.13%
23	Laden	Manoeuvering	At Sea	2	2469.1	872.6	10%	9.91	0.08%
24	Laden	Manoeuvering	At Sea	3	2484.6	888.0	10%	11.27	0.04%
25	Laden	Manoeuvering	At Sea	4	5041.7	874.9	21%	13.30	0.02%
26	Laden	Manoeuvering	At Sea	5	5942.4	844.8	25%	3.78	0.11%
27	Laden	Manoeuvering	At Sea	6	6034.6	853.9	25%	4.52	0.20%
28	Laden	Manoeuvering	At Sea	7	7564.6	858.0	31%	3.66	0.34%
29	Laden	Sailing	At Sea	8	9303.1	726.5	39%	2.36	0.53%
30	Laden	Sailing	At Sea	9	8780.3	749.5	37%	3.61	0.75%
31	Laden	Sailing	At Sea	10	11246.2	759.2	47%	7.83	3.38%
32	Laden	Sailing	At Sea	11	12613.4	765.9	53%	3.71	18.77%
33	Laden	Sailing	At Sea	12	12188.4	749.1	51%	12.39	12.44%
34	Laden	Sailing	At Sea	13	14475.6	787.4	60%	13.63	6.38%
35	Laden	Sailing	At Sea	14	15645.4	766.5	65%	9.50	4.67%
36	Laden	Sailing	At Sea	15	15654.3	767.0	65%	0.21	0.04%

For each CCS capacity, the following technical specifications must be calculated:

- CCS status: The amount of CO_2 captured as a percentage of the CC system capacity (see Appendix Algorithms).
- Capture rate: The exhaust gas flow driven to the CC system for treatment as a percentage of the overall exhaust gas flow.
- ME emissions without CCS.
- ME emissions with CCS (see Appendix Algorithms).
- CCS reboiler demands (see Appendix Algorithms).
- CCS electricity demands (see Appendix Algorithms).

- AE load corrected and no of AE used: The load to cover the overall electricity demands and corresponding number of AE.
- Nautical miles in each operational condition.
- ME fuel oil consumption: Already know by vessel data.
- AE fuel oil consumption: new calculations due to extra electricity demands of CCS system.
- Boiler fuel oil consumption: new calculations due to extra demands of CCS system.
- Overall CO_2 emitted.

All FO consumptions (ME, AE, Boiler) were calculated by using a polynomial equation which calculates the consumption as a function of ME load. The equations for ME and AE were illustrated in section 5.2 while, the equation for reboiler follows below:

The algorithms used for some technical specifications above are described in the last section of this study. The emissions were calculated through IMO Cf=3.206.

The main results of the calculations explained above are shown in table 6.4.

Table 6. 4: Main results of annualization for each carbon capacity.

Design ME load	30%	45%	50%	55%	60%	65%	75%
CII with CCS	1.49	1.24	1.17	1.15	1.14	1.13	1.15
Days/year	320						
nm	70523						
ME fuel tons/year							12279.5
AE fuel tons	4372.8	5613.2	5971.1	6226.3	6378.9	6460.1	6613.8
Reboiler fuel tons	1730.9	1800.3	1789.3	1790.6	1793.1	1780.8	1814.4
FO _CCS tons/year	18383.2	19693.0	20039.9	20296.4	20451.5	20520.4	20707.7
FO_noCCS tons/year	15896.57						
FO Increase %	13.53%	19.28%	19.28%	21.68%	22.27%	22.53%	23.23%
FO Increase tons/year	2486.7	3796.5	4143.4	4399.8	4555.0	4623.9	4811.1
CO_2 tons reduction/year	19433.3	24754.1	26125.7	26686.9	26895.8	26995.2	26561.7

The performance of the CCS system over the vessel trade pattern is described for different capacities in the table above. Despite having a generic view of the performance of the CCS system, there are no data for the economic evaluation of the carbon capacities to investigate the optimum one. Table 6.5 contains economic calculations for each carbon capacity with the equivalent CII. Figures 6.7 and 6.8 demonstrate the CAPEX and OPEX with variation on design ME load correspondingly, while figure 6.9 shows a comparison between CO_2 reduction and cost per CO_2 reduction with variation on carbon capacity. The formula used for the calculation of the economic elements is described in section 5.5.

Table 6.5: Economic evaluation for each carbon capacity.

Capacity of CCS system	30%	45%	50%	55%	60%	65%	75%
CAPEX ($)	5,831,563	7,154,775	7,511,116	7,940,659	8,359,464	8,765,987	9,497,674
ACAPEX ($)	546,294	670,251	703,632	743,871	783,104	821,187	889,730
FOPEX ($)	174,946	214,643	225,333	238,219	250,783	262,979	284,930
MEA/year ($)	67,045	115,316	123,969	128,732	131,149	132,348	132,668
VOPEX ($)	1,616,325	2,467,693	2,693,185	2,859,887	2,960,728	3,005,503	3,127,209
TAC ($)	2,337,566	3,352,587	3,622,151	3,841,978	3,994,617	4,089,670	4,301,870
CO_2 reduction/year (tons)	19,433.3	24,754.1	26,125.7	26,686.9	26,895.8	26,995.2	26,561.7
CO_2 captured/year (tons)	24,058.0	33,425.0	35,933.1	37,313.6	38,014.3	38,361.7	38,454.3
$/ton CO2 (decrease in total emissions)	120.29	135.44	138.64	143.96	148.52	151.50	161.96
CII with CCS	1.490	1.239	1.174	1.147	1.138	1.133	1.153

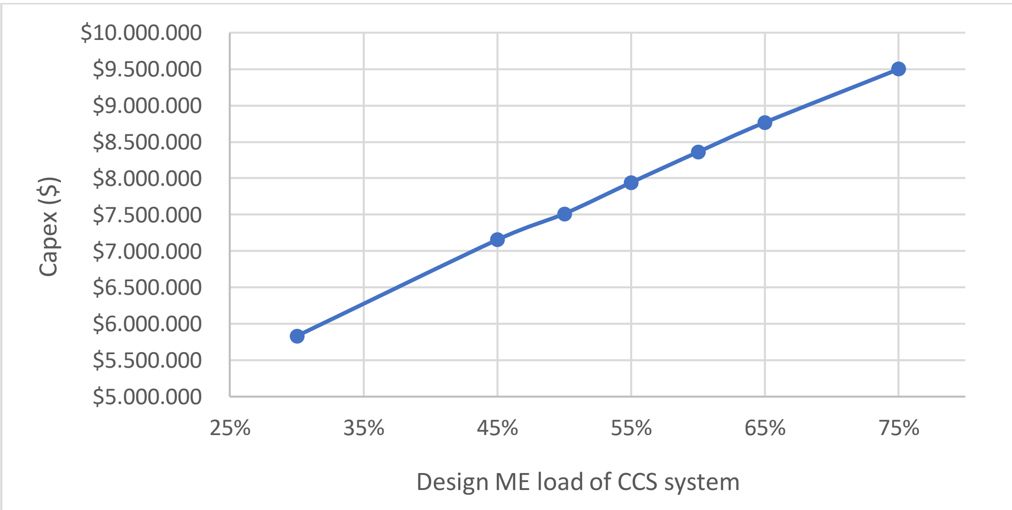

Figure 6.7: Capex with variation on design ME load.

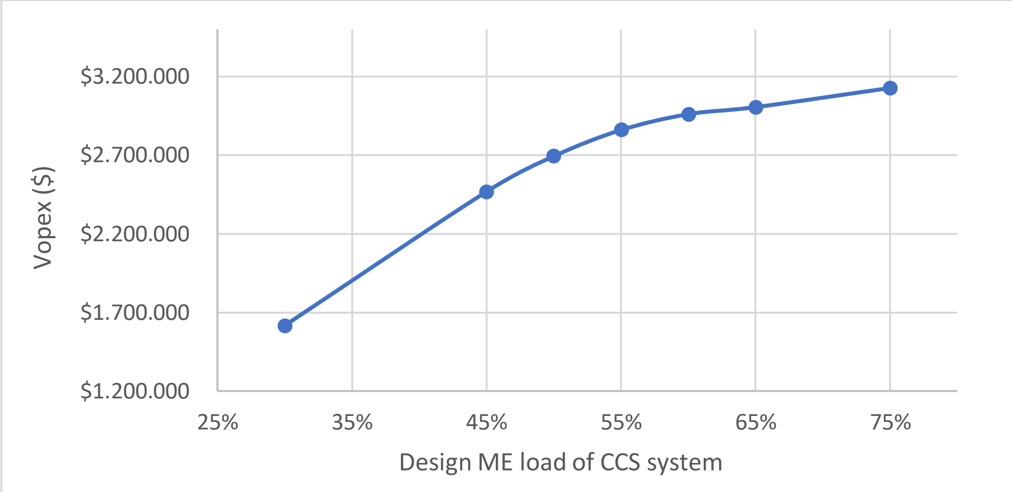

Figure 6.8: Vopex with variation on design ME load.

