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

THESIS

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Marine carbon capture systems: literature survey and critical analysis.

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Abstract

Human-caused emissions of greenhouse gases have been steadily rising over the years, compelling the International Maritime Organization (IMO) to establish stringent goals for cutting emissions in the shipping industry. Carbon capture (CC) emerges as a potential solution within the spectrum of decarbonization due to its capacity for substantial emission reduction. Within the shipping sector, efforts are underway to investigate CC solutions through conceptual examinations, collaborative development initiatives, and trial demonstrations. This thesis investigates the efficacy and feasibility of implementing carbon capture systems on board various modes of transportation and industrial vessels. Focused on mitigating carbon emissions directly at the source, the study evaluates different technologies, their adaptability, and the potential impact on reducing greenhouse gas footprints in marine and airborne operations. Through a comprehensive analysis of existing carbon capture methodologies, the research aims to provide insights into the challenges, opportunities, and advancements required for successful integration, emphasizing the crucial role of these systems in achieving sustainable and environmentally responsible practices within the transportation and industrial sectors. In this thesis, a preliminary estimation of the energy demand for the capture and the storage of CO2 is proposed, while the cost evaluation and sizing of such a carbon capture system on board.

Acknowledgements

I extend my gratitude to my thesis advisor, Mr George Dimopoulos, for his invaluable guidance and profound expertise throughout this academic journey. His mentorship, insightful feedback and patience guidance were instrumental in shaping the direction and quality of this work. Furthermore, I am deeply thankful to my family for their boundless love, encouragement and understanding during the challenging phases of this undertaking. I express my gratitude to friends and colleagues whose encouragement and discussions have been a source inspiration and motivation throughout my whole academic experience. Finally, I would like to dedicate this work of my thesis to my grandparents, especially my grandfather, and my whole family. Thank you!

Nomenclature

a	Cost constant.
ACE	Monoethanolamine.
AMP	2-amino-2-methyl-propanol.
ASU	Air Separation Unit.
b	Cost constant.
c	Specific heat of the absorbent (kcal/kg°C).
C	Total capital cost
C_e	Purchased equipment.
CC	Carbon Capture.
CCS	Carbon Capture System.
CCGT	Combined Cycle Gas Turbine.
CCU	Carbon Capture Utilization.
CCUS	Carbon Capture Utilization and Storage.
CFPP	Coal-Fired Power Plant.
CH_4	Methane.
CII	Carbon Intensity Index [gr/(tn·nm)].
CO_2	Carbon Dioxide.
C_t	Total molar concentration.
DAC	Direct Air Capture.
D_c	Column Diameter [m].
DCC	Direct Contact Cooler
DEA	Diethanolamine.
DGA	Diglycolamine.
D_L	Mass Diffusion of Gas.
D_v	Mass Diffusion of liquid.
DIPA	Disopropanolamine.
DWT	Deadweight [t].
E	Heat Energy requirement (kcal/h).
e_1	Electric power for liquefaction/Storage of captured CO_2 per CO_2 captured [kWh/kg].
e_2	Total electric power for the CCS per CO_2 captured [kWh/kg].
e_3	Total electric power for the CCS per exhaust gas flow [kWh/kg].
ECAs	Emission Control Areas.
EEDI	Energy Efficiency Design Index.
EOR	Enhanced Oil Recovery.
F	Installation Factor.
FO	Fuel Oil.
F_p	Packing Factor.
f_1	Liquid viscosity correction factor.
f_2	Liquid density correction factor.
f_3	Liquid tension correction factor.
G	The mass rate in the bottom of the tower (kg/h).
g	Grams.

GCU	Gas Combustion Unit.
GA	General Arrangement.
GHG	Green Houses Emissions.
G_m	Molar gas flow rate per unit cross-sectional area.
GT	Grosses tonnage.
H_G	Height of a gas-phase transfer unit [m].
H_L	Height of a liquid-phase transfer unit [m].
H_{OG}	Height of an overall gas-phase transfer unit.
H_{OL}	Height of an overall liquid-phase transfer unit .
h_1	Heat demand for the Capture System per CO_2 captured [kWh/kg]
h_2	Heat demand for the Capture System per Exhaust gas flow [kWh/kg]
h_1	Heat demand for the Captured System per CO_2 produced [kWh/kg]
HFO	Heavy Fuel Oil.
IGCC	Integrated Gas Combine Cycle
IMO	International Maritime Organization.
IPCC	Intergovernmental Panel on Climate Change.
K	Kelvin.
K_2CO_3	Potassium Carbonate.
kg	Kilogram.
kJ	kilojoule.
km	klometers.
kW	kilowatt.
kWh	Kilowatt-hours.
L_C	Length of Column [m].
LCA	Life Cycle Assessment.
$LeanLoad$	CO2 loading of lean solution [mol/mol].
Lm	Molar liquid flow rate per unit cross-sectional area.
LNG	Liquefied Natural Gas.
$L_{\dot{W}}$	Liquid mass flow rate per unit cross-sectional area [kg/m^2]
$\frac{L}{D}$	Length to diameter ratio.
$\frac{L}{G}$	Liquid to gas ratio.
m	Mole fraction in vapor per mole fraction in Liquid.
M	Molecular mass of solvent.
M_a	Molecular mass of component a.
M_b	Molecular mass of component b.
MAC	Main Air Compressor.
MCR	Maximum Continuous Rating [kW]
MDO	Marine Diesel Oil.
ME	Main Engine.
MEA	Monomethylamine.
MHE	Main Heat Exchanger.
MEPC	Marine Environment Protection Committee.
MPa	Megapascal.
n	Exponent for a specific type of equipment.
$Na_2\ CO_3$	Sodium Carbonate.
NGCC	Natural Gas Combined Cycle.

NH_3	Ammonia.
N_{OG}	Number of stages.
N_{OL}	Number of an overall liquid-phase transfer unit .
NOx	Nitrogen Oxides.
OCC	Onboard Carbon Capture.
OCGT	Open Cycle Gas Turbine.
P	Pressure [bar].
P_{AUX}	Power of Auxiliary units [kW].
P_{blower}	Power of blower [Kw].
P_{comp}	Power of Compressor [kW].
P_{el}	Electric Power of the CCS system [kW]
PC	Pulverised Coal.
PCC	Post-Combustion Capture.
psig	Pounds per square inch gauge.
PZ	Piperazine.
RichLoad	CO2 Loading of rich solution [mol/mol].
S	Size parameter.
SCR	Selective Catalytic Reduction.
$(Sc)_v$	Gas Schmidt number.
$(Sc)_L$	Liquid Schmidt number.
SFOC	Specific Fuel Oil Consumption [gr/kWh].
SO_x	Sulfur Oxide.
SO_2	Sulfur Dioxide.
t_W	Thickness of column.
T	Temperature [K].
TEA	Triethanolamine.
VLCC	Very Large Crude Carrier.
V_m	Molar Volume of the solute at its boiling point [m^3/kmol].
$V_{\dot{W}}$	Gas mass flow rate per unit column cross-sectional area [kg/m^2]
WHRS	Waste Heat Recovery System.
WGS	Water Gas Shift.
Z	Column Height [m].
y_e	The concentration in the gas that would be in equilibrium with the gas coc.
x_e	The concentration in the liquid that would be in equilibrium with the gas coc.
x_1	Mol fraction of the solute in the liquid at the bottom of the column.
x_2	Mol fraction of the solute in the liquid at the top of the column.
y_1	Mol fraction of the solute in the gas at the bottom of the column.
y_2	Mol fraction of the solute in the gas at the top of the column.
α	Interfacial surface area per unit volume.
K_3	The efficiency of the reboiler.
μ_L	Liquid viscosity [Ns/m^2].
ρ	Density of the Column's material [kg/m^3].
ρ_v	Vapor densities [kg/m^3].
ρ_L	Liquid densities [kg/m^3].
$\sum C_F$	Total delivered cost of all the major equipment items.
ψ_h	H_G factor.
φ	Association factor for the solvent.

ϕ_h	H_L factor.
%w/w	Weight percent weight by weight.
%wt	Weight percent.
°C	Celsius.

1. Introduction

1.1. Motivation

Implementing carbon capture technologies on ships is imperative due to the substantial impact of vessel emissions on global carbon dioxide levels. The shipping industry stands as a significant contributor to atmospheric pollution, generating a substantial portion of carbon emissions worldwide. Given the scale of maritime transport and its essential role in global trade, developing effective carbon capture systems tailored for vessels is crucial. These technologies aim to mitigate the environmental footprint of shipping activities by capturing and potentially storing carbon dioxide emitted from ship engines. By investing in and deploying such innovative solutions, the industry can actively contribute to reducing greenhouse gas emissions, promoting a more sustainable future for marine transportation and the planet.

In addition to emitting greenhouse gases, shipping also releases particulate matter, nitrous oxides, Sulphur, and other hazardous compounds into the atmosphere. The International Maritime Organization (IMO) created Emission Control Areas (ECAs), wherein Sulphur and nitrous oxide emissions are limited, in an effort to reduce the emission of these pollutants. Capturing and storing carbon dioxide can help reduce CO_2 emissions from fossil fuels by preventing it from entering the earth's atmosphere. Carbon capture and storage, or CCS, is considered by the Intergovernmental Panel on Climate Change (IPCC) as a significant short-term solution for lowering global CO_2 emissions. Most of the CCS research focuses on fossil fuel-fired power plants, such as those that burn coal and natural gas. Nonetheless, CCS may also be a means of lowering shipping-related CO_2 emissions.

The Carbon Intensity Index (CII) is an established framework by the International Maritime Organization (IMO) designed to gauge and decrease the carbon intensity within the shipping industry. This system evaluates the quantity of carbon dioxide emissions per unit of transportation activity, considering ship size, the capacity the distance which is covered by the ship. By establishing a standardized method for measuring and disclosing carbon emissions, the CII framework aims to prompt the implementation of strategies that lessen emissions. Immediate measures like adjusting vessel speed or optimizing ship routes can serve as short-term solutions, while long-term reductions in CII could be achieved through technological advancements such as utilizing alternative fuels, enhancing energy efficiency through design alterations, or employing CCS (carbon capture and storage) systems. The IMO's objective is to cut international shipping's CII by at least 40% by 2030 compared to 2008 levels and to achieve a minimum of 50% reduction in total annual greenhouse gas emissions from international shipping by 2050 compared to 2008 levels. IMO. (2020) [1]. A stricter scenario involves a CII reduction of 100% by 2050 (zero-50 scenario), which will be investigated as well. Achieving these objectives demands substantial commitment from the shipping sector, necessitating the adoption of robust regulatory actions that encourage and enforce emission reductions. The effectiveness of the CII regulatory framework in meeting these objectives will hinge upon various elements such as technological viability, economic feasibility, the efficacy of regulations, and global collaboration.

The goal of this thesis is to evaluate the technical and economic feasibility of implementing a marine carbon capture system on ship.

1.2. Target of thesis

The aim of this thesis is to describe the different methods of carbon capture system which are possible to be implemented on ships, the develop a preliminary estimation of the energy requirement and the unit's dimensions of these systems and finally the cost evaluation for the installation onto the ship. The research questions that will be addressed in this thesis include:

- Determining the required thermal and electric energy demand for the CCS system
- Analyzing the costs associated with the CCS system and the implementation of this.
- Estimating the dimensions of the different units which are required for the operation of the carbon capture system.

1.3. Summary of Contents

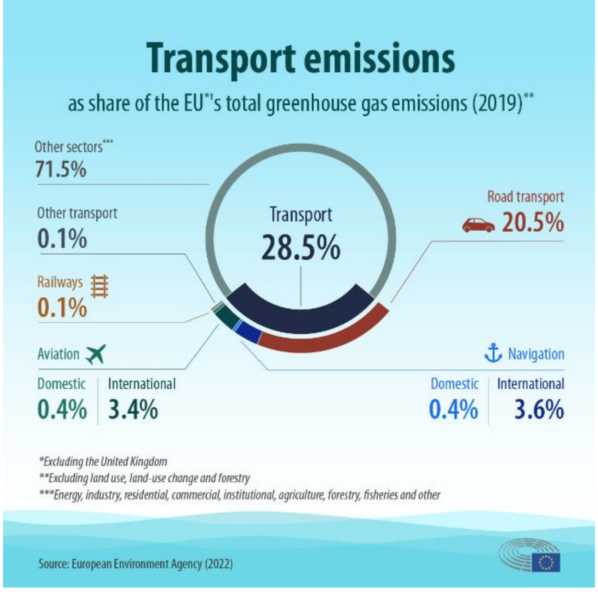
The main goal of section 2 is to describe the environmental and legal reasons for which the importance of the Carbon Capture System is necessary in shipping industry. In section 3, the focus will be in Carbon Capture Technologies review. Specifically, a general description of a CCS is presented, while the different kinds of technologies which have been evolved. Furthermore, a description of storage, sequestration and utilization of CO_2 captured in combination with the supply chain problem is developed. Finally, study review of land-based projects is introduced. The maritime application of carbon capture system is described in section 4, presenting studies which have been implemented though the years. The whole analysis of the energy performance, the establishment, and the cost evaluation of a carbon capture system onto a ship is illustrated in section 5. Last but not least, Section 6 focuses on the application study for a specific carbon capture system presenting the energy demand of the system and the costs needs for the installation of such a system onto ship.

2. Marine Environmental Regulations and CCS.

2.1. CO_2 emissions: Environmental and legal challenges

It is widely known that shipping industry plays a pivotal role in global trade, facilitating the movement of goods and commodities across the world's oceans. In terms of total value, more than 80% of goods are transported by sea, which accounts for 70% of the total international trade [2]. However, this indispensable sector is also a significant contributor to environmental challenges, particularly concerning carbon dioxide (CO_2) emissions. The environmental and legal challenges associated with CO_2 emissions in the shipping industry have gained considerable attention in recent years as the world grapples with the urgent need to address climate change and its adverse effects.

Shipping vessels, powered predominantly by fossil fuels, emit substantial quantities of CO_2, making them a noteworthy source of greenhouse gas emissions. These emissions not only contribute to global warming and climate change but also have detrimental effects on marine ecosystems, air quality, and human health in coastal areas. As such, the environmental impact of CO_2 emissions from the shipping industry cannot be overlooked. It is a matter of great importance to mention that ships are responsible for a substantial portion of Global CO_2 emissions. It is estimated that the international shipping industry is responsible for around 2-3% of the world's total CO_2 emissions [3].

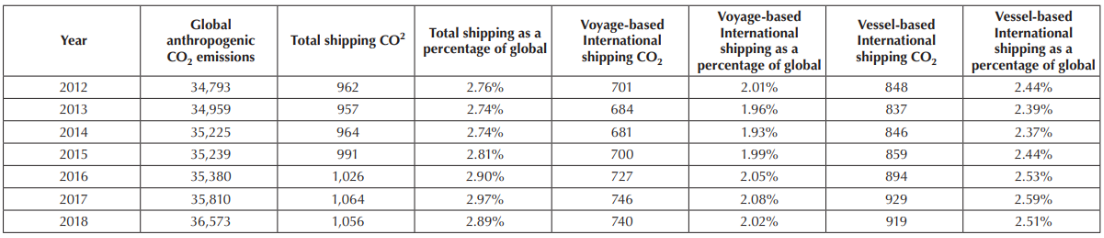


*Excluding the United Kingdom
**Excluding land use, land-use change and forestry
***Energy, industry, residential, commercial, institutional, agriculture, forestry, fisheries and other

Source: European Environment Agency (2022)

Figure 1: Transport Emissions [1].

This share has been increasing over the years due to the growth in global trade. According to the International Maritime Organization (IMO), the international shipping industry was responsible for approximately 1.076 billion metric tons of CO_2 emissions in 2018, accounting for about 2.89% of the world's total CO_2 emissions for that year. This data is based on the Third IMO Greenhouse Gas Study. Shipping emissions have been on the rise in recent years due to an increase in global maritime trade. Between 2012 and 2018, CO_2 emissions from shipping increased by approximately 9.3% [4]. The trend is expected to continue if no significant measures are taken to curb emissions. With the continuous growth of maritime transport demand, this will eventually lead to the CO_2 emissions from 10 million tons in 2018 to 10 - 15 million tons in 2050, an increase of 0 - 50% over the level in 2018, equivalent to 90 - 130% of the level in 2008. IMO's emission reduction target is to reduce the total GHG emissions of the international shipping industry by at least 50% by 2050 compared with 2008[1].



Year	Global anthropogenic CO_2 emissions	Total shipping CO^2	Total shipping as a percentage of global	Voyage-based International shipping CO_2	Voyage-based International shipping as a percentage of global	Vessel-based International shipping CO_2	Vessel-based International shipping as a percentage of global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1,026	2.90%	727	2.05%	894	2.53%
2017	35,810	1,064	2.97%	746	2.08%	929	2.59%
2018	36,573	1,056	2.89%	740	2.02%	919	2.51%

Figure 2: Total shipping and voyage-based and vessel-based international shipping carbon dioxide emissions 2012-2018 (million tonnes) [1].

After 1 January 2013 MARPOL Annex VI Energy Efficiency for Ships regulation entered into force to regulate CO_2 emissions caused by the new and existing ships [5]. After the Kyoto Protocol, Annex VI was the first regulation about climate change. Energy Efficiency Design Index (EEDI) regulation was adopted at the Marine Environment Protection Committee (MEPC 62) for new building vessels. EEDI encourages the use of less pollutant and more efficient engines and equipment onboard. With EEDI, vessels' energy efficiency is calculated by taking ship speed, emissions, and capacity into consideration [6]. The unit of the calculation is grams of CO_2 per ship tonne-mile. Lower EEDI is better since this means a vessel is more energy-efficient and less pollutant. Two types of EEDI are defined with Annex VI regulation, which are attained EEDI and required EEDI, attained EEDI is the calculated EEDI for the ship and the required EEDI is the maximum EEDI limit for the ship [7]. Every five years the maximum limit will decrease incrementally for new building ships.

In April 2018, IMO adopted a preliminary strategy for reducing GHG emissions from ships. This policy framework sets key goals to reduce the carbon intensity of a single ship by implementing the further stage of EEDI for new ships. It is also proposed that by 2050, the annual GHG emissions of ships engaged in international navigation will be reduced by at least half compared with the level in 2008. [8]. In addition, in the 21st century, efforts should be made to gradually achieve zero GHG emissions from ships as soon as possible. By 2030, the carbon emission intensity of ships engaged in international navigation should be reduced by at least 40% on average, and efforts should be made to reduce the carbon emission intensity by 70% compared with the level in 2008. The strategy will be revised in 2023 and assess the impact of all proposed measures on countries.[9]

In June 2021, IMO adopted key short-term measures aimed at reducing the carbon intensity of all ships by at least 40% by 2030, which is in line with the IMO's initial strategic objectives. These measures combine technical methods with operational methods to improve ship's energy efficiency. All ships must calculate their EEXI, and ships with more than 5000 gross tons will establish their annual operational carbon intensity index (CII) and carbon intensity rating mechanism. According to the regulations, CII is applicable to ship types above 5000GT (international voyage). According to the CII reached, a ship will be rated from A to E every year, where A is the best and C is the lowest rating requirement [135]. This is the first time that IMO has established a formal rating mechanism for ships. It also sends a strong signal to the market that government departments, port authorities and other stakeholders are encouraged to provide incentives for ships rated A or B. For ships rated as Class D or Class E for three consecutive years, an improvement plan shall be submitted to clarify how to reach the required level (Class C or above) [4].