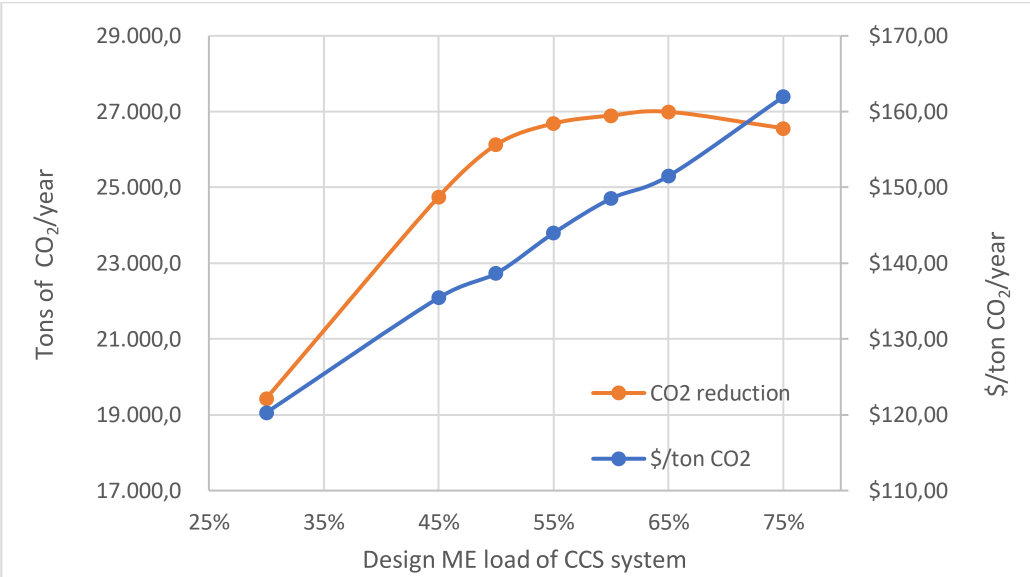

Figure 6.9: Comparison between CO2 reduction and cost per CO2 reduction with variation on carbon capacity

At Figures 6.7 and 6.8 it can be observed that the capital expenditure and variable operating expenditure increase proportionally with the increase in carbon capacity. Additionally, the fixed operating expenditure which is expressed as a percentage of CAPEX, also shows an increasing trend.

However, when considering the overall CO_2 reduction, it is noteworthy that a peak is observed in the curve with respect to variations in capture capacity, specifically the design ME load. In Figure 6.9 this observation is clear, as CO_2 reduction is compared with cost per CO_2 reduction. This inference suggests that a certain optimal point exists in terms of carbon capture capacity beyond which increasing the capacity would not result in significant benefits, while incurring higher costs in terms of CAPEX, VOPEX, and FOPEX. Therefore, careful consideration and analysis of the associated costs and benefits are crucial in determining the appropriate level of carbon capture capacity to achieve a balance between the desired reduction in CO_2 emissions and the associated economic feasibility.

6.3 Investigation on optimum capacity

The CII with CCS at different capture capacities is calculated, as shown in Figure 6.10. To ease the presentation of results, we associate the capture capacity to an equivalent ME load (each capture capacity equals the CO_2 in the exhaust flow of a specific engine load). The observed plateau of the curve with CCS indicates the counteracting effects of CO_2 capture and total fuel consumption, over the total emissions of the vessel with CCS. The higher the CCS system size, the higher the consumptions and, thus, the ability of the CCS system to clean all emission stream. Furthermore, we observe that the variation with the load is low. This is because the vessel operates mostly at low speeds, as it was shown in Table 6.3 and, therefore, from an engine load and on, any increase in the capture capacity does not affect the capture potential and the effect on CII. Figure 6.11 shows the regulatory lifetime extension of the vessel with variation on design ME load of the CCS system.

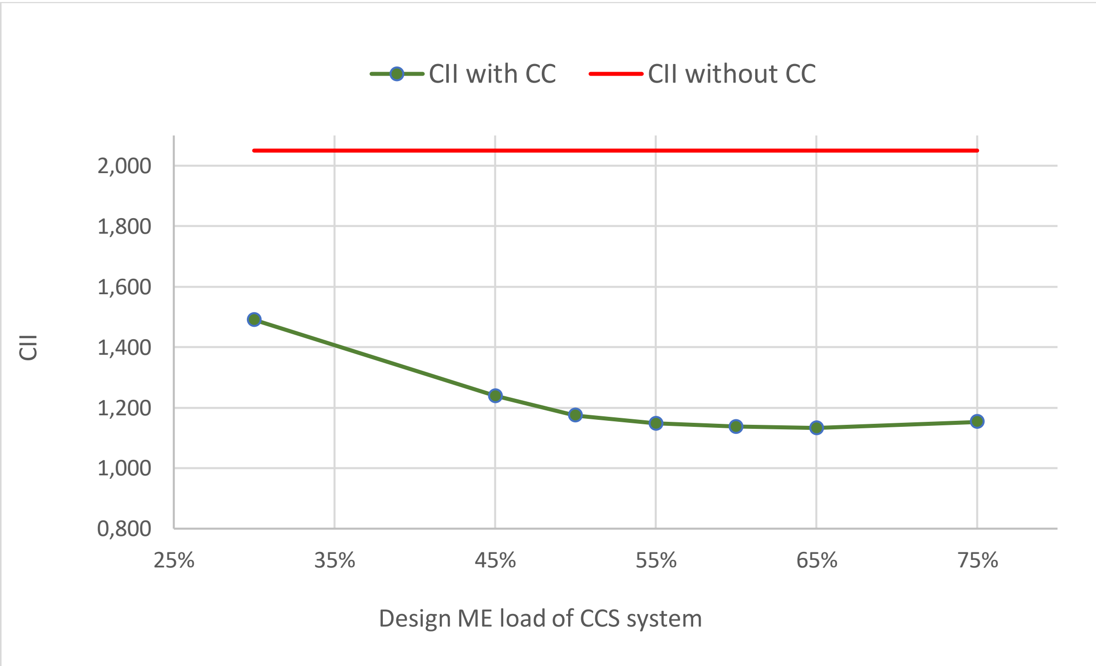

Figure 6.10: CII with CCS, with variation on design ME load

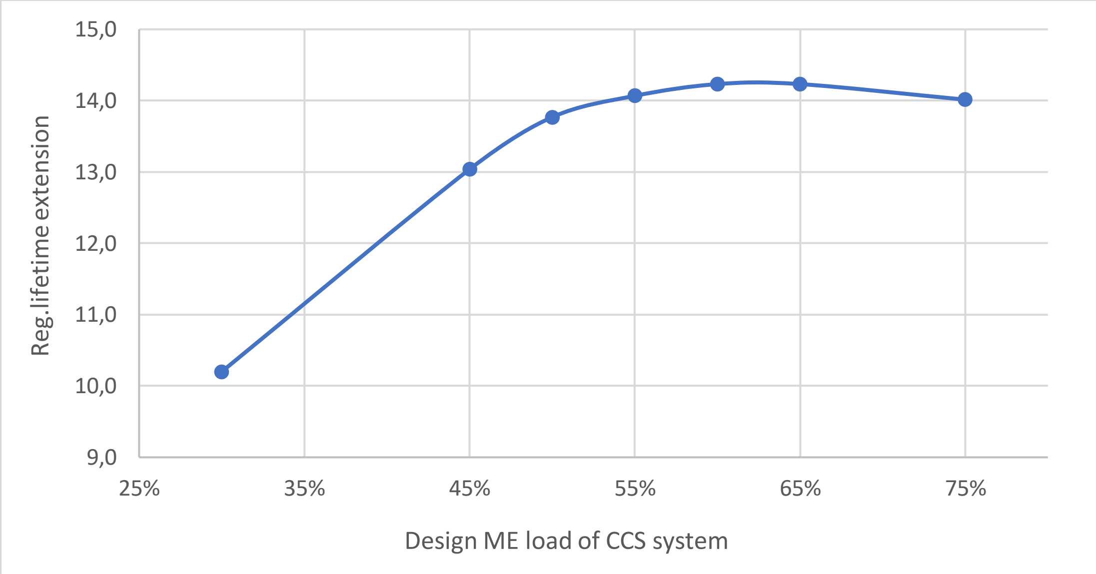

Figure 6.11: Regulatory lifetime extension with CCS, with variation on carbon capacity

The parametric analysis indicates that the optimum capture capacity in terms of CII reduction belongs to design ME load of 65%. The CII decreases by 44.7% (from 2.05 to 1.13) with a corresponding reduction of CO_2 of 26995 tons. This design secures a lifetime extension of 14.2 years if we consider the zero-50 scenario and an extension of 24.3 years if we consider the 2% CII reduction annually as figures 6.12 and 6.13 illustrate. Although, the Fuel oil consumption increases by 23% (from 15897 to 20520 tons). The economic aspect of the CCS system is crucial for the shipowners and thus investment analysis will follow in the next section. Despite the fact that the design ME load of 65% has the best performance in CII reduction there may exist other designs more economically beneficial if costs of fuel, biofuel to be compliant with IMO regulations in the whole vessel lifetime, capex and opex are counted in.

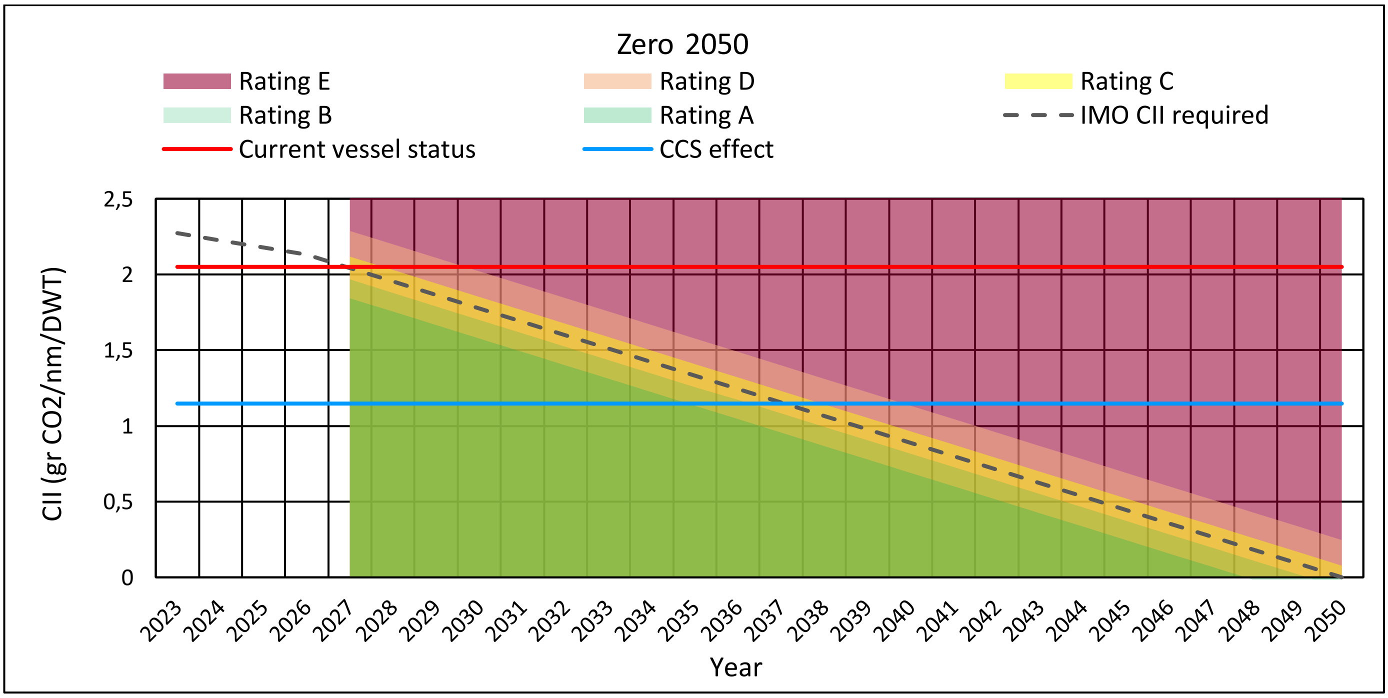

Figure 6.12: Lifetime extension for zero-50 scenario

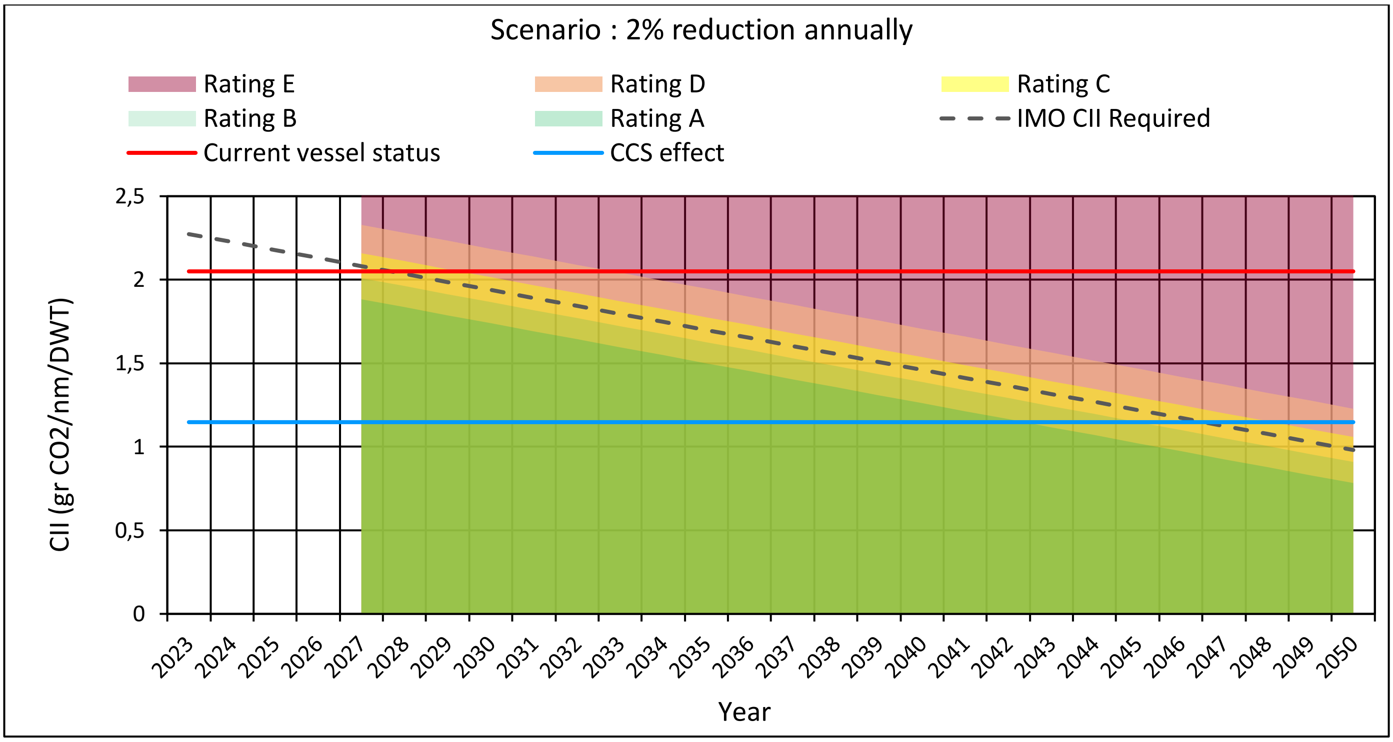

Figure 6.13: Lifetime extension for 2% scenario

Net present value estimation – Scenario 1; 2% reduction annually

Both scenarios regarding the CII reduction will be taken into consideration, as there is a big variation between them. For the NPV calculation there have been accounted the following:

a. The total annual cost (TAC) as shown in table 6.5 and described in section 5.5.

b. The fuel Operational expenditure (OPEX) based on a price of 650$/ton conventional Marine Diesel Oil (MDO), for the years where the CII is below CII_{ref} (cells colored with light green in tables below). The regulatory lifetime extension per capture capacity is shown in Figure 6.11. The fuel tons per year, based on which the fuel cost is estimated, are shown in table 6.4.

c. The fuel OPEX of the combination of biofuels and CCS to ensure that the CII is below CII_{ref}. We assume that the biofuel price is twice the price of conventional MDO. The share of biofuels into the fuel mix is analogous to the necessary emissions reduction to achieve a CII equal to CII_{ref}. The biofuels are green (no carbon footprint) and the CCS system will be out of use during the time that biofuels are used.

d. The NPV calculation represents the NPV of the total costs of owning and operating the carbon capture system.