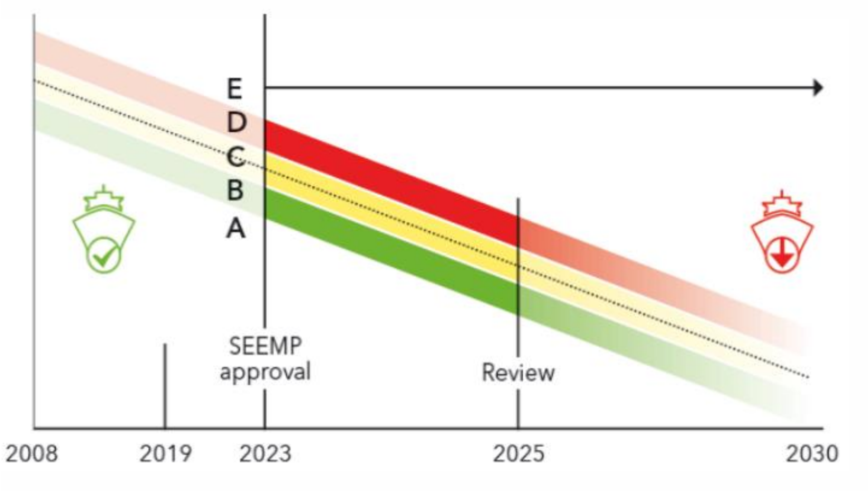


Figure 3 : Required annual operational CII [137].

Furthermore, addressing these emissions poses a complex web of legal challenges. The maritime sector operates on a global scale, with vessels traversing international waters and ports in multiple jurisdictions. This transboundary nature of shipping complicates the enforcement of environmental regulations and necessitates international cooperation and legal frameworks to curb CO_2 emissions effectively. The International Maritime Organization (IMO) has taken a central role in developing and implementing regulations to reduce CO_2 emissions from ships, but the path toward achieving meaningful reductions remains a work in progress. The legal framework is now very strict also in the case of navigation as ships contribute about 7% of total CO_2 emissions from ship from the transport sector [10]. The MARPOL Convention was adopted in 1973 and has recently revised in 2010 by the Marine Environment Protection Commission with the addition of annexes [11] The revision tightens Nox limits and sulphur and allows for the installation of alternative devices on ships for the purpose of compliance with the limits of the specific pollutants. The Treaty has also established the Emission Control Areas (ECAs) from which where the passage of ships is subject to specific legal restrictions as towards polluting emissions. Beyond the environmental benefit, there is a a growing market where CO_2 can be used in various industrial applications processes such as in enhanced oil recovery (EOR) applications. In this case, the combined operation of CO_2 capture units and units EOR is a beneficial solution for both applications [12] reducing the important cost of CO_2 captured.

3. Carbon Capture Technologies

3.1. Carbon Capture Review

Carbon capture technologies have emerged as a promising solution to mitigate the escalating issue of greenhouse gas emissions. These innovative technologies offer a glimmer of hope in the fight against climate change by capturing and storing carbon dioxide emissions from various sources, such as power plants and industrial facilities. By preventing a substantial amount of CO_2 from entering the atmosphere, these technologies hold the potential to significantly reduce our carbon footprint. While there are challenges to overcome, including cost-effectiveness and scalability, ongoing research and development are steadily improving the efficiency and feasibility of carbon capture technologies. As we continue to grapple with the urgent need to combat climate change, these innovations represent a crucial piece of the puzzle in our quest to create a more sustainable and environmentally responsible future.

The process selection is usually based on the chemical and physical conditions of the gaseous stream being processed (flowrate, pressure, temperature, CO_2 concentration, impurities present, etc.). Carbon Capture (CC) processes have been widely used to remove CO_2 in natural gas processing, hydrogen and ammonia production, and many other industrial processes [13]. CC technologies encompass a diverse range of methods, each with its unique advantages and limitations. These technologies can be broadly categorized into three primary groups: post-combustion capture, pre-combustion capture, and oxy-fuel combustion capture.

(i) Post-combustion capture involves the removal of carbon dioxide from the exhaust gases of power plants and industrial facilities after the combustion process. It is a versatile approach since it can be retrofitted to existing infrastructure, making it an attractive option for reducing emissions from older plants. However, it tends to be energy-intensive and can impose a considerable cost burden.

(ii) Pre-combustion capture, on the other hand, captures carbon dioxide before combustion occurs, primarily in processes like gasification. This approach is more energy-efficient and can yield high-purity CO_2 streams, making it suitable for specific applications. Nonetheless, it is limited to new facilities or major modifications to existing ones, making it less versatile than post-combustion methods.

(iii) Oxy-fuel combustion capture involves burning fuels in an oxygen-rich environment, which produces a flue gas with a higher concentration of CO_2. This process simplifies carbon capture but necessitates an oxygen production unit. It offers potential energy savings and high CO_2 purity but is not widely adopted due to infrastructure challenges [14].

The selection of carbon capture technology is influenced by a number of variables, such as the facility's age, energy efficiency objectives, and infrastructural needs. Adapted strategies that carefully integrate these techniques could provide the best way to cut carbon emissions in many industries. With continued research and development in these areas, carbon capture technology should become more viable, raising hopes for a more ecologically conscious and sustainable future.

3.2. Carbon Capture System general description.

In general, a carbon capture system consists of three main parts. At first, the capture of CO_2 from industrial processes takes place. In order to storage the CO_2, it is important to transport it under some specific conditions, such as high pressure and low temperature. Finally, after the the transportation, follows the storage of CO_2, usually in geological formations or using it in other applications.

The categorization of carbon dioxide capture methods is carried out at the first level depending on the time of capture and at the second level considering the physical phenomenon that occurs during capture. Carbon dioxide capture can take place before or after the combustion of the fuel. This categorization therefore divides the capture methods into pre-combustion technologies (producing carbon-free fuel) and post-combustion technologies (separating CO_2 from the flue gas). In addition to these methods, there is the more specialized method of combustion under pure oxygen conditions in which the flue gas produced contains mainly carbon dioxide and water vapor. Thus, once the other pollutants have been removed, condensation of the water vapor takes place by cooling the exhaust gas and a nearly CO_2-free gaseous stream is produced. On the basis of this technology, advanced variants have been developed, such as the chemical looping mechanism, which is based on the use of metal oxides which used as oxygen carriers from the combustion air to the fuel and is known as Oxy-Fuel combustion [15].

Post-Combustion Capture

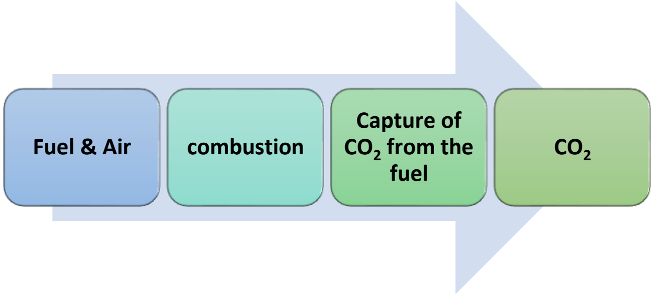


Figure 4: Post Combustion Capture Process.

Pre-Combustion Capture

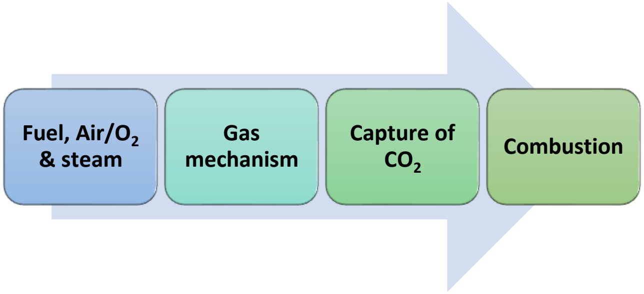


Figure 5: Pre-Combustion Capture Process.

Oxy-fuel Combustion

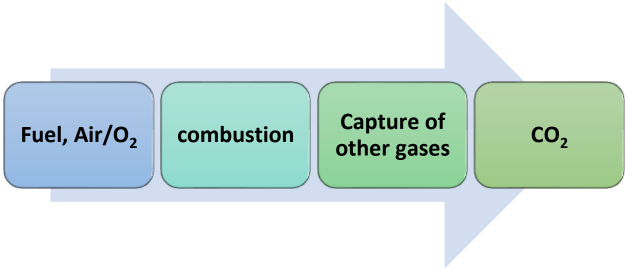


Figure 6: Oxy-fuel Combustion Process.

3.3. Carbon Capture Technologies

It is already mentioned that CO_2 is captured at the source, typically from the flue gas of industrial processes or power plants. There are different capture technologies, such as post-combustion capture, pre-combustion capture, and oxyfuel combustion, each suited for different types of sources [16]. In all cases the carbon dioxide is separated at the same time from the use of fossil fuels or biomass from other gaseous media [17].

3.3.1. Oxy-fuel Combustion

Oxy-fuel combustion is one of the three main routes being pursued toward cost-effective, technically viable carbon capture [18]. Oxy-fuel combustion is not technically a capture technology but rather is a process in which coal combustion occurs in an oxygen-enriched (nitrogen depleted) environment thereby producing a flue gas comprised mainly of CO_2 (up to 89vol.%) and water [18]. Specifically, it is a process with high purity of oxygen and recirculated gas flow. Main goal of oxygen-fuel combustion technology is to reduce atmospheric nitrogen through separation processes. These processes include the initial separation of oxygen (to achieve a purity level above 95%) and nitrogen from the air that feeds the boiler, resulting in the partial or total elimination of nitrogen [21]. The water is easily separated, and the CO_2 is ready for sequestration. CO_2 concentrations are very high during oxy-fuel combustion. Whereas the chemical effect of CO_2 is more subtle than that of oxygen concentration, the effect of CO_2 on heat capacity and gas transport properties can be significant, and these properties have a strong influence on the combustion process [19]. Nitrogen oxide emissions are completely prevented due to the lack of nitrogen unless there are fuel impurities or leaks from the outside environment. Moreover, the exhaust gases contain a lot of CO_2 due to the lack of nitrogen. When compared to combustion using regular air, the lack of nitrogen in the oxidant mixture causes smaller volumes in the combustion chamber as well as distinct combustion properties. Getting oxygen for burning is a crucial problem [20].

Oxy-fuel combustion for CO_2 capture incorporates three main components: the air separation unit (ASU) that provides oxygen for combustion, the furnace and heat exchangers where combustion and heat exchange take place, and the CO_2 capture and compression unit. [19]. In oxy-fuel combustion, conventional boiler technology is deployed to prepare and combust the fuel, and to transfer the combustion heat from the flue gas to a working fluid (typically steam) to generate electricity. In most implementations, a large portion of the flue gas is recycled back to furnace to control flame temperature and to reconstitute the flue gas volume to ensure proper heat transfer [22]. Recent research shows that for Oxy-fuel process, materials are chosen to be high temperature resistant, especially for the adsorption process.

Pulverized coal is burned in an atmosphere of almost pure oxygen (more than 95% and up to 99%) combined with recycled flue gas in the most common oxyfuel process [23]. Current building materials cannot tolerate the high temperature produced by burning coal in pure oxygen, thus it is important to mix recycled flue gas with pure oxygen to give the right heat transfer properties [24]. Studies have demonstrated that in order for the pulverized coal oxycombustion flame to have heat transfer characteristics akin to those of an air-fired system, the oxygen/recirculated flue gas flow needs to be maintained. About 30 to 35 vol% of oxygen must be present in the gas that enters the boiler for this to work [25].

A major advantage of the technology is that it produces a flue gas that consists primarily of CO_2 (>80vol.%) and water. The water can be removed easily by condensation allowing the CO_2 to be purified relatively inexpensively. Roughly three times more oxygen is needed for oxy-fuel systems than for an IGCC plant of comparable size, so the ASU adds significantly to the cost. [26]. Below it is presented table 1 with some important advantages and disadvantages of Oxy- fuel Combustion.

Table 1 : Advantages/Disadvantages of Oxy-fuel Combustion.

Advantages and Disadvantages of Oxy-Fuel combustion		
no	Advanatages	Disadvantages
1	Oxy-combustion power plants should be able to deploy conventional, well-developed, high efficiency steam cycles without need to remove significant quantities of steam from the cycle for CO_2 capture.	Not possible to develop subscale oxy-combustion technology at existing power plants as it requires commitment of the entire power plant.
2	Extra equipment consists mainly of conventional equipment and heat exchangers. The boiler and air pollutions control devices utilize conventional designs, materials of construction and arrangements, all well established in industry.	Energy penalty results from power needed for ASU air compression and CO_2 compression in the CO2 purification unit will reduce net plant output by up to 25% compared to an air-fired power plant of the same capacity without CO_2 capture.
3	Very low emissions of conventional pollutants, which are usually achievable at relatively low cost.	Currently, little geological or regulatory consensus on what CO_2 purity needed for compression, transportation and storage. If purity requirements are lower, oxy-combustion costs could be reduced.
4	On a cost per CO_2 captured basis, it should be possible to achieve ≥ 98% CO_2 capture at an incrementally lower cost than achieving a baseline 90% capture.	Need to reduce overall costs although thi issue is common to all capture methods.
5	Any oxy-fuel power plant will look and operate in a similar manner to a conventional power plant.	Technology needs proving through the integrated operation on a larger scale and under various operating conditions.
6	Should be easier and less complex to repower or retrofit into an existing power plant than pre or post combustion capture.	Installation must be air tight to avoid in-leakage. If over pressurized , there is risk of CO_2 leakage.

3.3.2. Pre- Combustion Capture

In pre-combustion capture systems, a fuel reacts with oxygen, air, or steam to produce primarily "synthesis gas," or syngas, which is made up of hydrogen and carbon monoxide. A physical or chemical absorption method is used to remove CO_2 from the fuel, and numerous applications, including fuel cells, produce and burn a fuel that is rich in hydrogen [27]. This kind or reaction is called gasification [28].

A typical pre-combustion carbon capture system for gasification power plant begins with gasification (or partial oxidation) of fuel to produce synthesis gas (or syngas) enriched with carbon monoxide and hydrogen. Syngas is processed in a water gas shift (WGS) reformer after particulate removal using a cyclone separation unit. In WGS, carbon monoxide interacts with steam to generate carbon dioxide and hydrogen, and the resulting product stream is delivered for desulphurization and carbon dioxide separation [29]. In the end, this carbon capture system produces hydrogen fuel stream with low sulfur dioxide generation for a variety of power generating applications (such as gas boilers, gas turbines, fuel cells, etc.), increasing the value of fuel by lowering its carbon content.[28]. Whereas in natural gas power plant, carbon dioxide separation unit is typically preceded by autothermal (steam) reforming and WGS processes [30].

Pre-combustion capture is often associated with process stream with higher carbon dioxide concentration (15–60% by volume, dry basis), elevated pressure (2–7 MPa) [31], and high temperature range of 200–400 °C [32]. After the catalyzed WGS process, the syngas stream typically contains 20–23 mol% carbon dioxide and 64–73 mol% hydrogen [32]. In comparison to the post-combustion capture strategy, high carbon dioxide atmospheric pressure in particular has thermodynamically pushed the carbon dioxide adsorption with greater efficiency and led to a lower energy demand for carbon capture and compression operation [28].

Physical solvents that are easily obtained and reasonably priced, like rectisol and selexol, are used to separate carbon dioxide from the gas mixture. The CO_2 is then compressed for ultimate storage after going through the conditioning process, which includes removing condensate and moisture, separating solid particles, cooling or heating the gas, and eliminating undesired gaseous components. [28] [33] [34]. In contrast, the residual gas containing a high concentration of hydrogen is utilized as fuel in gas turbines or boilers as part of an integrated gas combine cycle (IGCC) system to produce electricity. Even though it is possible to achieve a fairly high level of carbon dioxide capture efficiency—up to 80%—prior to the combustion process, the technology's actual implementation is closely linked to expensive operating and capital expenses. The mandatory gas synthesis process is the main source of these expenses, which lessens the CO_2 capture method's economic appeal [35].

Table 2: Advantages/Disadvantages of Pre-Combustion Capture.

Advantages and Disadvantages of Pre- Combustion		
no	Advanatages	Disadvantages
1	Technologies for precombustion capture of CO_2 via gasification are well established in the process industries.	Lower (but still significant) energy loss compared to postcombution capture.
2	Capture using the water-gas shift reaction and removal of the CO_2 via AGR process is used widely.	Capital costs of IGCC without capture are much higher than supercritical pulverized coal plant without capture.
3	As a smaller reaction volume is involved , at lower volumetric flow rates , elevated pressure and higher component concentration , the CO_2 separation step consumes less energy than post combustion capture.	Barriers to commercial application of gasification/IGCC are common to precombustion capture, such as availability, cost of equipment , extensive supporting systems requirements.
4	Syngas produced as the first step of the process can bused to fuel a turbine cycle.	Applicable mainly to new plants as relatively few coal gasification-based plants are in operation.
5	Lower water use compared to postcombustion capture.	
6	Syngas contains high concentration of CO_2 and is at high pressure resulting high CO_2 partial pressure, increased driving force for seperation, more technologies available for seperation and finally potential for reduxtion in compression costs/loads.	

3.3.3. Post-Combustion Capture

Post-combustion involves the capture of CO_2 from treated flue gas and is widely used in the chemical processing industry. Post-combustion capture technology can be retrofitted to existing large point sources such as fossil fuel power plants, cement producers or refineries, as these are the main source of carbon dioxide emissions to the atmosphere.

Technologies used after fossil fuel combustion to extract CO_2 from exhaust gases are called post-combustion capture technologies. . Post-combustion capture deals with the treatment of exhaust gases on the output side of natural gas combined cycle (NGCC) or pulverised coal (PC) power plants [36] The technology is well known and is currently used for other industrial applications. This technology is largely based on chemical absorption/desorption using a liquid sorbent such as monoethanolamine (MEA) at 30%wt in water or even dry adsorbents [37]. In post-combustion capture technology, the exhaust stream is treated prior to combustion to reduce the concentration of secondary species in the flue gas such as nitrogen oxide (NOx), sulfur oxide (SOx), water vapor and particulate matter [38] as these species affect the operation, even in dilute concentrations. The capture plant is often located between the stack and the flue gas desulfurization unit. At this point, flue gases are maintained at near atmospheric pressure and temperature in the range of 50–150°C [39] and represents between 10% and 15% by volume of CO_2 concentration [40]. CO_2 from conventional thermoelectric power plant is often subjected to post-combustion capture, where the fuel is burned to produce a flue gas and the subsequent compression, transportation and separation or sequestration of CO_2 from the flue gas [41]. Post-combustion CO_2 capture (PCC) is considered important for its short-term applicability, as it can be easily retrofitted to existing power plants and can switch flexibly between capture and non-capture modes during operation [42].