Tables 6.6-6.8 demonstrate the %biofuel use of total fuel, the sequent tons of biofuel and the extra cost due to biofuel use correspondingly. Table 6.9 contains the calculation of the cashflows for each carbon capacity, while figure 6.14 illustrates the results from table 6.9. Scenario 1 will be referenced as 2%.

Table 6.6: % biofuels use of total fuel for each reference year with variation on design ME load. Scenario 2%.

		%Biofuel use of total fuel						
Ref. year	CII_{ref}	30%	45%	50%	55%	60%	65%	75%
2039								
2040	1.46	2.1%						
2041	1.41	5.3%						
2042	1.36	8.5%						
2043	1.32	11.7%						
2044	1.27	14.9%						
2045	1.22	18.1%	1.5%					
2046	1.17	21.3%	5.4%	0.1%				
2047	1.12	24.5%	9.2%	4.2%	2.0%	1.2%	0.7%	2.5%
2048	1.08	27.8%	13.1%	8.3%	6.2%	5.4%	5.0%	6.7%
2049	1.029	31.0%	17.0%	12.4%	10.3%	9.6%	9.2%	10.8%
2050	0.981	34.2%	20.8%	16.4%	14.5%	13.8%	13.4%	15.0%

Table 6.7:Usage of biofuel in tons for each reference year with variation on design ME load. Scenario 2%.

	Biofuel tons						
Ref. year	30%	45%	50%	55%	60%	65%	75%
2039							
2040	381						
2041	971						
2042	1561						
2043	2152						
2044	2742						
2045	3332	296					
2046	3922	1057	28				
2047	4512	1817	845	406	236	152	519
2048	5103	2578	1662	1253	1096	1019	1378
2049	5693	3339	2479	2099	1956	1886	2237
2050	6283	4099	3295	2946	2816	2752	3096

Table 6.8: Total extra cost due to biofuels use with variation on design ME load. Scenario 2%.

	Overall Extra cost (Biofuel=2xMDO$)						
Ref year	30%	45%	50%	55%	60%	65%	75%
2039							
2040	0.21						
2041	0.55						
2042	0.88						
2043	1.21						
2044	1.54						
2045	1.87	0.17					
2046	2.20	0.60	0.02				
2047	2.54	1.03	0.48	0.23	0.13	0.09	0.30
2048	2.87	1.46	0.95	0.71	0.63	0.58	0.79
2049	3.20	1.90	1.41	1.20	1.12	1.08	1.28
2050	3.53	2.33	1.88	1.68	1.61	1.57	1.77

Table 6.9: NPV detailed calculation for scenario 2% with annual cashflows of reference years and variation on design ME load.

Carbon capacity	30%	45%	50%	55%	60%	65%	75%
Year after investment	Cashflows (m$)						
1	2.34	3.35	3.62	3.84	3.99	4.09	4.30
2	2.34	3.35	3.62	3.84	3.99	4.09	4.30
3	2.34	3.35	3.62	3.84	3.99	4.09	4.30
4	2.34	3.35	3.62	3.84	3.99	4.09	4.30
5	2.34	3.35	3.62	3.84	3.99	4.09	4.30
6	2.34	3.35	3.62	3.84	3.99	4.09	4.30
7	2.34	3.35	3.62	3.84	3.99	4.09	4.30
8	2.34	3.35	3.62	3.84	3.99	4.09	4.30
9	2.34	3.35	3.62	3.84	3.99	4.09	4.30
10	2.34	3.35	3.62	3.84	3.99	4.09	4.30
11	2.34	3.35	3.62	3.84	3.99	4.09	4.30
12	5.54	3.35	3.62	3.84	3.99	4.09	3.84
13	5.87	3.80	3.62	3.84	3.99	4.09	4.59
14	2.34	3.35	3.62	3.84	3.84	3.84	3.84
15	2.55	3.35	3.62	3.84	3.84	3.84	3.84
16	2.88	3.35	3.62	3.84	3.84	3.84	3.84
17	3.22	3.35	3.62	3.84	3.84	3.84	3.84
18	3.55	3.35	3.62	3.84	3.84	3.84	3.84
19	3.88	3.35	3.62	3.84	3.84	3.84	3.84
20	4.21	3.52	3.62	3.84	3.84	3.84	3.84

Carbon capacity	30%	45%	50%	55%	60%	65%	75%
21	4.54	3.95	3.64	3.84	3.84	3.84	3.84
22	4.87	4.38	4.10	4.07	3.98	3.93	4.14
23	5.21	4.82	4.57	4.56	4.47	4.42	4.63
24	5.54	5.25	5.03	5.04	4.96	4.92	5.12
25	5.87	5.68	5.50	5.52	5.45	5.41	5.61
NPV(m$)	85.77	91.75	95.28	99.87	101.52	102.59	105.99

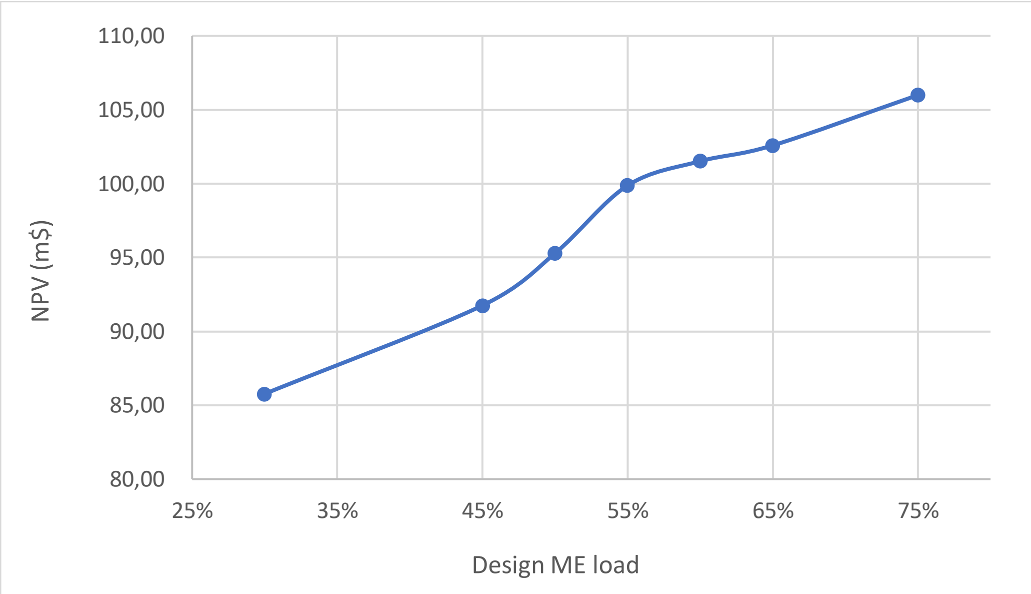

Figure 6.14: NPV with variation on design ME load. Scenario 2%.

Net present value estimation – Scenario 2; Zero 50

Scenario 2 will be referenced as zero-50. In table 6.10 the detailed calculation of NPV for scenario 2 can be found, following the methodology described for scenario 2%. Figure 6.15 shows the cashflows with variation on carbon capacity.

Table 6.10: NPV detailed calculation for scenario zero-50 with annual cashflows of reference years and variation on design ME load. Scenario zero-50.