In Post-Combustion Capture (PCC) CO_2 is separated from the other gases in the exhaust gas as it leaves the engine and is then cleaned and filtered. Specifically, the reaction between CO_2 and amines offers currently the most cost-effective solution to directly obtain high purity CO_2. The flue gases from the power plant are cooled and treated for reduction of particulates and SOx and NOx. Then the flue gases, boosted by a fan to overcome pressure drops in the system, pass through an absorber. A lean amine solution counter-currently interacts with the flue gases and absorbs the CO_2. The clean flue gases continue to the stack. The CO_2 rich amine solution is pumped into a stripper (regenerator) to separate the amine from the CO_2. The energy to desorb the CO_2 from the solution is provided by steam. The CO_2-rich solution at the top of the stripper is condensed for water removal and the gaseous CO_2 is sent for further drying and compression, the CO_2 is afterwards compressed and kept in a tank. [42]. Due to the fact that this capture process is more developed than other capture methods, post-combustion capture is the most alluring method [43]. PCC of CO_2 from flue gases can be done by various methods: distillation, membranes, adsorption, physical and chemical absorption. Absorption in chemical solvents, such as amine types, is a proven technology and in many applications performed consistently and reliable. It is the most promising technology between them for post-combustion capture [44].

PCC can be typically built into existing industrial plants and power stations (known as retrofitting) without significant modifications to the original plant.

•PCC can be integrated into new plants to achieve a range of greenhouse gas intensity reductions near to zero emissions.

•In contrast to competing technologies, PCC offers high operational flexibility (partial retrofit, zero to full capture operation) and it can match market conditions for both existing and new power stations.

•PCC offers a lower technology risk compared to competing technologies; this is further enhanced by the ability for staged implementation, which is not possible with competing technologies.

•Renewable technologies can be integrated in the PCC process, in particular, PCC allows the use of low-cost solar thermal collectors to provide the necessary heat to separate CO2 from sorbents, effectively reducing the loss of electrical output caused by capture.

•PCC can be applied to capture CO_2 from natural gas fired power stations and other large stationary sources of CO_2, for instance, smelters, cement kilns and steelworks.

Post-combustion capture has the advantage that it can be retrofitted and does not require any changes to the combustion system. Furthermore, the amount of captured CO_2 can be changed to adjust the energy demand. However, there are some important disadvantages, such as the reduction in thermal efficiency by 10-40%, three quarters due to CO_2 capture and one quarter due to compression of the CO_2 [45]. An extremely important additional disadvantage that we must emphasize is the energy required because the exhaust gas contains only 4-14% CO_2.

Despite the numerous advantages, the process must overcome the associated technical challenges before it can be implemented on a commercial scale. Researchers are making great efforts to overcome the technical challenges involved and to make the deposition technology efficient in terms of both cost and energy. Table 3, Shows an insight of the advantages and disadvantages of post-combustion capture technology.

Table 3: Advantages/Disadvantages of Post-Combustion Capture

Advantages and disadvantages of Post - Combustion Capture Technology			
no	Advanatages	Disadvantages	References
1	The easiest technology to apply to existing emission sources. Considered one of the most important green and economic technologies	Require development of efficient adsorbents (dry) for relatively concentrated streams to make it more efficient in terms of both.	[46]
2	An effective means of reducing greenhouse gas density that can be applied to existing power plants after retrofitting.	Limited availability of ideal sorbent for post-combustion carbon dioxide capture.	[40]
3	The operation of the technology does not have to be stopped for maintenance and can be easily regulated or controlled.	Additional energy requirement for the compression of the separated carbon dioxide, necessity of treating large quantities of gas, as the partial pressure and the concentration of carbon dioxide in the flue gas are low, large energy requirement for the regeneration of the sorbent, e.g. amine as a solvent.	[47]
4	Post-combustion capture technology has higher thermal efficiency for conversion to electricity.		[21]
5	These technologies have the greatest potential for reduction of CO_2.		[48]
6	Use of activated carbon as one of the adsorbents makes the process environmentally friendly.		[49]

3.4. Carbon Capture Technologies

The technologies of carbon capture systems which are going to be investigated are based, chiefly, on Post- Combustion Capture, due to the convenience of application in existing facilities, without requiring significant modification of the system. In this case, the exhaust gas from several combustion processes, such as producing energy from conventional fuels, is transferred to the capture system. Afterward, the CO_2-water stream generated by the system's regeneration section is directed to the condenser, where it produces high-purity CO_2 [50].

The carbon capture technologies based on Post -Combustion Capture are shown on the following figure 7.

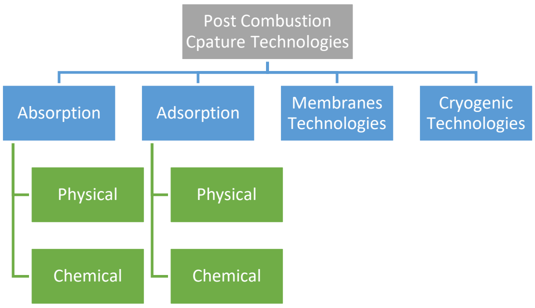


Figure 7: Technologies of Post-Combustion Capture.

3.4.1. Absorption

Absorption methods of separation, whether chemical or physical, are broadly used in the oil and gas and chemical industries for removal of CO_2 from gas streams. Chemical absorption focuses on the reaction between the liquid absorbent, typically an aqueous solution of amines, and CO_2. On the other hand, physical absorption there is no reaction between the liquid absorbent and the CO_2 [51]. Specifically, physical absorption involves the physical interaction between the absorbent and CO_2. No significant chemical reactions occur, and the absorption is often based on weak molecular forces.

3.4.1.1. Physical Absorption

In physical absorption of CO_2, sequestration is often accomplished from an aqueous solution using Henry's law, which states that the solubility of the gaseous adsorbed material in the liquid is proportionate to its partial pressure. Certain effective aqueous solutions that are used in the physical absorption process—such as methanol absorption (Rectisol process) and dimethyl ether absorption (Selexol process)—have been patented [52]. Other absorbents such as morpholine and propylene carbonate are also utilized in physical absorption. The technique has several benefits, including the solution's low toxicity and corrosiveness and its quick regeneration through straightforward compression [53]. Physical absorption is valued for its ability to selectively capture CO_2 from flue gas and its compatibility with existing infrastructure in many industrial settings [54].

3.4.1.2. Chemical Absorption

The chemical absorption of CO_2 is one of the most efficient methods of capturing the pollutant from the exhaust gases of conventional fuels. Among the advantages of the method is the maturity of the technology. In addition, the use of chemical solutions is usually preferred due to their high efficiency and selectivity as well as low energy requirements compared to other methods [55]. Nevertheless, the energy cost of the process remains significant, negatively affecting the overall performance of the unit in which it is applied. For example, the regeneration process, which is also the most energy demanding, can reduce the overall efficiency of a power plant by up to 14% [56] [57]. In order to reduce this energy cost, researchers are looking for various solutions which mainly concern the utilization of waste heat, innovative solutions that combine high efficiency and low heat of regeneration as well as other methods. [58,59,60].

The absorber and the desorber, sometimes known as the stripper, are the two primary columns that make up the chemical absorption system. While the solvent from the upper section of the column flows counter currently with the exhaust gas, the exhaust gas flow reaches the absorber through the bottom. To improve the mass and heat exchange surface between the two fluids, the filler material is made up of precisely formed metal, plastic, or ceramic particles [61]. Diffusion, absorption, and chemical reaction processes occur when the two fluids come into contact, resulting to the alkanolamine molecules capture of carbon dioxide. As a result, the CO_2-enriched solution exits the lower portion of the absorber and the CO_2-free exhaust gas exits the upper part, both of which are directed toward the regeneration column. While regeneration needs higher pressures (generally 1.7–2 bar) to prevent unintentional vaporization of the solution because of the high temperatures at which the process is conducted, absorption is often carried out at pressures close to atmospheric pressure. [62]. The reboiler, located in the lower section of the regenerator, uses heat to make steam from a portion of the rich solution. As steam rises into the regenerator, it breaks the chemical connections that have formed between the solution and CO_2. The temperature of the rich solution exiting the regenerator rises as the regenerated solution enters the exchanger at a high temperature, lowering the reboiler's energy burden. Finally, the pure CO_2 is compressed to a supercritical condition for easy transportation.

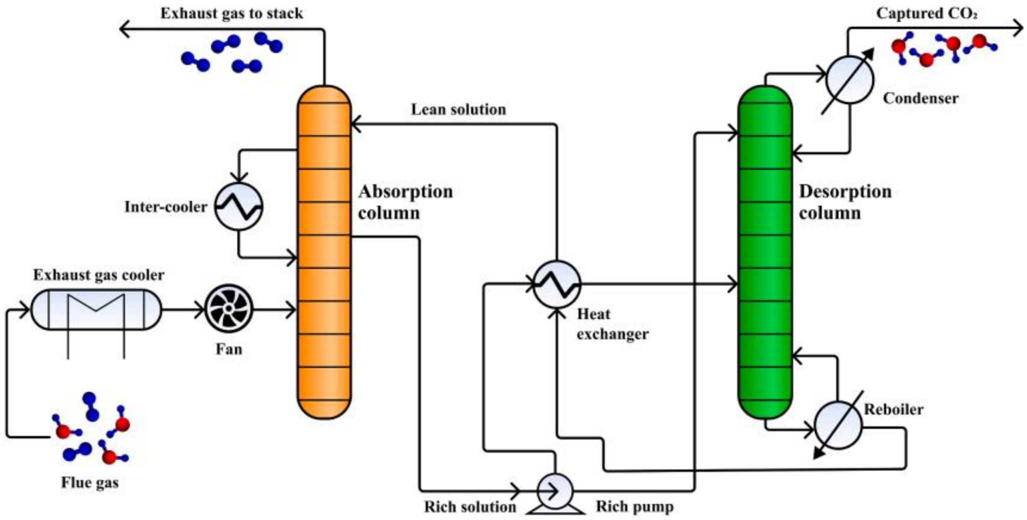


Figure 8: Chemical Absorption Process [17].

Some of the most common solvents which are used for capturing the CO_2 are amines and alkali salts such as ACE (monoethanolamine), DEA (diethanolamine), PZ (piperazine)TEA (triethanolamine), DIPA (diisopropanolamine), DGA (diglycolamine) as well as ammonia. Of the alkaline salts, the most important is potassium carbonate (K_2CO_3) and sodium carbonate ($Na_2 CO_3$) [36]. However, MEA is the baseline chemical solvent for absorption technology and investigation into more effective solvents is ongoing in the literature. Solvents such as piperazine, various ionic liquids, 2-amino-2-methyl-propanol (AMP), diethanolamine (DEA) and methydiethanolamine (MDEA). [58,59,60].

Before chemical absorption can be applied to the removal of CO from the exhaust gases of coal power plants, two important conditions must be satisfied. First, the energy required for sorbent regeneration (which increases with decreasing CO_2 partial pressure) needs to be considered through sorbent screening and characterization to select the best sorbent that will have high absorption capacity, fast-reaction rate, and low absorption enthalpy. Second, sorbent degradation brought about by impurities (such as nitrogen oxides [NOx], sulfur oxides [SOx], and incondensable gases) contained in the flue gases must equally be considered before chemical absorption can be adjudged suitable for CO_2 capture from exhaust gas streams [36].

The efficiency of chemical absorption for capturing carbon dioxide (CO_2) depends on several factors, including the properties of the gas stream, the properties of the scrubbing solution, the type of equipment used, and the operating conditions The kind of cleaning solution that is utilized is one of the most crucial elements. The selectivities and capacities of various solvents to absorb CO_2 vary, which may have an impact on the process's efficiency. For instance, monoethanolamine (MEA), a widely used solvent, is a good option for CO_2 capture due to its excellent selectivity and capacity for CO_2 absorption [63]. The operational parameters, such as temperature, pressure, and gas flow rate, can also have an impact on efficiency. The efficiency of CO_2 absorption can be increased by raising the temperature or lowering the pressure, but doing so may result in an increase in the amount of energy needed for the process [61]. The efficiency of the equipment might also be impacted by its type. A popular kind of CO_2 collection apparatus that can produce good removal efficiency is the packed bed column. They may, however, also call for a substantial volume of solvent, raising the process's cost.[64]

Overall, chemical absorption can be an effective method for capturing CO_2, with reported efficiencies ranging from 80% to over 90%. However, the process can be energy-intensive and can generate waste streams that require proper disposal. Therefore, it is important to carefully consider the properties of the gas stream, the properties of the scrubbing solution, and the operating conditions to optimize the efficiency of the process while minimizing its environmental impact.

3.4.2. Adsorption

A solid adsorbent material absorbs the substance during adsorption either from its surface or from the network of its interior pores. Adsorption is a phenomenon that can be classified as chemical or physical depending on whether chemical reactions are involved. Strong chemical bonding is observed during chemisorption, which results in the formation of a persistent layer of chemically attached molecules solely on the solid's surface. Because of this irreversible process, the adsorbent is not acceptable for use in the future. Thus, the physical adsorption technique is preferred for the capture of gases such as CO_2. During physical adsorption, weak Van Der Vaals forces are created between the solid and the adsorbed particles which are usually reversible [21].

To accomplish the goal of separation, the adsorption method employs an adsorbent to selectively adsorb a certain gas. Adsorption and desorption are the two phases that make up the entire adsorption process. To finish the carbon dioxide concentration and adsorbent material renewal, periodic adsorption and desorption are employed. Adsorption towers operating in parallel can accomplish continuous operation. The adsorbed gas will create an adsorption layer on the surface of the adsorbent when it encounters it because of the attraction of the adsorbent surface. The term "adsorption phase" refers to this layer of adsorption. The adsorption phase's density is significantly higher than the gas's density. The adsorption force is the result of the mutual interaction of the gravitational forces of the gas molecules and the residual gravitational force on the surface, which produces an adsorption affinity. [35] Adsorption force typically originates from three sources: 1) Van der Waals force, which is the repulsive and attractive forces that predominate between atoms and molecules; 2) Coulomb force electrostatic between charged particles; 3) Charge displacement produced by neighboring molecules as a result of the permanent dipole moment induces polarization and generates the induced force of the induced dipole moment.

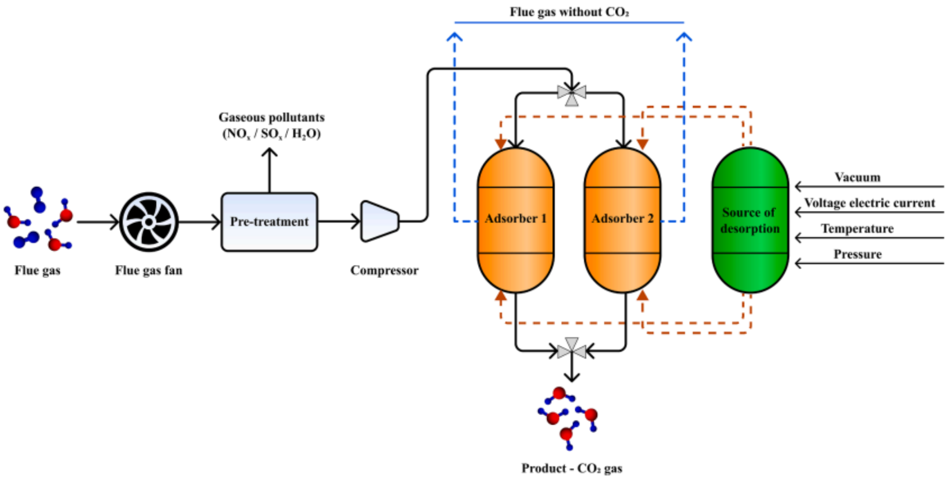


Figure 9: Adsorption Process [17].

Adsorption can be classified into two types: physical adsorption (also known as physisorption), and chemical adsorption (also known as chemisorption). Physical adsorption involves weak intermolecular forces between the adsorbate and adsorbent, while chemical adsorption involves the formation of covalent or ionic bonds between the adsorbate and adsorbent surface [45]. In physical adsorption, the flue gas enters an adsorber, which is a column filled with proper solid material (like alumina, zeolite and activated carbon). CO_2 sticks to the surface of the solid material forming weak bonds under high pressure or temperature. The cleaned gas leaves the column from top. In regular cycles, the solid material is regenerated, and a pure CO_2 stream is produced by changing pressure or temperature of the column. In chemical adsorption, CO_2 diffuses into a solid material and reacts with it, to form a new molecule. The solid material is then collected as process by-product [65].

About chemical adsorption, the technology is unsuitable for large-scale applications. CO_2 capture capacity of the adsorbent is low that requires big spaces for storage of the sorbent. Low CO_2 selectivity of the adsorbent is another drawback of the technology. In addition, process efficiency depends on the surface area, pore structure, partial pressure, temperature, and humidity [45].

3.4.3. Membrane technology

Membrane processes for CO_2 capture can, in a manner similar to other technologies, be classified as pre-combustion, oxycombustion and post-combustion processes. Here, we focus our discussion on the opportunities for process intensification using membranes in CO_2 capture.

Membrane systems, which consist of semipermeable elements (polymeric membranes), separate gases by selective permeation of the gas constituents in contact with the membrane. When high-pressure gas is supplied to one side of the membrane while the permeate side is kept at considerably lower pressure, the gases dissolve in the membrane material and pass through the membrane barrier under an imposed partial pressure gradient. Specifically, the flue gas is fed into tubes made of suitable porous materials, positioned in appropriate configurations (hollow fibers) that selectively enable CO_2 to pass through them. On the one side of the hollow fiber membrane, the gas mixture is fed, while on the other (shell) side, a CO_2 capture medium flows co-currently or counter-currently and chemically capture it, therefore enabling its removal. CO_2 passes through the membranes and flows on the other side of the membrane (the shell), which is often at lower pressure. The cleaned gas flows out the tubes to the environment. The reverse setting can also be found: gas flowing through the shell and CO_2 flowing through the tubes.

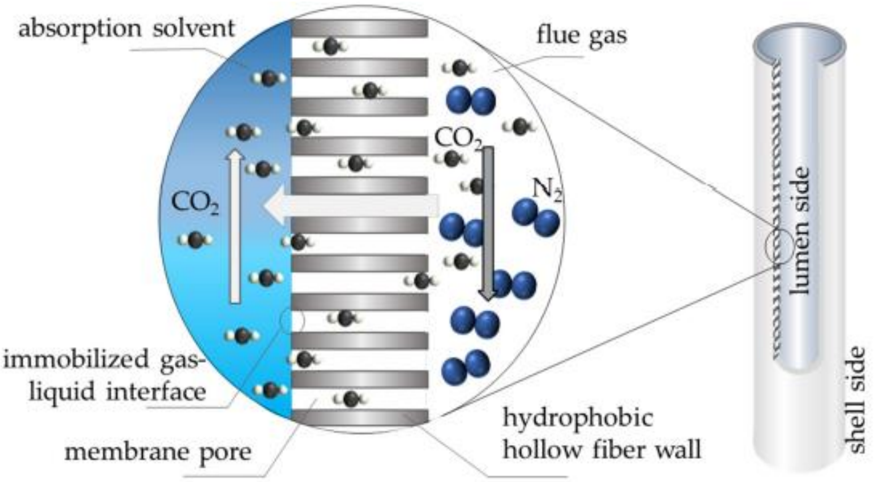


Figure 10: Schematic representation of a membrane contactor for CO_2 capture [138].

In this technology the energy required per unit mass of CO_2 removed, is one of the lowest of all the currently available technologies [66]. The process's drawbacks are related to the low removal efficiency and low purity of CO_2 extracted [66]. To achieve a high level of CO_2 purity, membrane separation is therefore employed in conjunction with other separation techniques (e.g., membrane with cryogenic or absorption procedures) [66]. Furthermore, when the feed stream's CO_2 content is less than 20%, the procedure becomes less feasible. The fact that membranes are sensitive to sulfur compound traces [67] which are almost certainly present in power plant flue-gas streams, is another issue working against the large-scale deployment of membrane separation for CO_2 removal in gas streams. To increase membrane efficiency, a lot of work has gone into improving the transport characteristics of membranes. Another advancement in technology is the composite membrane, which combines two membranes to create a matrix [68].

Membranes come in two primary varieties that are utilized. Inorganic membranes are specifically used for high-temperature operations. By combining these membrane processes with reforming, shift, and oxidation reactions, intensification is accomplished. We refer to the second kind as organic membranes. Not only are these membranes unsuitable for high temperatures, but most of them are also unsuitable for processes that operate at low temperatures (around 180°C-250°C) [27].

In the case of the ideal application to carbon capture system processes we seek for membranes which are characterized by high temperature and they are selective for hydrogen, oxygen and CO_2 permeation. Permeability is regarded as a crucial characteristic of membrane materials and it has no specific connection with the geometry. Knowing exactly the permeability of the membrane, as well as its size and the driving force across them we could assume the computation of flux and process design. However, this is assuming that transport within the membrane is the rate-determining step. the rate may be determined by surface exchange processes or indeed mass transfer processes [27].

3.4.4. Cryogenic Technology

Nitrogen and oxygen can be produced in huge quantities using cryogenic separation. Four blocks comprise the entire process: the rectifying section, the Main Heat Exchanger (MHE), the Main Air Compressor (MAC), and further compression. Since it is expected that the oxygen product is 99 mol% pure, less inert chemicals could be added to the gasifier in order to meet regulatory requirements for the final product's heat value. Thus, this technology is used for the separation of CO_2 from gases with a high content of CO_2 (usually more than 50%) [21]. Cryogenics have been gaining interest in both carbon capture and biogas upgrading to liquefied natural gas (LNG). Biogas upgrading utilizes cryogenics as a means of removing impurities, such as CO_2 and H_2S [69].

Commercial cryogenic separation occurs at extremely low temperatures, where the feed gas component begins to liquefy. Process functioning requires an extra compression and cooling of the feed gas. In order to liquefy and isolate CO_2, the gas must be cooled to an extremely low temperature using the cryogenic method [70]. Cryogenic distillation is a widely used technique for purifying and liquefying CO_2 from sources with a relatively high purity (90%) and for sweetening natural gas. Significant energy is needed for this method to deliver the required refrigeration. In order to prevent process equipment clogs and freezing of lines, feed gas must also be pretreated to remove components with a freezing point higher than the operating temperature [71]. the technique involves cooling the gas to a temperature lower than -73.3°C so that CO_2 can liquefied and separated [70]. Based on the fact that carbon dioxide has a higher boiling point than carbon monoxide (78.2°C vs. 161.5°C), it uses a refrigeration system to cool the combination of gases so they can separate. In order to decarbonize using this approach, the raw material gas must first be compressed, dried to prevent freezing, and then cooled. Condensed CO_2 is either liquid or solid, but CH_4 stays gaseous. Thus, CH_4 can be isolated and purified [72].

The main advantage of cryogenic CO_2 collection is that atmospheric pressure can be used throughout the operation, and no chemical sorbent is needed. Because the CO_2 produced in this fashion can exit as a liquid, which is the phase required to transport CO_2 via pipeline, it also lowers the cost of compression. The main flaw with this process is that there is some water present in the flue-gas stream going to the cooling units. This water might condense into ice, which can clog pipes and increase pressure loss. Therefore, before beginning cryogenic operations, a variety of expensive procedures will be required to eliminate any traces of water from the exhaust gas stream [73]. The most promising cryogenic application for the removal of CO_2 is in pre-combustion and oxy-fuel combustion in which the inlet gas contains a high concentration of CO_2. Advantages and disadvantages of cryogenic process are summarized in Table 4.

Table 4: Advantages/Disadvantages of Cryogenic Process.

Advantages and Disadvantages of Cryogenic Technology		
no	Advanatages	Disadvantages
1	There is no need of additives or chemical reagents.	High capital cost.

2	Suitable for CO_2 concentration greater than 50vol%.	High energy required for refrigeration purposes.
3	Produced pure liquid CO_2 ready for transport.	Need preremoval of possible freezing compound that may block the process such as water, NOx and SOx.

3.5. Storage/Sequestration and utilization of CO_2 after Capture Process

In order to combat climate change and lower greenhouse gas emissions, sequestering and using CO_2 after it has been captured is essential. This method entails absorbing carbon dioxide emissions from a variety of sources, including power stations and industrial facilities, and either storing the carbon dioxide underground (a process known as sequestration) or using it for other advantageous purposes [74].

Sequestration involves the long-term storage of CO_2 in geological formations, such as depleted oil and gas reservoirs, deep saline formations, or unmendable coal seams. This method prevents CO_2 from entering the atmosphere, effectively reducing its impact on global warming. The success of sequestration relies on secure and reliable storage, ensuring that the stored CO_2 remains contained without any leakage over extended periods. [74]

By repurposing the gas in different businesses, using captured CO_2 offers an inventive way to reduce emissions. Utilizing captured CO2 for more effectively oil recovery in the energy industry or in the manufacturing of synthetic fuels, chemicals, or construction materials is one such technique known as carbon capture, utilization, and storage (CCUS) Furthermore, CO_2 can be transformed into useful items like polymers and plastics or used in greenhouses to promote plant growth. [75]

3.5.1. Storage / Sequestration of Captured CO_2

Carbon sequestration refers to the capture and long-term storage of carbon dioxide (CO_2) from the atmosphere. It's a vital process in mitigating climate change by reducing the amount of CO_2 in the atmosphere, which is a major contributor to global warming [76]. In this point, it is important to be mentioned that Storage and sequestration of CO_2 is not exactly the same meanings. Specifically, CO_2 storage generally refers to the containment of carbon dioxide in various forms and locations to prevent its release into the atmosphere. This can include storing CO_2 in geological formations, such as depleted oil and gas reservoirs, deep saline formations, or unmendable coal seams. It also encompasses storage in man-made structures, like tanks or containers, to prevent CO_2 from escaping into the air. CO_2 storage generally refers to the containment of carbon dioxide in various forms and locations to prevent its release into the atmosphere. This can include storing CO_2 in geological formations, such as depleted oil and gas reservoirs, deep saline formations, or unmendable coal seams. It also encompasses storage in man-made structures, like tanks or containers, to prevent CO_2 from escaping into the air [77].

Generally, there are two different CO_2 storage ways:

(1) Deep geological storage.
(2) Mineral storage.

Geological formations are currently considered the most promising storage sites. Areas such as the North Sea and the US Gulf Coast are believed to contain a large amount of geological storage space. On the other hand, Deep ocean storage will increase ocean acidification, a problem that also stems from the excess of CO_2 already in the atmosphere and oceans [74].

3.5.1.1. Geological storage

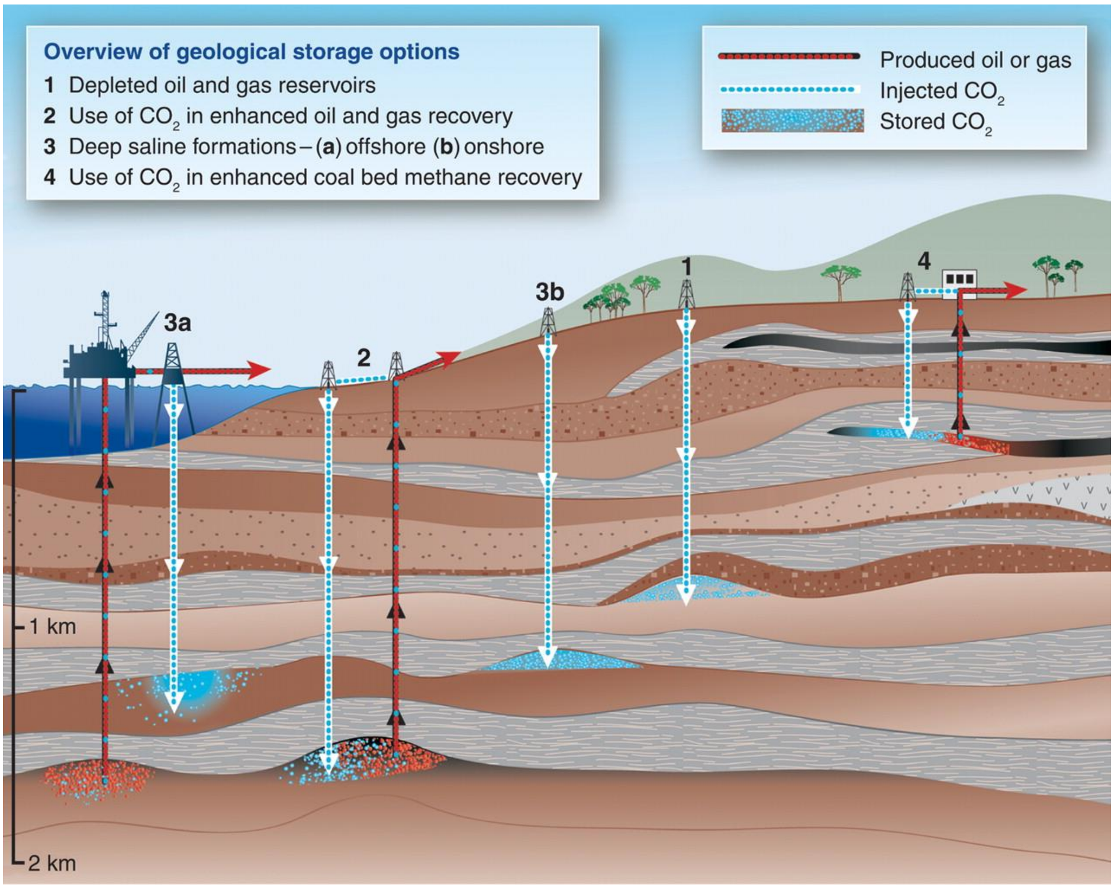


Figure 11 :Storage Options of CO_2 captured [139]

3.5.1.1.1. Oil displacement in reservoirs

Carbon dioxide is a good solvent for organic compounds because it reduces oil viscosity and the interfacial tension (capillary pressure) [78]. Its ability to increase oil mobility and remove up to 40% of the residual oil left in an active reservoir after primary production and water flooding has led to its usage in more than 70 tertiary enhanced oil recovery (EOR) operations globally [79]. The method was created and extensively implemented in established sedimentary basins prior to the issue of climate change. Sequestration and usage of CO_2 are combined in EOR processes. Only light crude oil (25° API or higher) can be used for EOR applications since only miscible displacement is feasible. Much of the CO_2 will remain stored in the reservoir, but a significant part ultimately breaks through at the producing well, together with the recovered oil and has to be re-circulated back in the system. As a result, the residence time is relatively small (of the order of months to several years) [80].

3.5.1.1.2. Storage in depleted hydrocarbon reservoirs

Over geological time, hydrocarbon reservoirs in structural and stratigraphic traps have shown good sealing and storing qualities, making them suitable for the sequestration of CO_2. The retention of hydrocarbons in the first place, whether structural, stratigraphic, or lithologic, should guarantee that CO_2 does not rise to the surface. Storage of CO_2 in depleted hydrocarbon reservoirs is a simpler and less expensive option than other forms of CO_2 sequestration because of the proven trap, known reservoir features, and existing infrastructure. Closed depleted gas reservoirs are the easiest to deal with since CO_2 may be utilized to restore the reservoir's pressure to its initial level and primary recovery often takes up to 95% of the original gas present [80].

3.5.1.1.3. Storage in deep aquifers

Water fills the pores and fractures in the crust of the Earth. Fossilized, highly salinized connate water from deep aquifers is unfit for human consumption or use in industry or agriculture. These aquifers are already utilized for injecting liquid waste, both hazardous and nonhazardous [80]. The high pressures encountered in deep aquifers indicate that they can withstand CO_2 injection. Some of the injected CO_2 (up to 29%) will dissolve in the water and the rest will form a plume that will over-ride at the top of the aquifer [81]. In sedimentary basins, deep aquifers are the most accessible and likely the second biggest naturally existent potential CO_2 storage. Furthermore, unlike ocean dumping, which is limited to areas close to the ocean, CO_2 sequestration in aquifers is a feasible option for all major CO_2 sources because these aquifers are present in landlocked, onshore, and offshore regions. As with sequestration in depleted hydrocarbon reservoirs and use in EOR and EGR operations, the technology is well established and reasonably simple and affordable to implement. Therefore, in terms of volume, length, economics, and little to no environmental impact, deep saline aquifers have by far the greatest potential for sequestering CO_2 in geological medium [80].

3.5.1.1.4. Displacement of methane and sequestration in coal beds

Carbon dioxide has a high affinity with coal, about twice that of methane, a gas abundantly found in coal beds. Injecting CO_2 into coal beds that are too deep or uneconomic for coal mining presents a twofold advantage [82]. The first step involves the adsorption of CO_2 onto the coal matrix. Second, methane is created. While methane is also a greenhouse gas, it is a far cleaner fuel that may be used in place of coal, thus lowering CO_2 emissions. The San Juan basin already uses carbon dioxide injection into coal beds to improve methane recovery, often known as enhanced gas recovery, or EGR. This works by boosting pressure drive and reducing the quantity of produced water that needs to be disposed of by injection back into deep formation [80]. The bulk of coalbed methane resources occurs in China, Russia, India, central and eastern Europe, Australia, USA and Canada, all countries basically with large coal deposits [85]. Unfortunately, the majority of coal seams, particularly those in China and Western Europe, have very low permeability due to their complicated geological setting [83 ,84].

3.5.2. Utilization of Captured CO_2

The utilization of CO_2 after a capture process involves repurposing captured carbon dioxide emissions for various beneficial applications across different industries. This approach aims to convert CO_2 from a waste product into a valuable resource, thereby reducing its environmental impact. One important use of CO_2 is the chemical synthesis. Specifically, it can be used as a raw material in chemical processes. It is utilized in the synthesis of various chemicals like methanol, formic acid or urea. These chemicals have a range of applications in industry, agriculture, and manufacturing [86]. Captured CO_2 is used as a feedstock in some inventive methods to make polymers and plastics. This lessens the need for fossil fuels as a source of raw materials for these goods. Furthermore, in agriculture, captured CO_2 can be used in greenhouses to enhance plant growth. Controlled release of CO_2 can promote photosynthesis and improve crop yield. One more important use of CO_2 is that it can be incorporated into building materials, like concrete, to reduce their carbon footprint. Carbonation of concrete involves a chemical reaction with CO_2, effectively sequestering the gas in the structure.[87]

The utilization of CO_2 after capture offers a dual advantage – it helps in reducing emissions by repurposing CO_2 and potentially offsets the costs of capture technologies by creating value from captured emissions. This approach not only contributes to reducing the carbon footprint across various industries but also encourages innovation in sustainable practices. However, the efficiency and scalability of these applications often depend on [88].

3.6. Land- Based projects of Carbon Capture Systems

As the pursuit of sustainable energy intensifies, post-combustion carbon capture systems have emerged as pivotal players in mitigating emissions from various land-based sources. These innovative systems, employed across diverse industries, aim to capture carbon dioxide after the combustion of fossil fuels, preventing its release into the atmosphere. Land-based applications of post-combustion carbon capture technologies are gaining prominence, demonstrating their effectiveness in curbing emissions from power plants, industrial facilities, and other sources. These systems often utilize advanced solvents or absorbents to selectively capture CO_2, offering a versatile approach to reduce greenhouse gas emissions. Despite their promise, challenges such as energy requirements, cost considerations, and infrastructure development persist. Nevertheless, ongoing land-based case studies employing post-combustion carbon capture systems underscore a commitment to exploring viable solutions that bridge industrial operations with environmental stewardship. According to the literature there are many different land-based projects of Carbon Capture Systems. In this thesis, 12 different study cases are considering, which provide important information about the dimensions of PCC units and the energy demand which is necessary for the process.

Table 5: Technology, Captured rate and Energy Demand for the Land Based Carbon Capture Cases.

Case no	Technology	Captured CO_2 (%)	Energy demand (kWh/kgCO_2 captured)	Source
1	Amine	95.2	0.778	[90]
2	Aqueous Ammonia	85	0.811	[91]
3	Amine	90	1.1	[92]
4	Amine	90	1.19	[93]
5	Amine	90	1.42	[94]
6	Amine	90	1.33	[95]
7	Aqueous Ammonia	90	0.777	[96]
8	Aqueous Ammonia	95	0.71	[97]
9	Amine	90	0.983	[98]
10	Amine	90	1.01 - 1.027	[99]
11	Amine	90	1.044	[100]
12	Amine	90	1.041	[101]
13	Amine	90	1.042-1.269	[102]

3.7. The supply chain problem

The ability of a supply chain infrastructure to permanently store the CO_2 that has been captured during the time horizon of interest can be recognized as its functionality. This infrastructure is defined as the collection of resources and systems that make up the network of CO_2 emitters, transport and storage. Consequently, in order to store CO_2 that has been caught, a resilient supply chain must be able to withstand disruptions and continue operating, or in the event that it does, resume operation as soon as feasible.[89]

It is important to focus on a resilient supply chain model of carbon capture system for various reasons. First of all, in case the infrastructure fails to operate properly it may cause many problems to the climate. Hazardous gases, such as CO_2 would release in the atmosphere creating serious damages to the environment and to human health. From an economic standpoint, if the CO_2 fails to arrive to the permanent storage location, there will either be a tax due for the emissions generated or a credit will be missed if the stored CO_2 helps to produce negative CO_2 emissions. Furthermore, based on existing legal and liability agreements, it is likely that the CO_2 emitter would have to cover additional costs to, for instance, the CO_2 transport or storage providers. Furthermore, because of its high density relative to air, releasing CO_2 should be avoided to prevent safety issues, even though statistics show that the risks are lower than those of releasing natural gas or other hazardous substances [89].

The disruption of supply chain to the nominal operation could stem from a failure in capturing the CO_2 at the emissions sites, from an interrupted connection between the capture site and the storage site, from delays in transporting the CO_2, or from an interruption in the operation of the storage facilities. The relevant failure mechanisms for CO_2 transport are similar to those found in natural gas pipelines, particularly at CO_2 pipelines. To be more precise, natural gas and CO_2 pipelines are both made of carbon steel, are installed with comparable tools and techniques, and are both susceptible to internal corrosion damage and possible excavation-related problems [89].