Carbon capacity	30%	45%	50%	55%	60%	65%	75%
Year after investment	Cashflows (m$)						
1	2.34	3.35	3.62	3.84	3.99	4.09	4.30
2	2.34	3.35	3.62	3.84	3.99	4.09	4.30
3	2.34	3.35	3.62	3.84	3.99	4.09	4.30
4	2.34	3.35	3.62	3.84	3.99	4.09	4.30
5	2.34	3.35	3.62	3.84	3.99	4.09	4.30
6	2.34	3.35	3.62	3.84	3.99	4.09	4.30
7	2.34	3.35	3.62	4.39	3.99	4.09	4.30
8	2.34	3.35	3.62	3.84	3.84	3.84	4.30

Carbon capacity	30%	45%	50%	55%	60%	65%	75%
9	2.83	3.35	3.62	3.84	3.84	3.84	3.84
10	3.44	3.35	3.62	3.84	3.84	3.84	3.84
11	4.06	3.35	3.62	3.84	3.84	3.84	3.84
12	4.67	4.06	3.62	3.84	3.84	3.84	3.84
13	5.29	4.80	4.58	4.59	4.46	4.46	4.64
14	5.90	5.54	5.36	5.39	5.27	5.27	5.43
15	6.52	6.28	6.15	6.18	6.08	6.08	6.23
16	7.13	7.02	6.93	6.98	6.89	6.89	7.02
17	7.75	7.76	7.71	7.78	7.70	7.70	7.81
18	8.36	8.50	8.49	8.58	8.51	8.51	8.61
19	8.98	9.24	9.27	9.38	9.32	9.32	9.40
20	9.59	9.98	10.05	10.18	10.13	10.13	10.20
21	10.21	10.72	10.83	10.98	10.94	10.94	10.99
22	10.82	11.46	11.61	11.78	11.75	11.75	11.79
23	11.44	12.20	12.39	12.58	12.55	12.55	12.58
24	12.05	12.94	13.17	13.37	13.36	13.36	13.38
25	12.67	13.68	13.95	14.17	14.17	14.17	14.17
NPV(m$)	125.46	135.05	137.64	141.77	141.61	142.25	145.03

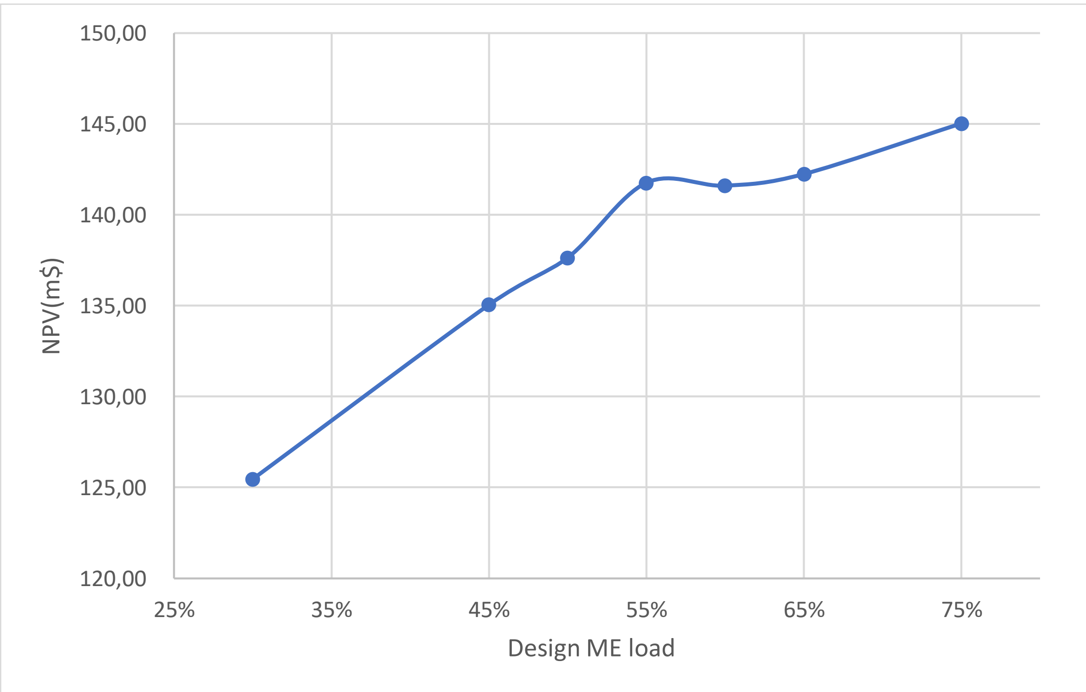

Figure 6.15: NPV with variation on design ME load. Scenario zero-50.

6.4 Fuel price sensitivity analysis

Performing a sensitivity analysis on biofuel price is of paramount importance when considering a future investment in maritime. Biofuel prices can fluctuate significantly due to various factors such as feedstock availability, production costs, government policies, and global market dynamics. By conducting a sensitivity analysis, investors can assess the potential impact of price variations on the profitability and viability of their maritime ventures. The following analysis allows for a comprehensive evaluation of the investment's sensitivity to changes in biofuel prices, enabling better risk management and informed decision-making. Furthermore, given the long-term nature of maritime investments, understanding the range of possible price scenarios can help investors devise robust financial strategies, negotiate favourable contracts, and develop contingency plans. Ultimately, a sensitivity analysis on biofuel price prediction provides the necessary insights and foresight to navigate the uncertainties inherent in the biofuel market, ensuring a more prudent and successful investment. The analysis will be conducted with the following estimations:

Estimation 1: Biofuel price =1.5xMDO Price

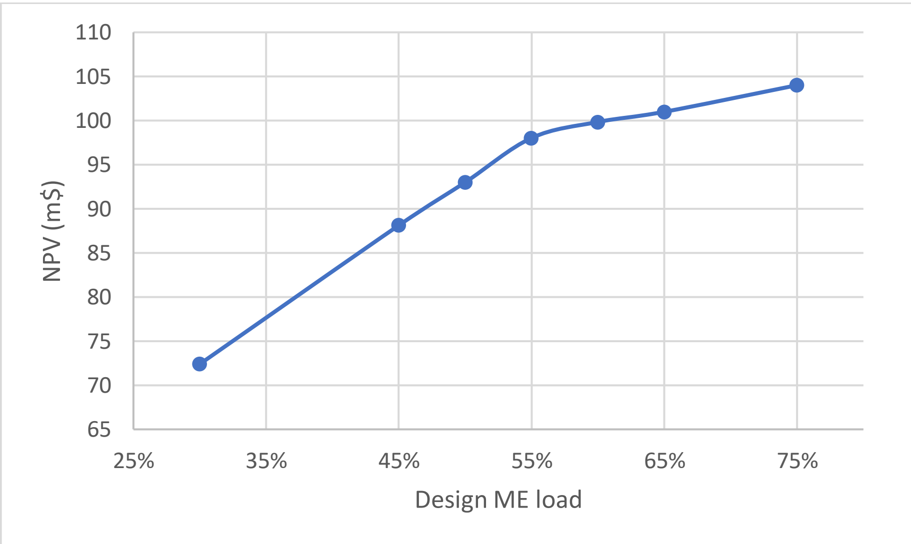

Figure 6.16: NPV with variation on carbon capture, estimation1. Scenario 2%.

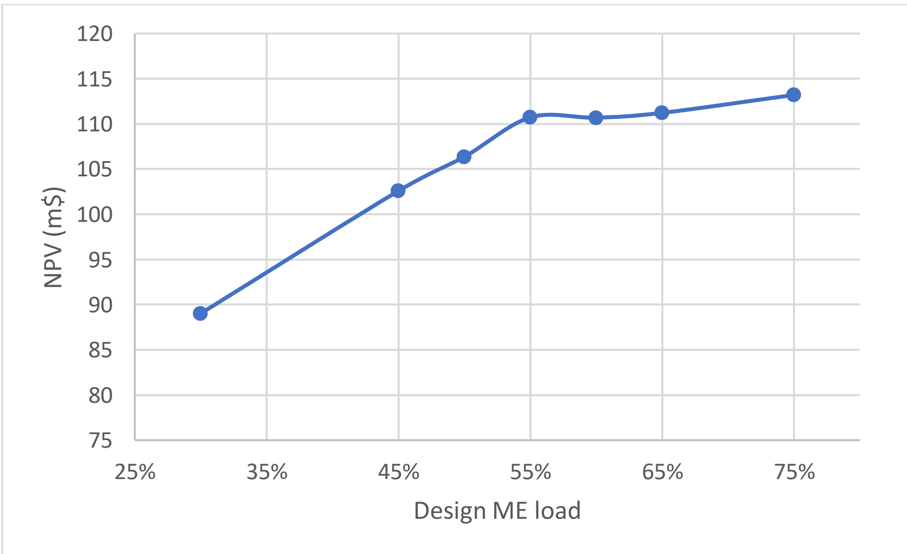

Figure 6.17: NPV with variation on carbon capture, estimation1. Scenario zero-50.