Finding a sustainable supply chain configuration with the lowest possible total annual cost and the least amount of environmental impact over the planning horizon is the goal. To succeed this goal, it is important to locate the capture plants close to emission sources to avoid the transportation of flue gas. Furthermore, an emission source node can be linked to only one storage, utilization node, but a storage/utilization node can receive CO_2 from multiple source nodes.

Generally, there are three different types of supply chains. The net-zero, net-positive and the net negative. Supply chains are also known as value chains which consists of three main elements:

- ✓ Capture of CO_2.
- ✓ Transportation.
- ✓ Storage/Utilization.

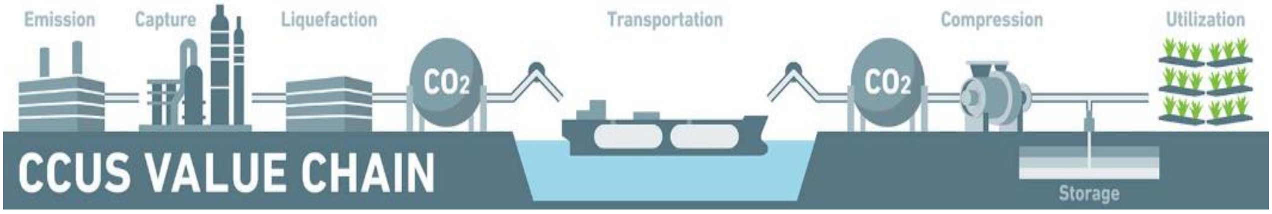


Figure 12: Schematic presentation of CCUS value chain [140].

3.7.1. The net-zero supply chain

In order to achieve a net-zero balance in terms of CO_2 emissions, net-zero value chains in CCUS seek to guarantee that the total amount of CO_2 emitted by various processes is offset by an equivalent amount that is captured and either utilized or stored.

As net-zero supply chain can be assumed the CCS with a fossil carbon source, if renewable/emission-free energy is used to drive the process. In this chain, the CO_2 extracted from and stored in a reservoir. There will be some emissions associated with such a value chain, and in order to assess the overall greenhouse gas performance of various value chains, it is also necessary to take into consideration greenhouse gas emissions resulting from the capture, transportation, and storage of CO_2 [27].

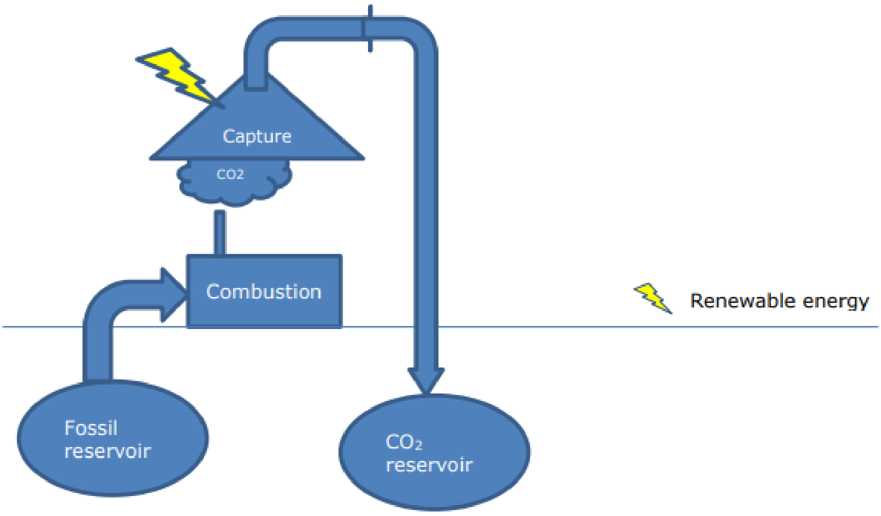


Figure 13: Net Zero supply chain.

A CCU with direct air capture (DAC) is also a net-zero supply chain. Specifically, the same amount of CO_2 is drawn from the atmosphere and released when a chemical product, like electrofuel, burns. This is comparable to using biomass as a source of carbon, in which the biomass absorbs and releases carbon. Once again, the emissions of greenhouse gases resulting from capture, conversion, and transportation determine the real GHG performance for this value chain [27].

3.7.2. The net-positive supply chain

A net-positive value chain for CCUS strives to go beyond mere emissions reduction by actively seeking ways to utilize captured carbon, thereby potentially creating a positive impact on both the environment and the economy. It not only mitigates the effects of carbon emissions but also explores opportunities to turn them into valuable resources, contributing to a more sustainable and economically viable future.

Comparing the net-positive and net-zero chain, if the CCU does not apply DAC and instead uses carbon from a fossil fuel source to capture and utilize the CO_2 , liberating more CO_2 to the atmosphere , then the loop can be characterized as net-positive. Even though more CO_2 is added to the atmosphere, a net-positive chain can lead to an overall CO_2 reduction equal to 50% compared to system which does not use a capture system [27].

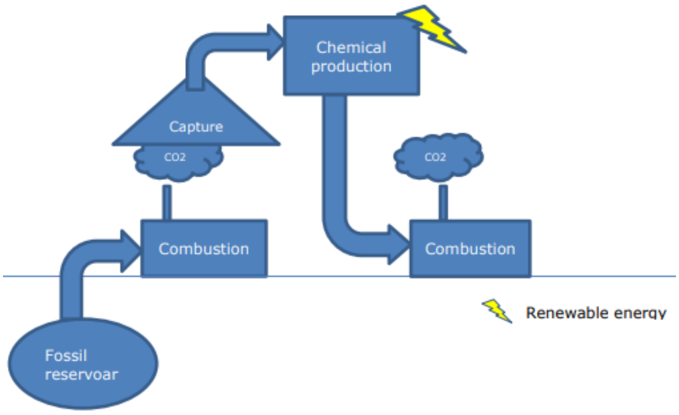


Figure 14: Net Positive Supply Chain [27].

3.7.3. The net-negative supply chain

In the case where the carbon is captured from DAC and stored , a net-negative chain can be obtained. The overarching goal of a net-negative supply chain for CCUS is not just to mitigate carbon emissions but to actively remove more carbon dioxide from the atmosphere than is generated throughout the entire lifecycle of a product or process. This involves a combination of technological innovation, strategic deployment, and holistic approaches across industries to achieve a net-negative impact on carbon emissions.

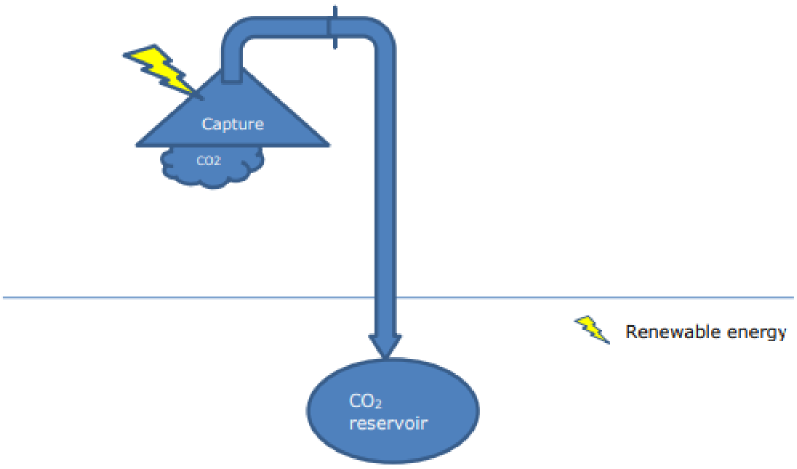


Figure 15: Net-negative Supply Chain.

A specific example of net-negative supply chain is the bioenergy with carbon capture where some or all the CO_2 emissions released to the atmosphere during the combustion of sustainable biofuel are captured and permanently stored [27].

A goal of net-negative supply chain is estimated to be achieved by between 2040 and 2060. On the route to a global energy system with net-zero emissions, CCUS will need to play a significant role in addition to hydrogen, electrification, sustainable bioenergy, and other technologies. As the only group of technologies that can directly reduce emissions as well as remove CO_2 to balance emissions that cannot be avoided, CCUS is essential to achieving net zero [27].

3.8. Review of land-based projects

3.8.1. Case study number 1

This study which takes place in Mexico is focusing on a post-combustion CO_2 capture system of flue gas from ammonia plant. The post- combustion carbon capture technology applied to the flue gas using a 30% wt MEA solvent solution with chemical absorption into the ammonia plant. The flue gas is a natural gas and it first cooled through a water scrubber before entering the absorber, where the CO_2 removed by chemical reaction with CO_2-depleted lean amine solution.[90] The CO_2-loaded rich amine solution from the absorber bottom is routed to a regenerator where the CO_2 is removed from the amine by stripping steam generated in a reboiler heated and condensing low pressure (LP) steam extracted from the ammonia plant. According to this study, using a MEA as solvent solution, 2.85MJ per ton of CO_2 captured are required.[90]

It is estimated that the flue gas in the PCC is equal to 346,55 kg/h and the CO_2 flow 44,388kg/h, while the capture rate is equal to 95.8%. For the electricity requirement, it is estimated that the 3 stage compressors demand 39561 kWh. Finally, for all the process of CO_2 capture, an absorber of 36m high/6.5 diameter and a stripper of 25m high/3.5m is required.

3.8.2. Case study number 2

For this study, 4 cases have been examined for the post-combustion capture process, using different solvent solutions. Since in Marine Studies the main solvents which are used are the aqueous ammonia and the MEA, for this land-based scenario, only the one case is being taken into account. Specifically, a pulverized coal power plant with aqueous ammonia post combustion carbon capture system is used for this purpose [91].

The fuel type for the process is coal and the solution solvent is aqueous ammonia. The process starts with the coal to be fed into the reboiler. Hot flue gases are formed from the coal combustion in the combustion process. These gases are used to pre-heat the air streams and to generate steam which is furthermore expanded in the steam turbine for power generation. A SCR unit is necessary to remove NO_x emissions using ammonia. The steam from hot flue gases which are formed into the reboiler will be used in the absorption process which is taking place after the SCR unit. The amine regeneration, following carbon dioxide capture and stripping is the thermally performed using heat and for the final part of the process, which is the liquefaction and storage of CO_2, it is estimated that the captured CO_2 need to be dehydrated and then compressed to 120 bar [91].

According to calculations and the data analysis of this study, the total electric power which is need in order to transport and storage the captured CO_2 is 37.3639 kW, while the heat demand in order to capture the 85% of CO_2 from the gases (with a flow rate of 316.05 t/h) is $0.8111 kWh/kg_{CO2\ captured}$ [91].

3.8.3. Case study number 3

In this case a CO_2 capture process with the use of MEA as chemical absorbent has been examined. The capture system which is used has been described extensively in literature previously. Specifically, into the absorber the MEA is used to absorb the CO_2 from flue gas, creating a rich-solvent solution. The solvent with the CO_2, after, passes through the stripper where stripping of the heat is performed by the addition of heat [92].

The use of pumps in the system provides the transportation of the solvent through the various parts of the CO_2 capture unit, while fans are installed to overcome the pressure drop encountered in the absorber [92].

After the process of capturing, the CO_2 needs to be compressed and dehydrated to 11MPa in order to be transported. According to literature, in this case, the CO2 flow need to pass through four compression stages with total amount of power equal to 40MW. At the final part of the process is the transportation of captured CO_2, which is achieved using pipelines of 95cm diameter, 10mm of thickness and 50km length [92].

The data analysis of this study shows that a heat demand of $1.1 kWh/kg_{CO2\ captured}$ and electricity demand of $0.0236kWh/kg_{CO2captured}$ is required for the energy operation of the carbon capture system [92].

3.8.4. Case study number 4

The main goal of this study was to evaluate the environmental impact of producing electricity and simultaneously capturing CO_2 by CaO looping in a sub-critical power plant. The environmental impact of electricity production with CO_2 capture by CaO looping was compared to three other cases, namely (i) producing electricity with no CO_2 capture, and (ii)–(iii) producing electricity with CO_2 capture by two MEA-based technologies However , because the CaO looping is not applied in Maritime Studies , the only data which is going to be taken into account is the MEA-based technology[93].

Specifically, the capture process follows the main method aw it has been described in previous studies. The gas in this land-based case it is used a coal and as solvent a conventional amine (MEA). According to data of this study, a flow case of coal is assumed to be equal to 200.4 t/h, while the heat requirement for the capture of CO_2 is calculated 1.19kWh/$kg_{CO2captured}$. Finally, the total amount of power which is used for the capture process is assumed 73.8 MW [93].

3.8.5. Case study number 5

This study develops an analysis of a chemical absorption method using amine solvent for post-combustion CO_2 capture. The flue gas of power plant is assumed 580kg/s and the capture rate 90% [94].

The process follows the main steps of a chemical absorption technology as it has already been mentioned. Specifically, the flue gas enters the bottom of absorber while the lean solvent enters from the top of the column. The operation conditions of the absorber are assumed to be 1 bar pressure and 40°C. After the absorber, the rich solution continues to a pump in order to increase the pressure of solvent for the stripper's duties. Stripper column has an operating pressure condition equal to 1.6 bar, while the usual pressure is assumed around to 1-86-2.1 bar. This pressure drop has consequently the increase of reboiler duty, which is the next unit for the process after the stripper column. At the reboiler, the steam enters in a temperature of 130°C and the heat duty is calculated equal to 1.42 kWh/$kg_{CO2capture}$, while in literature is assumed around to 1-1.1 kWh/$kg_{CO2captured}$ [94].

The pure steam of CO_2, now, needs to be dried and compressed before being sent to storage. 4 stages of compression with cooling in between the stages is used to compress the CO_2 to a supercritical liquid at 152,7 bar [94].

3.8.6. Case study number 6

This study provides a framework for comparison of the probabilistic performance of a coal-fired power plant (CFPP) in CO_2 capture retrofit scenarios. Main target of this study is to provide valuable information on the equipment operating envelope that would help designers assessing the number of equipment trains and their operating limits [95].

According to the data, this study uses as fuel Coal and the solvent solution for the capture of the CO_2 is amine. The heat required for the capture process is estimated 469300 kW, the amount of the captured CO_2 is 351540 kg/h. and the capture level is 90%. The heat demand in a CO_2 captured parameter is estimated 1.33 kWh/$kg_{CO2cpatrured}$. The absorber works in a temperature of 40°C and a pressure of 1 bar, while the stripper's temperature and pressure are estimated at 122.4 °C and 1.7 bar respectively. The heat demand is much higher than the typical one according to the literature, such as in case 5, because of the stripper's pressure which is lower than this of the literature.

3.8.7. Case study number 7

The current work develops and investigates a low energy CO_2 capture method using aqueous ammonia. The main problems with the current process configurations are addressed by this innovative substitute. At the cost of adding a solid handling section that includes a saturation reactor, a crystallizer, and a filter, the overall energy penalty is decreased. The current configuration, in contrast to the conventional solvent-based CO_2 capture, is focused on the thermal breakdown of a solid [96].

This research offers a novel design for the ammonia-based CO_2 capture process that simultaneously reduces the specific energy needed and addresses the problem of absorber clogging. The process configuration's innovation is based on a redesigned solid handling section and solvent regeneration unit. The goal is to enable integration to low- and mid-temperature waste heat by lowering the operating temperature. The following provides specifics on the key components of the CO_2 capture procedure.[96]

The capture level of this process is estimated 90%, while the CO_2 captured is calculated 85931.82 kWh/$kg_{CO2captured}$. According to data analysis of the study, the heat required for the capture process equals to 0.777kWh/$kg_{CO2captured}$. The system uses two absorbers. The first one is operated above 20°C and the second one above 10°C. Finally, the temperature of the reboiler is 140-150°C.

3.8.8. Case study number 8

The target of this study is to evaluate the net CO_2 reduction performance of a modeled ammonia-based CCS system and to identify principal processed with high CO_2 emissions. Specifically, a life cycle assessment (Life cycle assessment (LCA) is an established method that takes into account the long-term environmental implication of products and services) was performed to quantify direct and indirect CO2 emissions associated with the life cycle and supply chain of the processes consisting of the CCS system based on operating data from a pilot scale ammonia-based CO_2 capture system [97].

The data which are selected for the analysis of this case are those of the pilot scale ammonia-based CO_2 capture system. For the calculation of the heat energy requirement, according to this study, it is used the following equation:

$$E = G * c * \Delta T * (1 + (1 - \eta_R)$$

Where:

- E: Heat energy requirement (kcal/h)
- G: the mass rate in the bottom of the tower(kg/h)
- c: Specific heat of the absorbent (kcal/kg °C)
- η_R: The efficiency of the reboiler

According to data of the study and the previous equation, the heat requirement for this process is 0.71 kWh/$kg_{CO2captured}$. Furthermore, the capture rate in this process is 90% while the quantity of captured CO_2 is 526148 kg/h. The captured CO_2 is transported via a pipe of 100km length and inner diameter of 0.355m. In order to transport the CO_2 captured safely, it is compressed to make it supercritical fluid at 80 bar and at 50°C. The electricity demand for the transport and storage of CO_2 is estimated 1.99kWh/$kg_{CO2\ captured.}$ [97].

3.8.9. Case study number 9

This study is intended to demonstrate the trade-offs and benefits of current solar-assisted CCS technologies and identify the target sites for technical development in China's sustainable power industry, which then can be used for future planning of technical and political strategies [98].

It uses different scenarios of solar-assisted CCS technologies, as well as a classic performance of a post combustion system using amine as a solvent solution for the capture of CO_2. The data which is selected is based on the classic performance of amine process.

According to this study, the fuel of the combustion is Coal and the capture rate of the process is 90%. The captured CO_2 is estimated to 171233 kg/h, the heat required for the captured, using MEA as solvent is equal to 0.983 kWh/$kg_{CO2captured}$ and the total electric energy of the system is calculated up to 28090 Kw (Compression and capture unit auxiliary equipment) [98].

3.8.10. Case study number 10

This study focuses on a specific instance of a natural gas combined cycle (NGCC) power plant that uses aqueous monoethanolamine (MEA) as a solvent in a post-combustion CO_2 capture plant. NGCCs are preferred due to their high efficiency and low capital costs [99].

The power of NGCC plant is estimated 650MW and in this study five different loads have been tested and their data are used in this thesis. First of all, the system uses two stripper and two absorber columns for the process. Both absorber and stripper have the same height of 20m. The diameter has been determined 15m for the absorber and 9 for the stripper. Furthermore, the absorber operates in

35°C and at a pressure of 1.016 bar, while stripper's pressure is determined 1.72bar and the temperature is the same as this of the absorber.

On the following table 6 is presented the overall data collection of this study.

Table 6: Data of CO_2 capture process in different Load of M/E for case number 10 [99].

Description/Load	100	90	80	70	60
Flue gas flow rate (t/hr)	3706.82	3481.8	3313.52	3021.3	2783.88
CO_2 capture rate (%)	90	90	90	90	90
CO_2 in flue gas (t/hr)	144.751321	135.650928	128.564576	116.501328	106.3998936
CO_2 captured (t/hr)	206.34	193.2	182.7	165.6	151.26
Heat duty (kWh/$kg_{CO2\ captured}$)	1.01	1.013	1.016	1.027	1.027
Electricity duty (kWh/$kg_{CO2\ captured}$	0.077057284	0.079192547	0.079365079	0.085144928	0.087928071

3.8.11. Case study number 11

This study seeks to determine the capture level design of a Natural Gas Combined Cycle (NGCC) with CO_2 capture according to significant factors, including the cost of CO_2 avoided, the electricity output penalty, the size of the absorber and stripper, the two EGR configurations and sequential gas turbine combustion which has not been previously studied or discussed in the literature [100].

Three different case studies are presented in this paper. However, for the data analysis, only the first case of NGCC was used. Specifically, this study is an amine solution technology of carbon capture with a gas flow rate of 4127796 kg/h, capture level up to 90% and CO_2 captured quantity equal to 258840 kg/h. According to data the heat which is required for the capture of CO_2 using MEA as solvent is estimated 1.044 kWh/$kg_{CO2captured}$.

3.8.12. Case study number 12

In this study is examined the importance of natural gas-fired Combined Cycle and Open Cycle Gas Turbine (CCGT and OCGT) for power generation. Three different cases are compared to a reference study in order to estimate the efficiency of CCGT to the Post Combustion Carbon Systems. The data which are used in this thesis are based on the reference case of this study [101].

As fuel it is used Coal with a gas flow rate 2368800kg/h. The exhaust gas enters the absorber, which operated in the temperature of 45°C. The carbon capture system uses a convention chemical absorption plant with monoethanolamine (MEA). The rich solution after the absorber, continues to stripper column at 40°C and 1.84 bar and finally compressed to 110 bar in order to be transported to store in supercritical phase. The capture rate is estimated up to 90% and the amount of CO_2 captured 275400 kg/h [101].

According to the data, the heat required for the capture of CO_2 is estimated 1.041 kWh/$kg_{CO2captured}$. The stripper and absorber column have the same dimensions. Specifically, the diameter of these columns is estimated 12 m and the height 19m [101].

3.8.13. Case study number 13

This study focuses on the integration of the steam jet booster application in a natural gas combined cycle with CO_2 capture at low part-load operation. For the functionality of the jet booster, the data of a classic natural gas combined cycle (NGCC) power plant that uses aqueous monoethanolamine (MEA) as a solvent in a post-combustion CO_2 capture plant in order to compare the energy demand, costs and the efficiency. Furthermore, different loads of NGCC are used in this study [102].

According to this case, the stripper temperature varies from 108.3°C to 120°C and the pressure from 1.3bar to 1.87bar. The capture rate level is estimated in all loads the same, 90%. For the storage and transportation of captured CO_2 is needed 7 stages of compression with intercooling into to 40°C. Finally, the size of all packed columns for the process is fixed in the model to reflect operation at off-design conditions [102].

On the following table 7 is presented all the necessary data which are used for the analysis in this thesis.

Table 7: Data for CO_2 captured process for case number 13[102].

Description/ Load	Flue gas rate (kg/h)	CO2 captured (kg/h)	Capture level (%)	Stripper pressure bar	Stripper temperature °C	Heat duty (kWh/kgCO2 captured)
100	2384280	126540	90	1.87	120	1.04166375
80	2070000	109152	90	1.87	119.2	1.06110814
70.5	1910160	100980	90	1.77	117.4	1.07777476
51.5	1616400	82368	90	1.57	113.3	1.16110786
42.3	1478160	72072	90	1.3	108.3	1.269444409

4. Maritime Carbon Capture Systems

4.1. The Maritime Application

A variety of technologies are used in onboard carbon capture (OCC) to collect carbon dioxide emissions from ships while they are in operation. Depending on the technology, OCC for post-combustion systems entails cleaning exhaust gases from CO_2, separating it, and storing it aboard for potential offloading in a variety of forms (gas, liquid, or mineral) [103]. Carbon is extracted from the fuel prior to burning in order to make hydrogen, which is then used in specialized energy conversion equipment.

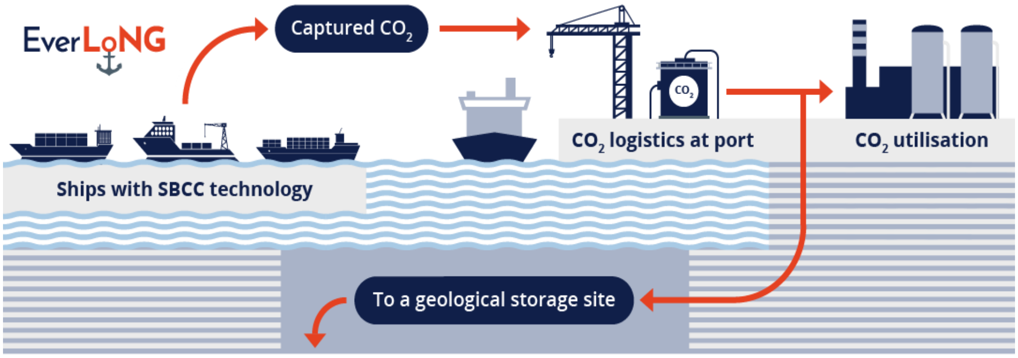


Figure 16: Maritime process of Carbon Capture Process, Utilization and storage.

There is growing interest in onboard carbon capture as a practical way to lower ship carbon emissions. Green energy carriers like ammonia, hydrogen, and methanol will face intense competition from other industries in addition to the maritime sector, making them pricey. Utilizing carbon capture on board can be a successful decarbonization strategy, enabling the continuous use of proven [103]. Systems for onboard carbon capture and treatment must be integrated with other systems, and CO_2 must be temporarily held before being offloaded to the proper infrastructure. This will have an impact on the ships' layout and design [103].

Some important key services which are associated with the onboard carbon capture are the following:

(1) **Feasibility support:** Assessment of the viability and possible advantages of adding a carbon capture system to a certain vessel or vessel design.
(2) **Technology qualification**: Development of an organized procedure for evaluating new technology's applicability for a particular use.
(3) **Techno-economical studies:** Evaluating and contrasting various systems and designs while taking operating and investment costs into account.
(4) **Classification**: Verification and certification of final design ready for construction.

Because carbon capture methods reduce the quantity of CO_2 emitted into the atmosphere, they may have a positive environmental impact in maritime applications. Ships are a major source of greenhouse gas emissions, especially large cargo ships. In these maritime environments, utilizing carbon capture and storage (CCS) or utilization (CCU) technology can assist reduce these emissions [104]. Even though OCC could reduce a big amount of GHG from ship's emissions to the atmosphere, there is some environmental effects which should take into serious consideration:

(1) **Chemical Solvents**: Chemical solvents are used by carbon capture systems to absorb CO_2. If these solvents are not produced, used, and disposed of properly, there may be environmental consequences. In the case that these chemicals were to leak or be discharged, there might be worries about how they would affect the environment. [107]

(2) **Energy Consumption:** Energy is needed for many carbon capture systems to function. If a non-clean or renewable energy source is utilized, this could result in higher energy consumption and possibly even higher emissions. [105]

(3) **Storage and transportation:** If captured carbon storage and transportation are not handled properly, there may be hazards. Leakage during transit or from storage locations may have detrimental effects on the environment. [106]

(4) By-products: Certain carbon capture techniques can generate byproducts that require cautious handling to avoid damaging the environment. For example, the environmental impact of converting the captured CO_2 into a different form for storage or utilization must be taken into account.

4.2. Commercial Systems Review

4.2.1. Units of Carbon Capture system on Ship

According to studies conducted for the implementation of carbon capture systems on board, engine room is the main spot of the CCS [27]. The following figure shows a typical CCS system on board.

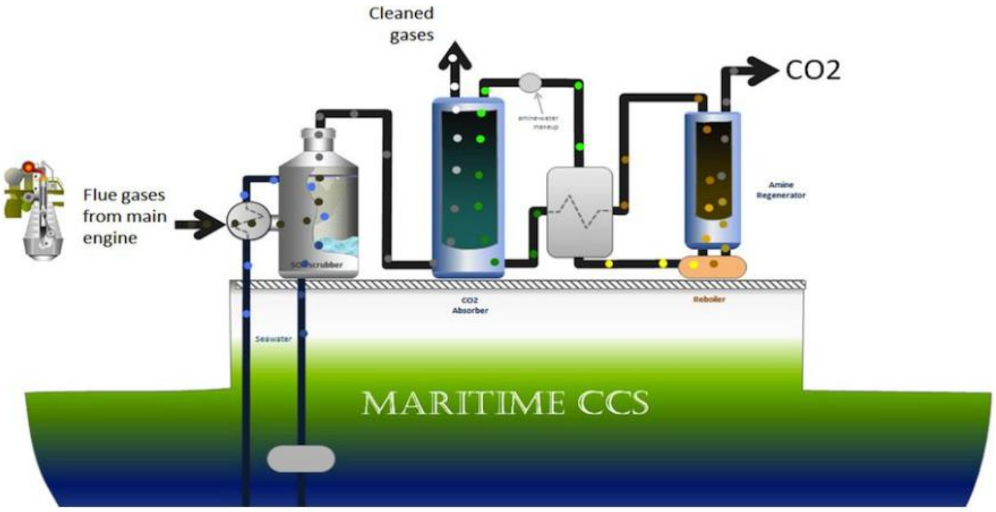


Figure 17:Maritime CCS units [141].

Absorber

Absorber uses countercurrent flow through a trayed or packed tower to provide intimate contact between the lean amine solvent and the sour gas so that the CO_2 molecules can transfer from the gas phase to the solvent-liquid phase [108]. The absorber's ability to operate effectively depends critically on the temperature of the amine solution that enters it. A small amount of gas condensate may form in the amine solution and cause the amine to foam if the amine intake temperature is lower than the sour gas inlet temperature.

The quantity of trays or the height of packing that can be placed inside an amine absorber determines how much sweetening can be achieved. Usually, the absorber is designed with 20 float-valve trays (or, for smaller vessels, an equivalent amount of packing). There should be enough tray separation to allow liquid foam to disengage. Generally, an outlet knockout drum is supplied to collect solvent carryover, and a mist eliminator pad is positioned close to the absorber's gas outlet (the distance between the top tray and the mist pad is 3-5 feet) to catch entrained solvent. The contactor design and the estimated probability of entrainment or foaming determine this need. If foaming is anticipated, it would be suitable to use a water spray to break up the foam [108].

Some absorbers, which are frequently found in low-pressure monoethanolamine systems, feature a water wash at the top that consists of two to five trays to reduce amine vaporization losses. In order to facilitate the slipping of an acid gas, usually CO_2, selective solvents frequently feature several supply sites on the absorber. All of the lean amines should be fed on the top tray, utilizing all available stages, if carbon dioxide absorption is needed [108].

Stripper

The amine stripper (regenerator) is usually a trayed tower (with approximately 20 trays), although packed towers are occasionally used [108]. To minimize amine vaporization loss, there may be a water wash section at the top of the column with an additional 4 to 6 trays [109]. Trays are normally on 24-inch spacing, and liquid and jet floods in the 65%–75% range with a 75% foam factor. It is highly recommended that trays be stainless steel due to the corrosivity of the environment.[108]. The pressure at the bottom of the column is a crucial parameter for the amine stripper. Choosing a high pressure would cause the bottom of the column to become hotter, which would cause amine degradation. In practical situations, it is generally recommended to operate amine regenerators at approximately 2.1–2.2 bar[109].

Reboiler

An amine stripper, which reverses the chemical processes and removes the acid gasses, receives heat input from an amine reboiler. Although there are other options, steam is typically employed as the heat medium. For each amine, the tube wall temperature must be maintained below a certain maximum. While keeping the reboiler duty as low as feasible, it is still necessary to ensure that the CO_2 loadings in the reboiler do not lead to undue corrosion and that the amine solution is sufficiently regenerated to meet the criteria for sweet gas. Increased reboiler duties only use energy and have no effect on circulation rates. Typically, heat flux rate should be kept in the 7,500–10,000 Btu/hr/ft2 range to assure no surface burning of the solvent.

Pumps

Pumps are used to transport the solvent through the various parts of the CO_2 capture unit [91]. Centrifugal, inline, or horizontal pumps are typically used for the boosting and reflux of amines. The contactor operating pressure and the amine circulation rate determine which circulation pump should be used. Consideration should be given to positive displacement pumps for discharge pressures above 250 gpm. Both large-volume, high-head cases and low-head cases are evaluated for centrifugal.

When treating a unit, the solvent circulation rate should always be lowered to the absolute lowest necessary, considering any limitations like the rich amine's maximum loading. Lower circulation rates decrease the overall energy requirements because the reboiler duty is nearly usually directly related to the circulation rate. Reduced circulation rates can also enhance the quality of the feed to the sulfur recovery unit and tend to increase CO_2 slip [110].

<u>Heat Exchanger/ Lean-Rich Amine Exchanger</u>

The heat exchanger is a heat conservation device used to decrease energy consumption [108]**.** It lowers the reboiler's duty while warming the rich amine solution. Additionally, it lowers the aerial cooler's duty and cools the lean amine. Standard options for exchangers include shell-and-tube and plate-frame designs. To reduce corrosion, the rich solution is pumped through the tubes—which are typically composed of stainless steel—at a slow entrance velocity (2–3.5 feet per second). To optimize heat recovery, the rich outlet's temperature should be around 200°F with a lean of 160°F [108]. The hot side pressure drop should be maintained at or below 2 psig, while the cold side pressure drop should be maintained at 5 psig or less, depending on whether booster pumps are included in the design. To prevent particles from entering the exchanger, strainers on both sides of the exchanger should be taken into account.

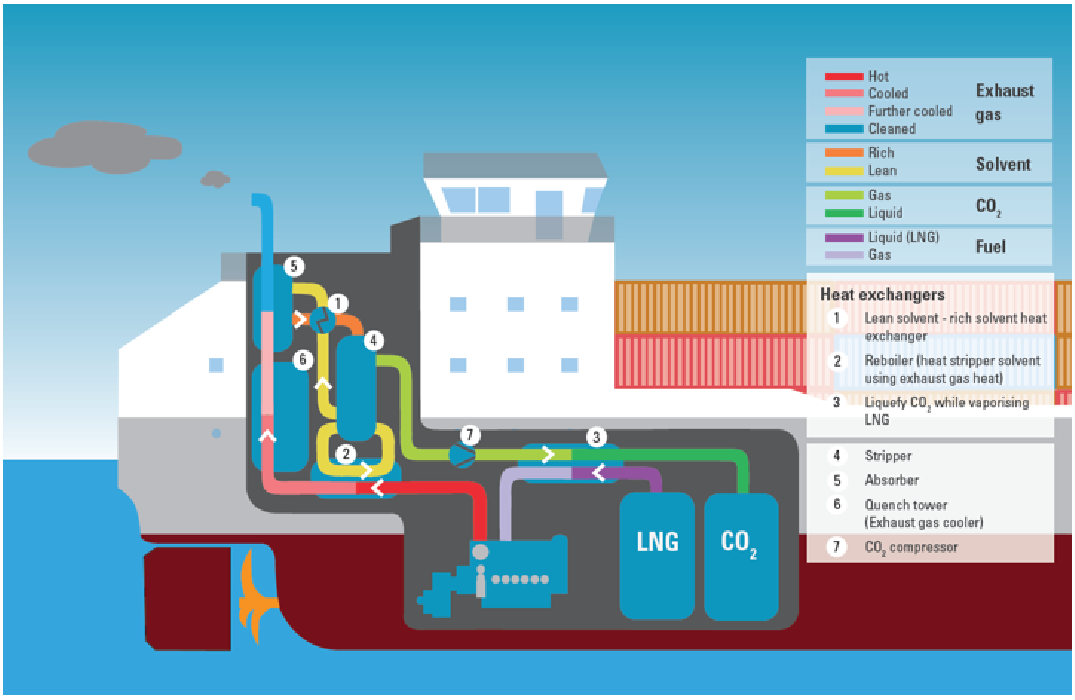


Figure 18: Carbon Capture Loop on board [143]

4.2.2. Storage of CO_2 on ship

Depending on the capture technology, the by-product stream that carries the captured CO_2 may be at different forms.

- ✓ Solid, if CO_2 is adsorbed in a solid material.
- ✓ Gas, if CO_2 is compressed and stored onboard -this solution may be economically attractive for cases of small capture volume or small distance trade routes.
- ✓ Liquid, if CO_2 is stored in cryogenic form. This is a typical transport condition where the pressure is kept with sufficient margin to the triple point to avoid risk of dry ice formation.

The storage of LNG or LPG on board a ship is comparable to the storage of CO_2 on board. Depending on the size of the ship, LPG is stored in a pressurized or cryogenic form (only pressurized for small ships, and only cryogenic for large ships) [27]. As a result, the CO_2 can be stored and transported on the ship as a pressurized cryogenic liquid using similar technology as for LPG [112]. It is important to note that LNG and LPG can remain liquid at atmospheric pressure, but CO_2 requires pressure to remain liquid. This, together with the fact that CO_2 has a higher density than LNG and LPG, has a significant influence on how the tanks and supports are designed [27].

The optimal storage conditions are at 7 atm pressure and -50°C for large scale ship transport of CO_2 [111].

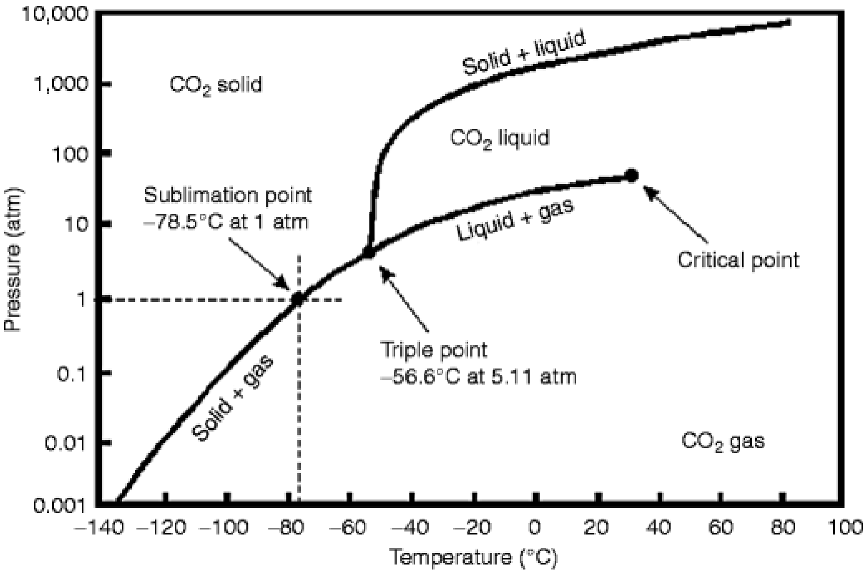


Figure 19: Pressure-Temperature phase diagram for CO_2.

According to fig. the optimal conditions storage are close to the triple point of condition of CO_2, in which the density is 1155 kg/m^3. In practice, a slightly higher storage pressure can be used to leave a safety margin [111]. This is also a balance between the costs of refrigeration energy and the costs of pressurization. Other studies show that a pressure of 15 bar and a temperature of -30°C are also potential practical conditions, giving a density of 1076 kg/m^3 [27].

Operations at the triple point are deemed hazardous because handling cargo may result in the development of dry ice. The tanks will be gradually filled during onboard capture. That is a dynamic phenomenon that is influenced by the insulation in the tank and the pressure-maintenance techniques.