Estimation 2: Biofuel price =3xMDO Price:

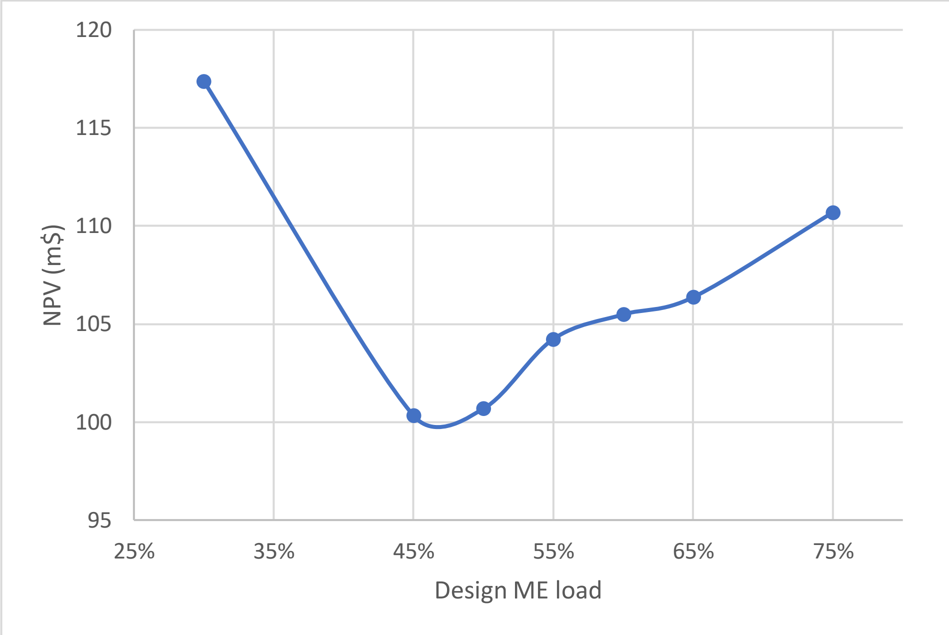

Figure 6.18: NPV with variation on carbon capture, estimation2. Scenario 2%.

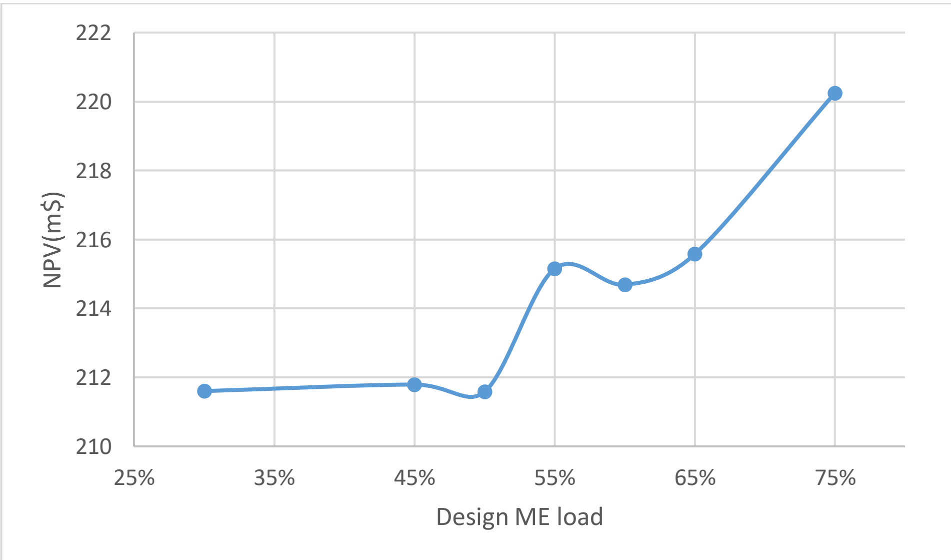

Figure 6.19: NPV with variation on carbon capture, estimation2. Scenario zero-50.

7 Conclusions

The thesis presented a method to assess the potential benefits for regulatory compliance with CCS, subject to the hypothetical assumption that CCS is considered as a decarbonization solution that could impact CII.

The scope wat to investigate the impact of a CCS system on CII and the extra energy requirements. A mathematical model was developed for a VLCC tanker, with and without CCS, plus with the option of WHR for additional power production onboard the vessel. The operational profile of the ship case was linked with the onboard integration to evaluate the performance of the CCS system in real conditions. It was shown how important the design-for-trade is for determining the right capture capacity of the CCS system, for minimizing CAPEX and OPEX and maximizing benefits.

The results indicated that there is significant CII improvement for all carbon capacities. Regarding the impact of the CCS system, when it is designed for capacities above 60% of the main engine load, there is no remarkable improvement on CII, because of the frequent presence of vessel's operation at low speeds. At the same time, CAPEX increases dramatically after 60%, and fuel OPEX increases above 50%, because of the need of one more generator to operate the CCS and liquefaction units.

The biofuel price and the decarbonization scenario of IMO are important parameters regarding the optimum carbon capacity and other possible solutions for CO_2 reduction. Currently the TAC of a CCS investment is high, making it hard to be considered an acceptable solution yet. Improved efficiency and its offshore maturity will lower significantly the investment cost

The main conclusions of the thesis are listed below:

- For vessels with a DWT of 300000 tons, that operate mostly at low speeds and correspondingly low ME loads, the smallest capacity of 30% design ME load has the best performance overall.
- The CCS system capacity design ME load of 30% reduces CII by 27.3% (from 2.05 to 1.49), extending the regulatory lifetime by 10.2 years.
- The fuel consumption increases by 13.5%, resulting in an additional CO_2 production of 7972 tons.
- The Capex of the plant is estimated at 5.8 million $, while the opex and vopex will be 1.8 million $ per year.
- To secure compliance till 2048 (lifetime of investment:25 years, zero-50 scenario) a usage of 4.7% of biofuels is required for the year 2034. The share of the biofuels increases proportionally till 2048 rising up to 88.1% usage.
- The NPV of costs of the CCS system (lifetime of investment:25 years, zero-50 scenario, biofuel price=2xMDO price) is expected to be 125.5 million $ for the capacity of 30% design ME load. A loss of 5 million $ is expected if CCS and biofuel usage combined are be the decarbonization solution for the reference vessel compared to only biofuel usage. When biofuel price increases to 3xMDO price, a gain of 65 million $ is expected for the investigated decarbonization solution.

8 References

1. IMO. (2020). *Fourth Greenhouse Gas Study 2020.* International Maritime Organization
2. DNV. (last accessed: 2023, June 11). *CII-Carbon Intensity Indicator*. DNV. https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/index.html
3. Global CCS Institute. (2021). *Global status of CCS: 2021, CCS accelerating to net zero.* Global CCS Institute
4. DNV. (2021). *Carbon Capture Utilization and Storage – Screening of Technology and Market from a Maritime Point of View*. DNV
5. ABS. (2022). *SETTING THE COURSE TO LOW CARBON SHIPPING: ZERO CARBON OUTLOOK*.ABS
6. TWI (last accessed:2023, June 11). *WHAT ARE TECHNOLOGY READINESS LEVELS (TRL)?*. TWI. https://www.twi-global.com/technical-knowledge/faqs/technology-readiness-levels
7. Mitsubishi Heavy Industries. (2021, last accessed:2023, June 15). *Mitsubishi Shipbuilding Successfully Separates and Captures CO2 from Exhaust Gas in World's First Marine-based CO2 Capture System Project-- Captured CO2 Has Purity Greater than 99.9%, Demonstrating Performance in Line with Plan* --. Mitsubishi Heavy Industries. Mitsubishi Heavy Industries, Ltd. Global Website | Mitsubishi Shipbuilding Successfully Separates and Captures CO2 from Exhaust Gas in World's First Marine-based CO2 Capture System Project -- Captured CO2 Has Purity Greater than 99.9%, Demonstrating Performance in Line with Plan -- (mhi.com)
8. Ionada. (last accessed: 2023, June15). *iDeCarbon*. Ionada. https://ionada.com/idecarbon/
9. Georgopoulou C., Dimopoulos G. (2021). *Carbon Capture Storage / Utilisation (CCUS) Technology & Market from a Maritime Point of View*. Greener Shipping Summit 2021.
10. AkerSolutions. (last accessed: 2023, June 15). *Carbon Capture, Utilization and Storage*. AkerSolutions. https://www.akersolutions.com/what-we-do/low-carbon-oil-and-gas-solutions/carbon-capture-utilization-and-storage/
11. Bahtić F. (2023, last accessed: 2023, June 15). *World's 1st liquid CO2 carrier intended for CCUS launched*. OFFSHORE ENERGY. https://www.offshore-energy.biz/worlds-1st-liquid-co2-carrier-intended-for-ccus-launched/
12. Porthos CO2 TRANSPORT & STORAGE.(last accessed: 2023, June 15). *Project*. Porthos CO_2. https://www.porthosco2.nl/en/project
13. Equinor.(last accessed: 2023, June 15). *Northern Lights. Equinor*. https://www.equinor.com/energy/northern-lights
14. Jasper A. Ros, Eirini Skylogianni, Vincent Doed´ee, Joan T. van den Akker, Alex W. Vredeveldt, Marco J.G. Linders, Earl L.V. Goetheer, Juliana G M-S Monteiro. (2022). *Advancements in ship-based carbon capture technology on board of LNG-fuelled ships*. International Journal of Greenhouse Gas Control
15. Feenstra, M., Monteiro, J. Gilling, E., Goetheer, E., vn den Akker, J. & Abu-Zahra, M. (2019). *Ship-based carbon capture onboard of diesel or LNG-fuelled ships.* International Journal of Greenhouse Gas Control, vol. 85, pp. 1–10, 2019.
16. Van Den Akker, J.T. (2017). *Carbon capture onboard LNG-fuelled vessels*. Master thesis, TU Delft, 2017.
17. Dimopoulos G., Georgopoulou C., and Stefanatos J. (2019). *A holistic approach to ship design, Vol. 1: Optimization of ship design and operation for life cycle, Ch. 14 Advanced ship machinery modeling and simulation.* Springer, A. Papanikolaou Edt., 2019, ISBN 978-3-030-02809-1.
18. Georgopoulou C., Koukoulopoulos L., and Dimopoulos G. (2021). *A holistic approach to ship design, Vol. 2: Application case studies, Ch. 9 Model-based systems engineering for the design and operational assessment of marine energy systems and retrofitting solutions.* Springer, A. Papanikolaou Edt., 2021, ISBN 978-3-030-71090-3.

19. Papanikolaou A. (2010). *Holistic ship design optimization. Computer- Aided Design*, Vol. 42, Pg. 1028-44, 2010.
20. Papanikolaou A. (2019). A holistic approach to ship design. Volume 1: Optimization of Ship Design and Operation for Life Cycle. Springer International Publishing, Ed. 1, 2019. DOI 10.1007/978-3-030-02810-7.
21. Towler G., Sinnott G. (2008). *Chemical engineering design*. Butterworth-Heinemann, Elsevier, ISBN 13: 978-0-7506-8423-1
22. Green D. W. and Perry R. H. (2008). *Perry's Chemical Engineers' Handbook*, 8th Edition, McGraw-Hill, 2008 ISBN: 9780071422949.
23. Adeola Awoyomi, Kumar Patchigolla, Edward J. Anthony. (2019). *CO_2/SO_2 emission reduction in CO2 shipping infrastructure*. International Journal of Greenhouse Gas Control. https://doi.org/10.1016/j.ijggc.2019.05.011
24. G. Puxty, R. Rowland, and M. Attalla. (2010). *Comparison of the rate of CO2 absorption into aqueous ammonia and monoethanolamine*. Chemical Engineering Science, vol. 65, pp. 915- 922, 2010.
25. H. Dang and G. T. Rochelle. (2003). *CO2 absorption rate and solubility in monoethanolamine/piperazine/water*. Separation science and technology, vol. 38, pp. 337-357, 2003.
26. S. Freguia and G. T. Rochelle. (2003). *Modeling of CO2 capture by aqueous monoethanolamine.* AIChE Journal, vol. 49, pp. 1676-1686, 2003.
27. A. Setameteekul, A. Aroonwilas, and A. Veawab. (2008). *Statistical factorial design analysis for parametric interaction and empirical correlations of CO2 absorption performance in MEA and blended MEA/MDEA processes.* Separation and Purification Technology, vol. 64, pp. 16-25, 2008/11/20/ 2008.
28. E. O. Agbonghae, K. J. Hughes, D. B. Ingham, L. Ma and M. Pourkashanian. (2014). *Optimal Process Design of Commercial-Scale Amine-Based CO2 Capture Plants.* I&EC research
29. Jasper A. Ros, Juliana G. M-S. Monteiroa, Joan T. van den Akker, Kurt Summer, Vincent Doedée, Eirini Skylogianni, Marco J.G. Linders. (2020). *Post-combustion Carbon Capture and Storage on LNG Fuelled Ships.* Conference Proceedings of INEC
30. Marcin Stec, Adam Tatarczuk, Tomasz Iluk, Mateusz Szul. (2020). *Reducing the energy efficiency design index for ships through a post-combustion carbon capture process.* International Journal of Greenhouse Gas Control, https://doi.org/10.1016/j.ijggc.2021.103333
31. L.S. Tan, A.M. Shariff *, K.K. Lau, M.A. Bustam. (2012). *Factors affecting CO2 absorption efficiency in packed column: A review*. Journal of Industrial and Engineering Chemistry
32. Abdul Hadi N. Khalifa. (2015). *Thermal and Exergy Analysis of Counter Flow Induced Draught Cooling Tower*. International Journal of Current Engineering and Technology
33. James R. Fair. (1990). *Direct Contact Gas-Liquid Heat Exchange for Energy Recovery*. ASME
34. Luo X., M. Wang. (2017). *Study of solvent-based carbon capture for cargo ships through process modelling and simulation*. Applied Energy (2017) 195:402-413.
35. Ralph H. Weiland,John C. Dingman, and D. Benjamin Cronin. (1997). *Heat Capacity of Aqueous Monoethanolamine, Diethanolamine, N-Methyldiethanolamine, and N-Methyldiethanolamine-Based Blends with Carbon Dioxide*. Journal of Chemical and Engineering Data, Vol. 42, No. 5, 1997
36. Chiu, L F, & Li, M H. (1999). *Heat capacity of alkanolamine aqueous solutions*. United States Journal of Chemical and Engineering Data. https://doi.org/10.1021/je990131j
37. Young Eun Kim, Jin Ah Lim, Soon Kwan Jeong, Yeo Il Yoon, Shin Tae Bae, and Sung Chan Nam. (2013). *Comparison of Carbon Dioxide Absorption in Aqueous MEA, DEA,*

TEA, and AMP Solutions. Greenhouse Gas Department, Korea Institute of Energy Research, Daejeon 305-343, Korea