Before storing the CO_2, it needs to convert into a storable state. Liquification is the most energy-efficient method for volumetrically storing CO_2 on board [111]. To succeed this goal, the captured CO_2 first compressed to required storage pressure and then refrigerated in or to be liquidated. Installing a refrigeration cycle, such as one based on ammonia, is necessary for ships that carry diesel or fuel oil. Boil-off gas in LNG carriers is processed via re-liquefaction, specialized subcooling, or burning in a specialized gas combustion unit (GCU). Cryogenic liquids, such nitrogen, whose boiling points are far lower than those of LNG, are used to accomplish the reliquefication. Re-liquefaction technologies are therefore currently available in the shipping industry and can be adjusted for the scenario of handling CO_2 on board [27].

4.2.3. Offloading and injection of CO_2

Following sea transport, carbon dioxide can be discharged either offshore before being sent to the ultimate storage location, or onshore at a port before being transferred by pipeline in port-to-port situations [104]. Offshore unloading is still unproven and presents some technical challenges for its implementation, whereas the former option, which covers port-to-port shipping, is well established due to the extensive experience matured in large-scale shipping of similar gases like LNG and LPG and currently applied in the food, beverage, and ammonia industries [113]. There is still no clear consensus on the best offloading approach, and related infrastructure selection will likely have a big impact on vessel design, process equipment, and costs [104].

There are auxiliary platforms that enable equipment installation or direct injection from the ship as part of the transfer systems to the wellhead [104]. The former method lowers the risk of cyclical temperature and pressure loading on casings and non-metallic materials by enabling one to generate a continuous flow into the reservoir, providing a temporary storage to counteract unfavorable weather conditions [114] . The drawback associated with these systems is the higher capital expenditure required for their implementation [115]. On the other hand, conditioning, pressurization, and heating of carbon dioxide must occur on board the ship to discharge to a flexible riser via a buoy for direct injection into the well. This can only be accomplished by pumping the stream to the proper pipeline pressure of 5–40 MPa and then heating it to 258–293 K, depending on the location, using ship waste heat or pre-warmed seawater [116]. Because the stream must have a certain temperature and pressure to prevent hydration, weather changes and consequently changes in seawater temperature could jeopardize the safety of operations [104]. It is discovered that, with the integration of compression and heating equipment on board, direct injection from the ship is feasible for many wells. Since offshore discharge is thought to be a novel technique in the CO_2 transportation chain, modern technology is needed to reduce the likelihood that dry ice would form during unloading and to reach an agreement on the best possible solution [117].

The injection of CO_2 is a challenging operation for different reasons. First of all, is really important to ensure the safety margin from the triple point during operations. One way to succeed this is to always avoid sudden stops in order to mitigate the risk of dry ice formation [113]. According to literature, ideal injection temperature is around to 288K to mitigate against formation of hydrates during operation [118]. It has been determined that direct injection from the carrier is feasible for a number of a large-scale injection wells, apart from shallow depleted reservoirs. Pre-injection conditioning can be accomplished through suitable ship installations, where the injection's heating source is supplied by saltwater or an excessive [119]. Re-offloading conditioning requires installing the proper heating and compression equipment on board the vessel since it involves heating the carbon dioxide to 273 K and compressing it to about 20–30 MPa. The ship's engines and the heat from the sea can produce the thermal and electrical energy needed to inject the stream [120]. In cases where big volumes are needed to be transferred by ships over long distances, using a seabed pipeline as a heat exchanger could be a more advantageous option [119]. Finally, the performance of offshore unloading is estimated to be from to 12 to 36 hours. In case of lack of temporary offshore storage increasing the injection time is increasing around to 30-50 hours [121].

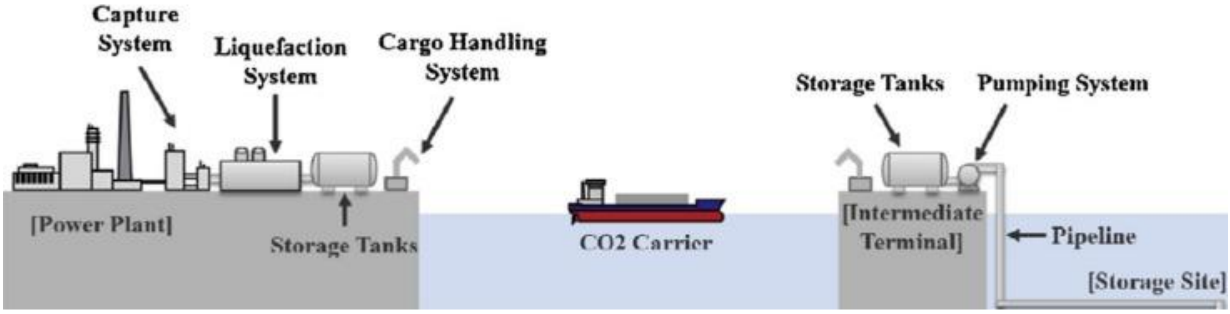


Figure 20: Offloading Schematic presentation [104].

4.3. Studies Review

Table 8: Maritime Case Studies Review.

Maritime Carbon Capture System studies							
Case no	Ship type	Technology	Captured CO$_2$	Energy Demand	CAPEX	OPEX	Source
1	Cargo ship with a 3000kW Wärtsilä 6L34DF dual fuel engine	Amine and Piperazine	90%	1.028 - 1.047 kWh/kg$_{\text{CO2 captured}}$ (Heat required per CO$_2$ captured) / 94.11-121.6 kW for Electric demand (Liquefaction-Compression-Storage)	4,477,521.00 €	100,104€ / year	[122]
2	LPG ship with a 8800 kW Wärtsilä 9L46DF , a 4-stroke dual-fuel engine	Aqueous Ammonia	90%	3.4Mwe Heat demand for CCS / 0.4 Mwe for Electric demand (liquefaction-Compression-Storage)	1,413,000$/year	43,000$/year	[123]
3	LNG ship	Amine	85%	4250 kW Heat demand for CCS/ 878.9255 kW for Electric Demand (Liquefaction-Compression-Storage)	12,300,000$-22,000,000$	2,700,000$-5,200,00$/year	[132]
4	Cargo Ship inland with a 1280 kW dual fuel Wärtsilä 8L20DF engine (use Diesel and LNG fuel)	Amine and Piperazine	60% and 90%	290kW to 520kW Heat demand for CCS/ 3kW to 18.1 kW for Electric Demand (Compression - Liquefaction-Storage)	1,000,000€ - 3,000,000€		[125]
5	Cargo ship with 2 four strokes’ engines Wärtsilä 9L46 of total 17000kW and 3 generators of 1000kW each one	Amine	73% and 90%	7800kW without gas turbine - 12210kW with gas turbine (Heat Demand for CCS) / 860kW without gas turbine - 1130kW with gas turbine (Electric Demand for Liquefaction-Compression - Storage)	35,000,000.00 €	1,140,000€/year	[129]
6	LPG ship with a 4 strokes 10200kW Wärtsilä 9L46 engines	Aqueous Ammonia and Amine	70%-75%	4000kW - 7300kW heat duty demand for CCS / 1000kW for Electric Demand (Liquefaction - compression - Storage)			[130]
7	Tanker ship with a 2 stroke diesel MAN 6S50ME-C8.5 of 9960 kW engine	Amine	90%	1234kW to 2249 kW Heat requirement for CCS/ 134.1 kW to 2885kW for Electric Demand (Liquefaction - compression - Storage)			[131]

4.4. Studies General Description

4.4.1. Case Study no 1

First of all is really important to mention the characteristics of the vessel which is examined. It is an LNG- powered cargo vessel with 8000 DWT capacity. The ship is powered by 3000Kw Wärtsilä 6L34DF dual fuel engine. This engine able to work with both LNG and marine diesel oil (MDO) as fuel [122].

Given that the capture system will be built to operate without adding any additional heat to what already exists in the flue gas, it is expected that the engine's maximum power will be adequate to meet any additional power requirements of the CCS system. Electricity will only be needed by the system's pumps, fans and compressors [122].

The CCS of this case works with the following way. First, the LNG is vaporized and then enters the engine, where it is combusted. The exhaust gases from the LNG, then, pass through the reboiler, heating the amine solution. After this, the exhaust gases are cooled in a direct contact cooler by seawater and then are fed t the absorber column at low temperature. In the absorber column the CO_2 is absorbed by the amine (30% wt MEA) solution and the cleaned exhaust gases are then released to the atmosphere. The rich amine solution with CO_2 is moved from the absorber to the stripper column, passing through a heat exchanger in which the rich solution is heated to 100°C. Extra heat that may be needed in the stripper is provided by circulating the amine through the reboiler. In the stripper column, the high temperature causes the amine solution to release its CO_2, creating a pure CO_2 stream from the stripper column. The CO_2 lean amine solution is then circulated back to the absorber column, again passing through the lean-rich heat exchanger. This part of the Carbon Capture process is the absorption [122].

After absorption, the process continues with the liquefaction and storage of CO_2. Specifically, the CO_2 from the stripper column is compressed to 10-11 bar in two stages. Then, it passes through the direct-contact cooler and dryer, which are fed with seawater, to remove excess moisture from the CO_2. The CO_2 is then liquefied by further cooling it in the LNG vaporizer. The process ends with the liquefied CO_2 to be stored in pressure of around 22 bar [122].

A schematic diagram of the Carbon Capture System flow is shown below:

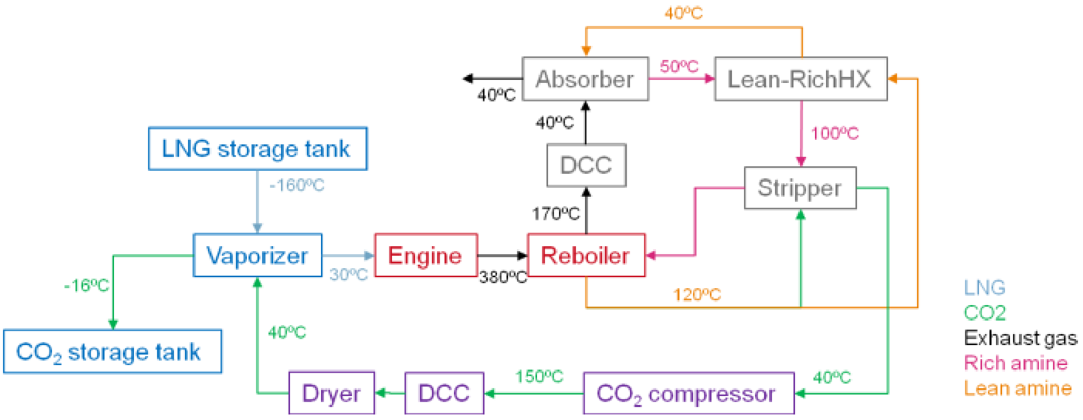


Figure 21: Schematic Diagram for the carbon capture process of case number 1.

On the following table 9 it is shown the dimension and weights of the components which are used for the Capture System.

Table 9: Dimension of components of CCS for case number 1.

Component	Diemensions	Weight
Absorber	H=10m	4.8 (ton)
	D=1.5m	
Stripper	H=14m	6(ton)
	D=0.76m	
Reboiler	L=4m	0.8 (ton)
	D=0.76m	
Lean-rich heat exchanger	L=6m	17.1(ton)
	D=1.15m	
Lean cooler	L=6m	0.94(ton)
	D=0.25m	
Stripper condenser	L=6m	0.6(ton)
	D=0.2m	
Condensate separator	H=2.6m	1.1(ton)
	D=1m	
DCC	D=0.45m	1.4 (ton)
	H=3.5m	

About the capture system performance, the next table shows all the specific characteristics of the energy demand and the gas compositions in every of three cases which are examined in this study. 3 different loads of engine are tested (100% MCR, 75% MCR, 50% MCR), in which the required heat duty, electric demand and the gas composition are calculated respectively.

Heat duty

To calculate the heat demand of the system, it is important to estimate the difference between the inlet temperature of the gas in the heat exchanger and the outlet temperature after the heat exchanger. Specifically, according to the date of the present stud, the minimum exhaust temperature after the exchanger heat in every case is 130°C and the exhaust gases temperature after the turbocharger are 380°C, 370°C,350°C respectively (at 100% MCR, 75% MCR, 50% MCR). Thus, the difference between gas inlet and outlet temperatures becomes:

$$\Delta T = 381℃ - 130℃ = 251℃ \; for \; 100\% \; MCR.$$

$$\Delta T = 370℃ - 130℃ = 240℃ \; for \; 100\% \; MCR.$$

$$\Delta T = 350℃ - 130℃ = 220℃ \; for \; 100\% \; MCR.$$

With an exhaust gas flow of each case and a heat capacity of 1kJ/kg, the reboiler heaty duty equals to:

$$\text{Heat duty} = 4{,}63\,\frac{\text{kg}}{\text{s}} * 1\,\frac{\text{kJ}}{\text{kgK}} * 251℃ \;\; = 1160\text{kW for } 100\% \text{ MCR.}$$

$$\text{Heat duty} = 4{,}63\,\frac{\text{kg}}{\text{s}} * 1\,\frac{\text{kJ}}{\text{kgK}} * 240℃ \;\; = 912\text{kW for } 100\% \text{ MCR.}$$

$$\text{Heat duty} = 4{,}63\,\frac{\text{kg}}{\text{s}} * 1\,\frac{\text{kJ}}{\text{kgK}} * 220℃ \;\; = 682\text{kW for } 100\% \text{ MCR.}$$

Electric Demand

Because of the heat integration of the capture process, no external energy is required for heating or cooling. However, the process does require some electric power. The two major consumers are the blower in the exhaust, necessary to compensate for the pressure drop in the DCC and the absorption column, and the compressors needed for CO_2 liquefaction [122]. In this study, the power is needed for the exhaust blower is estimated around to 26.6 kW.

For the Calculation of compressor energy, it is assumed that the compressors have 90% efficiency, and the CO_2 is compressed in two stages from 2 to 22 bar. The total enthalpy over both compressor is around 185 kJ/kg. In each case, there is different amount of CO_2 which is captured because of the different exhaust gas flow in each MCR. The required compressor power is calculated by the following equation:

$$P_{comp} = \frac{1}{\eta} * flow_{CO2} * \Delta_{enthalpy}$$

The total electric power is given by the total summary of all other power consumers (such as pumps), which assumed not to exceed 30kW in total.

$$P_{el} = P_{blower} * P_{Comp} * P_{AUX}$$

The following table 10 of calculations result from the previous assumptions:

Table 10: Data of Carbon Process for case-study number.

Description/MCR	100%	75%	50%
Gas flow rate (kg/s)	4.63	3.80	3.10
Gas flow rate (kg/h)	16666	13691	11168
CO_2 production (kg/h)	1254	990	724
CO_2 captured at 90% (kg/h)	1128.6	891	651.6
Heat for CCS (kW)	1160	912	682
Electric power of blower	26.6	26.6	26.6
Electric power of AUX	30	30	30
Electric power of compressors	65	51.3	37.5
Total electric power	121.6	107.9	94.1

4.4.2. Case Study no 2

This study is focusing on the process performance of solvent-based post combustion capture process for an LNG-fueled ship (LPG). The capture system uses an aqueous ammonia solution in different concentration to ascertain the effect of this on the reboiler duty, hence the thermal energy demand [123].

The solvent solution choice of NH_3 over MEA is based on the fact of the total energy demand requirement for such a process [123]. Specifically, it is estimated that NH_3 need only 27% of the energy requirement in contrast to MEA-based process [124]. Some of the most important benefits which provide the use of NH_3 are mentioned in this study by the author:

- ✓ No corrosion problems.
- ✓ Higher loading capacity.
- ✓ Multi-pollutant capture and production of value-added products such as ammonium sulphate, ammonium nitrate and ammonium bicarbonate.

About the process and the design of the system, the model involves a Waste Heat Recovery System (WHRS), which is used in order to retrieve heat from flue gases to supply thermal energy if it is necessary. After WHRS, the flue gas continues to the post-combustion capture system passing through an integrated heat exchanger for thermal energy generation and is further cooled down. Starting with the absorber unit, the flue gas contacts the solvent counter-currently there, after passing through a blower, and the CO_2- depleted stream is released to the top of the absorber after passing through a wash column. Then, the CO_2-rich stream is pumped to the stripper column for regeneration. At the end of the process, it is the storage of clean CO_2 on board [123]. It needs to be stored as a liquid in order to minimize space used for storage tanks. The LNG vaporization unit on-board LNG-fueled vessels can serve as a heat sink for the liquefaction of CO_2, thus avoiding the need for refrigeration unit [125]. The storage conditions in this study are close to the triple point (-50°C and 7 bar). The desorption pressure at 6 bar was selected and one only compressor was enough to attain the desired storage pressure of 7 bar. For the required temperature of storage, a cross heat-exchanger was added to provide the cooling duty necessary for liquefying CO_2. Finally, the cooling duty could be feasible from the already stored LNG, upon entering the engine for combustion [123].

On the following table 11 are presented all the necessary characteristics of the post-combustion capture which are used in the study.

Table 11: Data of Carbon Process for case-study number 2.

Data for Post-Combustion Process	
Flue gas (kg/s)	16.35
Capture level %	90
CO_2 production (kg/s)	1.1445
CO_2 captured (kg/s)	1.03005
Heat for CCS (Mwe)	3.4
Electric power for CCS (Mwe)	1
Electric power for Liquefaction (Mwe)	0.4
Electric power for AUX (Mwe)	0.1

4.4.3. Case Study no 3

The process of post-combustion capture, in this study, is based on LNG-fuelled baseline vessel. For the system of capture, the electricity demands are covered by the provided AUX engines or shaft generator. The main purpose of electricity is for the fluid circulation and the CO_2 treatment for storage. The components which are used for the previous demands are the gas blower and solvent pumps for the fluid circulation and a Liquefaction plant operation for the CO_2 treatment. Heat requirement for the absorption process in the Stripper reboiler is covered by steam extraction and waste heat recovery from exhaust gas [132].

The gas flow rate from the engine at the 75% of load is calculated equal to 151076kg/h. The capture rate of the system is around to 82-88% with an average CO_2 emission of 7269 tons. The process of capturing the CO_2 is taking place at around to 110°C -120°C, with a head demand of 614kWth - 988kWth. For the electricity demand of the system is estimated that for the AUX components (exhaust gas fan and pumps) is around to 35kWh/ton$_{CO2\ captured}$ - 69 kWh/ton$_{CO2\ captured}$. Furthermore, for the liquefaction process, the electricity demand is calculated 66 kWh/ton$_{CO2\ captured}$ - 95 kWh/ton$_{CO2\ captured}$ [132].

The following table 12 shows the summary of data which are used or the analysis of this study:

Table 12: Data of Carbon Process for case-study number 3.