38. José I. Huertas, Martin D. Gomez, Nicolas Giraldo, and Jessica Garzón. (2015). *CO_2 Absorbing Capacity of MEA*. Hindawi Publishing Corporation, Journal of Chemistry, Volume 2015, Article ID 965015, 7 pages
39. Ugochukwu E. Aronu, Shahla Gondal, Erik T. Hessen, Tore Haug-Warberg, Ardi Hartono, Karl A. Hoff, Hallvard F. Svendsen. (2011). *Solubility of CO_2 in 15, 30, 45 and 60 mass% MEA from 40 to 120 ºC and model representation using the extended UNIQUAC framework*. Chemical Engineering Science, 2011 Elsevier Ltd. All rights reserved. doi:10.1016/j.ces.2011.08.042
40. Chenxi Ji Shuai Yuan, Mitchell Huffman, Mahmoud M. El-Halwagi, Qingsheng Wang. (2021*). Post-combustion carbon capture for tank to propeller via process modeling and simulation.* Journal of CO2 Utilization 2212-9820/© 2021 Elsevier Ltd https://doi.org/10.1016/j.jcou.2021.101655
41. A.B. Rao, E.S. Rubin. *A technical, economic, and environmental assessment of amine-based CO2 capture technology for power plant greenhouse gas control.* Environmental Science and Technology, 36 (2002) 4467-4475
42. Youngkyun Seo, Hwalong You, Sanghyuk Lee, Cheol Huh, Daejun Chang. (2015). *Evaluation of CO2 liquefaction processes for ship-based carbon capture and storage (CCS) in terms of life cycle cost (LCC) considering availability.* International Journal of Greenhouse Gas Control, https://doi.org/10.1016/j.ijggc.2015.01.006
43. S Jackson and E Brodal. (2018). *A comparison of the energy consumption for CO2 compression process alternatives.* IOP Conf. Ser.: Earth Environ. Sci. 167 012031
44. MARPOL. (2021). *2021 Guidelines on operational carbon intensity indicators and the calculation methods (CII guidelines, G1).* Annex 10, Resolution MEPC.336(76), June 2021.
45. MARPOL. (2021).*2021 Guidelines on the reference lines for use with operational carbon intensity indicators (CII reference lines guidelines, G2).* Annex 11, Resolution MEPC.337(76), June 2021.
46. MARPOL. (2021).*2021 Guidelines on the operational carbon intensity rating of ships (CII rating guidelines, G4).* Annex 13, Resolution MEPC.339(76), June 2021.
47. Jackson S. and Brodal E. (2018). *A comparison of the energy consumption for CO2 compression process alternatives*. 8th International Conference on Environment Science and Engineering (ICESE 2018) Barcelona, Spain.
48. Ung Lee, Seeyub Yang,†Yeong Su Jeong,Youngsub Lim, Chi Seob Lee, and Chonghun Han. (2012). *Carbon Dioxide Liquefaction Process for Ship Transportation.* dx.doi.org/10.1021/ie300431z | Ind. Eng. Chem. Res. 2012, 51, 15122−15131
49. Youngkyun Seoa, Hwalong Youa, Sanghyuk Leea, Cheol Huhb, Daejun Changa. (2015). *Evaluation of CO2 liquefaction processes for ship-based carbon capture and storage (CCS) in terms of life cycle cost (LCC) considering availability*. International Journal of Greenhouse Gas Control, 1750-5836/© 2015 Elsevier Ltd, https://doi.org/10.1016/j.ijggc.2015.01.006
50. Lars Erik Øi1, Nils Eldrup, Umesh Adhikari , Mathias Håvåg Bentsen, Jayalanka Liyana Badalge, Songbo Yang. (2016). *Simulation and cost comparison of CO2 liquefaction*. 1876-6102 © 2016 The Authors. Published by Elsevier Ltd, 8th Trondheim Conference on CO*2* Capture, Transport and Storage doi: 10.1016/j.egypro.2016.01.051
51. Han Denga, Simon Roussanalya, and Geir Skaugena. (2019). *Techno-economic analyses of CO_2 liquefaction: Impact of product pressure and impurities*. International Journal of Refrigeration DOI: 10.1016/j.ijrefrig.2019.04.011
52. BUSINESS analytyiq.(last accessed: 2023, June 15*). Monoethanolamine price index*. BUSINESS analytyiq. Monoethanolamine price index - businessanalytiq

53. KRAMMER. (last accessed: 2023, June 15). *Catalog KM-FSD-0313A*. KRAMMER. https://static-htpg.globalimageserver.com/_WP/img/docs/literature/kramer/km-FSFD-0313A.pdf
54. Efthymia Ioanna Koytsoumpa, Christian Bergins, Emmanouil Kakaras.(2018). *The CO_2 economy: Review of CO2 capture and reuse technologies*. The Journal of Supercritical Fluids, Volume 132, 2018, Pages 3-16, ISSN 0896-8446, https://www.sciencedirect.com/science/article/pii/S0896844617300694
55. Gao et al. (2016). *Integration study of a hybrid solvent MEA-Methanol for post combustion carbon dioxide capture in packed bed absorption and regeneration columns*. Separation and Purification Technology, Volume 167, 2016, Pages 17-23, ISSN 1383-5866, https://www.sciencedirect.com/science/article/pii/S1383586616302155
56. Gary Rochelle, Eric Chen, Stephanie Freeman, David Van Wagener, Qing Xu, Alexander Voice. (2011). *Aqueous piperazine as the new standard for CO_2 capture technology.* Chemical Engineering Journal, Volume 171, Issue 3, 2011, Pages 725-733, ISSN 1385-8947, https://www.sciencedirect.com/science/article/pii/S1385894711001793
57. Idem et al. (2015*). Practical experience in post-combustion CO2 capture using reactive solvents in large pilot and demonstration plants*. International Journal of Greenhouse Gas Control, Volume 40, 2015, Pages 6-25, ISSN 1750-5836, https://www.sciencedirect.com/science/article/pii/S1750583615002583

9. Appendix-Algorithms

- CCS status:
  IF(MEload<0.01, 0, IF(MEload >0.2*designload, IF(MEload /designload> 1, 1, MEload /designload), 0))

  The given algorithm is a nested conditional statement that calculates a value based on the input value MEload and constant value designload.
  If the MEload is less than 0.01, the result of the algorithm will be 0.
  If the MEload is greater than 0.2 times the designload, the algorithm checks whether MEload / designload is greater than 1. If it is, the result of the algorithm will be 1, otherwise, the result will be MEload / designload.
  If the MEload is between 0.01 and 0.2 * designload, the result of the algorithm will be 0.

- ME emissions with CCS:
  IF(MEload<0.01, 0,
  IF(MEload<0.2*designload, (a*MEoad^2 + b*MELOAD +c)*D,
  IF(MEload<=designload, a*MEload^4 +b*MEload^3+c*MEload^2+d*MEload+ e,
  (a*MEload^2 + b*MEload +c)*D – CO2cap)))

  The given algorithm is a nested IF statement that calculates a value based on the input value MEload, the constant value designload, and coefficients a, b, c, d, e, and D.
  If the MEload is less than 0.01, the result of the algorithm will be 0.
  If the MEload is greater than or equal to 0.01 and less than 0.2 * designload, the algorithm will calculate the result using the quadratic formula (a * MEload^2 + b * MELOAD + c) * D.
  If the MEload is greater than or equal to 0.2 * designload and less than or equal to designload, the algorithm will calculate the result using the quartic formula a * MEload^4 + b * MEload^3 + c * MEload^2 + d * MEload + e.
  If the MEload is greater than designload, the algorithm will calculate the result using the quadratic formula (a * MEload^2 + b * MEload + c) * D - CO2cap. In summary, this algorithm calculates a value based on the MEload, designload, a, b, c, d, e, D, and CO2cap inputs, and returns a result based on which condition of MEload the input falls into.

- CCS reboiler demands:
  IF(MEload<0.2*designload, 0, a*MEload^2+b*MEload+ c)

  The given algorithm is a conditional statement that calculates a value based on the input value MEload and constant values designload, a, b, and c.
  If the MEload is less than 0.2 times the designload, the result of the algorithm will be 0.
  If the MEload is greater than or equal to 0.2 times the designload, the algorithm will calculate the result using the quadratic formula a * MEload^2 + b * MEload + c.
  In summary, this algorithm calculates a value based on the MEload, designload, a, b, and c inputs, and returns either 0 or the result of a quadratic formula depending on the value of MEload.

- CCS electricity demands:
  IF(MEload<0.2*designload,0,IF(MELOAD<designload,a*MEload^4+b*MEload^3+c*MEload^2+d*MEload+e,maxeldemand))

  The given algorithm is a nested conditional statement that calculates a value based on the input value MEload and constant values designload, a, b, c, d, e, and maxeldemand.
  If the MEload is less than 0.2 times the designload, the result of the algorithm will be 0.
  If the MEload is greater than or equal to 0.2 times the designload and less than designload, the algorithm will calculate the result using the quartic formula a * MEload^4 + b * MEload^3 + c * MEload^2 + d * MEload + e.
  If the MEload is greater than or equal to designload, the algorithm will return the value maxeldemand.
  In summary, this algorithm calculates a value based on the MEload, designload, a, b, c, d, e, and maxeldemand inputs, and returns either 0, the result of a quartic formula, or maxeldemand depending on the value of MEload.