Date for Post-Combustion Process	
Flue gas rate (kg/h)	151076
CO_2 captured (tons)	7269
Capture rate	88%-82%
Thermal energy for capture	2000-2440 Mj/ton CO_2
Electric energy for liquefaction	66-95kWh/ton CO_2
Electric energy for AUX (exhaust gas fan - pumps	35-69kWh/ton CO_2
Main engine load	77%
L/G ratio	1.62

4.4.4. Case Study no 4

A reference vessel for this case of post-combustion CO_2 capture is an inland cargo ship ship with a 1280kw dual fuel Wärtsilä 8L2ODF engine of 8000 deadweight tonnage. In this study, it is used two different fuels (Diesel and LNG). If the engine operates on diesel, there is more flue gas produced, but with a lower temperature, when compared to LNG [125].

About the post-combustion process, in the absorber column the flue gas contacts the solvent solution counter-currently. The solvent solution is a 30%wt MEA or 30%wt PZ. At the top of the absorber, the CO_2-depleted gas is discharged into the environment. The stripper column receives a pumping of the CO_2-rich solution. The reboiler at the base of the stripper column receives heat. By turning back, the carbamate production cycle, heat restores the amine and releases CO_2. The engine exhaust gas in SBCC provides this heat. At the top of the stripper column, free CO_2 is generated as a gas. Liquifying the CO_2 is necessary for economical storage [125]. When a ship runs on LNG, the CO_2 liquefaction unit's heat sink might be the LNG vaporization unit, saving the need for a refrigeration unit. Ships powered by diesel require a separate refrigeration unit. The cycle is completed by pumping the lean amine back into the absorption column. You can get a more thorough explanation of the absorption-desorption cyclic process elsewhere [126].

The use of these two different solvents solution is tested from an economic evaluation scope. Specifically, according to the research, the use of 30%wt Piperazine decrease the economic cost involved in the compression of captured CO_2 [127]. The concentration of piperazine is selected as 30 wt%, since it has been shown to outperform higher concentration solutions due to improved mass transfer [128].

Table 13 shows the differences in heat demand and electricity for the Carbon Capture System, for the two solvents in different variations and the table shows the CO_2 capture and compression components with their respective sizing and weight.

Table 13: Data of Carbon Capture Process for case-number 4 for different solvents.

Solvent	MEA	MEA	PZ	PZ	MEA	MEA	PZ	PZ
Flue gas (kg/s)	2	2	2	2	2.7	2.7	2.7	2.7
CO_2 production	0.096	0.096	0.096	0.096	0.1296	0.1296	0.1296	0.1296
CO_2 capture %	90	60	90	60	80	60	90	60
CO_2 captured	0.0864	0.0576	0.0864	0.0576	0.10368	0.07776	0.11664	0.07776
Liquefaction (kW)	18.1	11.7	3	8.8	21.1	15.8	11.4	9.8
Fuel type	LNG	LNG	LNG	LNG	Diesel	Diesel	Diesel	Diesel
L/G ratio	1.84	1.98	1.72	1.63	1.39	1.25	2.06	2.1
Reboiler duty (kWth)	440	310	440	290	520	380	520	340
mSolvent (kg/s)	3.68	3.96	3.44	3.26	3.753	3.375	5.562	5.67

Table 14: Dimensions of components for Carbon Capture System of case-study number 4.

Component	Dimension	Weight (ton)
Absorber	H=10m	4.8
	D=1.5m	
Stripper	H=14m	6
	D=0.76m	
Reboiler	L=4m	0.8
	D=0.35m	
Condenstate seperator	H=2.6m	1.1
	D=1m	
Lean-Rich heat exchanger	L=6m	17.1
	D=1.15m	
Lean cooler	L=6m	0.94
	D=0.25m	
Compressor (2)	H=0.76m	8.5
	W=1.14m	
	L=7.01m	
DCC	D=0.45m	1.4
	H=3.5m	

4.4.5. Case Study no 5

The selected reference ship for this study is a middle size cargo ship with a two 9L46 marine diesel Wärtsilä engines OF 17000 kW propulsion power and 3 power generators of 3000 kW electricity supply in total. The fuel which engine consumes is diesel.

The process of capture is based on chemical solvent of monoethanolamine (MEA), using WHR. This study applies two different cases of Carbon Capture Process. The first one is the main method which has already been described in previous studies and the second one uses an additional gas turbine power plant. In first case, the energy utility required be carbon capture is supplied by ship energy system itself. Furthermore, the use of WHR system seems to be applied in this situation, thus, the flue gas from the diesel engine was directly linked to the stripper reboiler. After exchanging heat with the solvent, the flue continues for the carbon capture process. In the second case, the gas turbine provides both electrical and heat energy to the carbon capture plant. It is important to mention that WHR was not used in this case as in the first one. Flue gases from both the marine diesel engine and the additional diesel gas turbine are directly linked to the stripper reboiler. The use of gas turbine provides to the system the following two benefits: [129]

(1) It avoids energy loss during a complex conversion process, such as the WHR system.
(2) It makes the diesel gas turbine power plant in balance between power generation and producing thermal heat to carbon capture plan.

Despite the fact that the usual condition of storage is at the temperature around -54°C per 6 bar to -50°C per 7 bar (near to the triple point of CO_2), in this study the captured CO_2 was liquified by a compression process with much less cooling utility requirement. The CO_2 tank storage conditions was set at pressure equal to 100 bar and temperature around to 20°C. This means that the captured CO_2 is in dense phase [129].

Table 15: Overall performance of carbon capture processfor case-study number 5.

Description	CCS , but without additional utilities supply	CCS and additional utilities supply
Diesel consumption of propulsion engines(kg/h)	3176.28	3856.28
Flue gas flow rate(kg/s)	32.84	40.13
Flue gas CO_2 content (mol%)	5.69	5.66
CO_2 captured (kg/S)	2.07	3.17
Capture level (%)	73	90
Propulsion power outpout (Mw)	15.26	15.26
Ship aux electric power generation (Mwo)	1.69	2.55
WHR electric power output (Mwo)	-	-
Electric power output of the additional diesel gas turbine (Mwo)	-	2.44
Electric power consumption of auxiliary in capture process (Mwo)	0.1	1.12
Electric consuption of CO_2 compression (Mwo)	0.76	1.01
stripper reboiler duty (MWth)	7.8	12.21
Fuel consumption pre single trip (tons)	184.22	223.67
CO_2 emissions per single trip (tons)	172	59.31
Capture level (%)	73	90
Overall energy efficiency (%)	45.35	42.16
Total electrci energy for CCS	0.86	2.13
absorber diameter(m)	4.2	4.9
absorber packing type	Mellapak 250Y	Mellapak 250Y
absorber packing height (m)	12.5	12.5
absorber flooding factor	0.651	0.639
stripper diameter(m)	1.6	2.1
stripper packing height (m)	6.5	6.5
stripper flooding factor	0.639	0.618
MEA tank volume (m^3)	0.65	1.02
CO_2 tank (m^3)	561.3	937.4
Stripper packing type	Mellapak 250Y	Mellapak 250Y

4.4.6. Case Study no 6

In this study, it was selected an LPG carrier ship with a 20.550m^3 capacity, an 4 strokes Wärtsilä 9L46 engine, auxiliary generators and a waste heat recovery system for energy efficiency. The type of fuel consumed by the engine is HFO, with a Sulphur content of 3.29%. For this case it was assumed that the marine engine operated at two loads. Specifically, at 85% and 75% of full power. Furthermore, as a solution solvent, it is used aqueous ammonia (in different variations) and MEA [130].

For the capture process, the system consists of one pre-treatment column, two absorber columns with individual wash columns at the top, stripper and heat exchanger. At first, flue gas enters the pre-treatment column to remove SO_2 and cool it. Afterwards, it is moving through the absorber from the bottom where it relates to the solvent solution, which enters from the top of the absorber column. Because ammonia is volatile, the wash columns near the absorbers' exit act as protection against ammonia slip. In order to allow for flexibility, there were two absorber columns that could be operated in parallel or series. The rich solvent enters the stripper column where the clean CO_2 follows the liquefaction process of the system to be storage in ideal conditions [130].

At the table 16 is shown the overall performance of carbon capture system and at the table the characteristics of the units which are used in the capture process

Table 16: Date of Carbon Capture Process for case-study number 6.

Condition	1	2	3	4	5
Flue gas rate(kg/s)	17.43	17.43	17.43	17.43	15.44
CO_2 content in flue gas (kg/s)	1.35	1.35	1.35	1.35	1.3
Capture level %	75	70	73	75	75
Electricity power for CCS	1000	1000	1000	1000	-
Heat duty(kW)	4556.25	4000	7300	6378.749998	4095
CO_2 captured (kg/s)	1.0125	0.945	0.9855	1.0125	0.975
Solvent	4.1% wt NH3	4.1% wt NH3	30% wt MEA	3.5%wt NH3	4.1% wt NH3

Table 17: Dimension of Carbon Capture components of case-study number 6.

Component	Dimension
Absorber	H=7.8m
	D=0.6m
Stripper	H=3.5m
	D=0.4m
wash columns	H=1.7m
	D=0.5m
Pre-treatment columns	H=3.5m
	D=0.5m

4.4.7. Case Study no 7

A tanker ship is selected as reference vessel with a 2-stroke diesel MAN 6S50ME-C8.5 engine with a propulsion power of 9960kW and an auxiliary engine of 498kW power. The capacity of the ship is 47000 DWT. The engine consumes heavy fuel oil (HFO).

In this instance, the exhaust gas flow is treated using a desulfurization system. The primary desulfurization column and the direct contact cooler (DCC) column make up this system's two columns. The purpose of the hollow scrubber, or DCC column, is to cool the gas by allowing some of the water in the circulating liquid to evaporate. As the gas cools, it enters the desulfurization column, where SO2 is absorbed. Moreover, the gas in the desulfurization column is cooled below the water saturation point, which leads to some degree of condensation of water. Relocating the surplus rich solution to the DCC column's circulation loop allows for the reabsorption of some of the water. Because of the low pH of the solution circulating in the DCC loop, which prevents SO2 from being absorbed, most SO2 goes through the DCC column and is subsequently absorbed in the desulfurization column. Therefore, a second column called the desulfurization column is utilized to absorb SO2, while the DCC column eliminates fly ash, initially cools the gas and creates humid exhaust gas due to water evaporation [131].

Regarding the carbon capture system, it is comprised of two CO_2 absorber columns and a CO_2 stripper. To raise the pressure of exhaust gas entering the absorber, a gas fan is employed. The energy used in the carbon capture process, particularly the fan duty, is decreased by the desulfurization system. The solvent high in CO_2 is injected from the absorber to the stripper. The rich stream is heated in the rich-lean exchanger before to entering the stripper. By employing the reboiler, which is supplied with steam made from heat recovered from hot exhaust gases and hot compressed CO_2, the CO_2 is removed from the rich solution. Condensed water is returned to the top of the CO_2 stripper after the CO_2 saturated with water vapor exits the stripper and cools in the condenser. CO_2 that has cooled is transported to the compressor. After exiting the stripper, the hot CO_2 lean solution is cooled to 40 °C mostly in the rich-lean exchanger and then in the lean amine cooler. Finally, the captured CO2 is compressed in two stages to be stored as liquid [131].

On the table 18 is shown the performance of the carbon capture process in different engine loads

Table 18: Data of Carbon Capture Process for case-study number 7.

Carbon Capture System - Absorption			
Engine	6S50ME-C8		
Exhaust gas flow (Kg/s)	19.3	18.7	17.1
Gas flow rate in PCC (kg/s)	6.755	8.976	10.602
Heat requirements (kW)	1234	1715	2249
Liquefaction demands (kW)	104.1	145.1	191
Auxiliary demands (kW)	30	48.1	97.5
CO_2 emissions (kg/s)	0.739	0.619	0.478
CO_2 captured (kg/s)	0.339	0.472	0.622
CO_2 in exhaust	0.239127	0.334805	0.436802
Total electric demand	134.1	193.2	288.5

5. Maritime Carbon Capture Systems Analysis

5.1. Important performance metrics

For the analysis of a carbon capture system, it is crucial to define several key performance metrics that describe the energy demand, efficiency, sizing, and economic aspects of the system. Specifically, the energy requirement of the system is determined by the heat demand for the capture process and the electricity needed for the transportation and storage of captured CO_2. The heat requirement of the system depends on various parameters, such as the CO_2 content in exhaust gas, the solvent used for capture, the stripper pressure, and the capture level, among others. To examine how these parameters affect the heat demand for the carbon capture process, the following parameters were utilized:

- $h_1 = \frac{Heat\ demand\ (kW)}{CO_2\ captured\ (\frac{kg}{h})}$.
- $h_2 = \frac{Heat\ demand\ (kW)}{Exhaust\ gas\ flow\ in\ PCC(\frac{kg}{h})}$.
- $h_3 = \frac{Heat\ demand\ (kW)}{CO_2\ produced(\frac{kg}{h})}$.

The electricity demand of the system can be categorized into three different supplies. The first pertains to the auxiliary units of the carbon capture system, primarily the blower. The second is associated with the liquefaction of captured CO_2 for transportation and storage, which occurs under specific conditions based on the unique requirements of each case. The primary factor influencing the electricity demand in the system is the volume of CO_2 flowing through and captured during operations. However, concerning the auxiliary components of the process, as they mainly operate before CO_2 capture, the key factor affecting their energy demands appears to be the mass gas flow entering the carbon capture system. Moreover, the temperature and pressure conditions for transportation and storage are crucial parameters affecting the electricity demand. Lower target storage temperatures lead to higher energy demands, while lower liquefaction temperatures combined with higher target pressures result in increased energy needs for the process. For the analysis of these factors, the following metrics were utilized.

- $e_1 = \frac{Electric\ for\ liquefaction/Storage\ (kW)}{CO_2\ captured\ (\frac{kg}{h})}$.
- $e_2 = \frac{Total\ electric\ power\ \ (kW)}{CO_2\ captured\ (\frac{kg}{h})}$.
- $e_3 = \frac{Total\ electric\ power\ \ (kW)}{Exhaust\ gas\ flow\ rate\ in\ PCC(\frac{kg}{h})}$.

In determining the system size, it is important to outline the steps aligned with Onda's and Cornell's method. Within the system, the primary units—absorber and stripper—share identical dimensions. The design of packed columns aims to operate at an optimal economic pressure drop to guarantee efficient distribution of both liquid and gas.

To determine the dimensions of packed columns, various metrics are used. First of all, the efficiency of the absorber depends on number of stages (N_{OG}), $m\frac{G_m}{L_m}$ factor and $\frac{y_1}{y_2}$:

- m = $\frac{mole\ fraction\ in\ vapor}{mole\ fraction\ in\ liquid}$.
- 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.

The diameter of the columns can be specified by the use of the following metrics:

$$\text{Factor } F_{LV} = \frac{L_{\dot{W}}}{V_{\dot{W}}}\sqrt{\frac{\rho_v}{\rho_L}}$$

where,

(1) $L_{\dot{W}}$= Liquid mass flow rate per unit cross-sectional area, kg/m^2.
(2) $V_{\dot{W}}$= gas mass flow rate per unit column cross-sectional area, kg/m^2.
(3) ρ_v= vapor densities , kg/m^3.
(4) ρ_L= liquid densities, kg/m^3.

According to this factor and the following figure 22 It is determined the term K_4 which is needed in order to calculate the gas mass flow rate per unit column cross-sectional area (V_W) in kg/m^{2}s. Figure correlates the liquid and vapor flow rates, system physical properties and packing characteristics, with the gas mass flowrate per unit cross-sectional area with lines of constant pressure drop as a parameter.

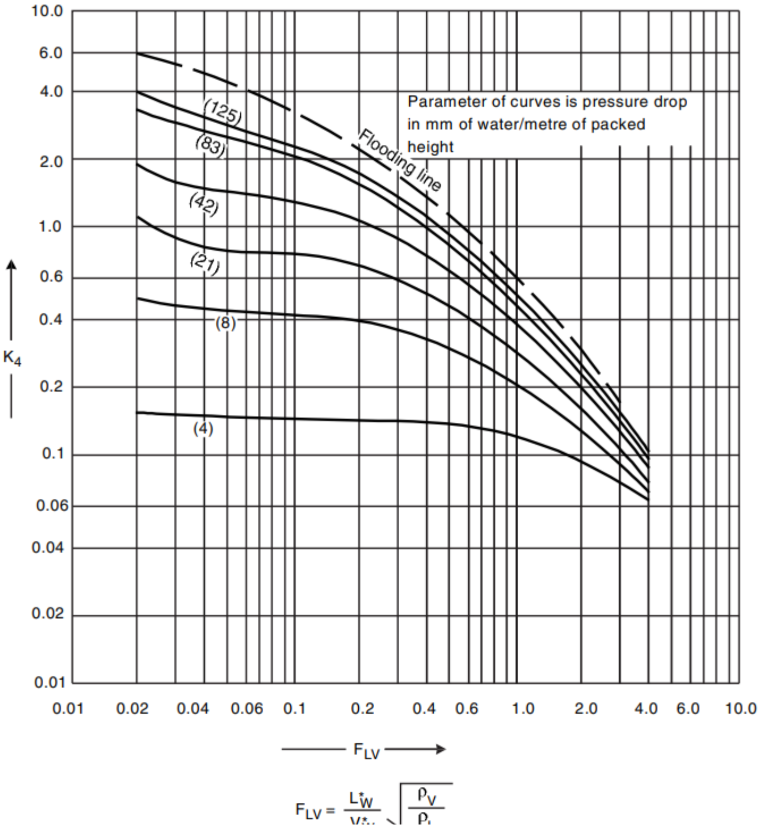


Figure 22:Pressure drop correlation

The height of the packed columns is a bit more complicated procedure, as many different parameters are used in the equations. To begin with, Cornell's method uses empirical equations for predicting the height of the gas and liquid film transfer units. Figures and equations are given for a range of sizes of Rasching rings and Berl saddles. Only those for Berl saddles are given here, as it is unlikely that Rasching rings would be considered for a new column. Though the mass-transfer efficiency of Pall rings and Intalox saddles will be higher than that of the equivalent size Berl saddle, the method can be used to make conservative estimates for these packings.

Cornell's equations are the following:

- $H_G = \frac{0.011\psi_h (Sc)_v^{0.5} (\frac{D_C}{0.305})^{1.11} (\frac{Z}{3.05})^{0.33}}{(L_{\dot{W}} f_1 f_2 f_3)^{0.5}}.$

- $H_L = 0.305\varphi_h (Sc)_L^{0.5} K_3 (\frac{Z}{3.05})^{0.15}.$

Where:

(1) H_G=height of a gas-phase transfer unit, m.
(2) H_L=height of a liquid-phase transfer unit, m.
(3) $(Sc)_v$ =gas Schmidt number $(\frac{\mu_v}{\rho_v D_v})$.
(4) $(Sc)_L$ =liquid Schmidt number $(\frac{\mu_L}{\rho_L D_L})$.
(5) D_c= column diameter, m.
(6) Z= column height, m.
(7) K_3= percentage flooding correction factor, from figure 38.
(8) Ψ_h= H_G factor from figure 39.
(9) ϕ_h= H_L factor from figure 37.
(10) f_1=liquid viscosity correction factor $(\frac{\mu_L}{\mu_W})^{0.16}$.
(11) f_2=liquid density correction factor $(\frac{\rho_W}{\rho_L})^{1.25}$.
(12) f_3= surface tension correction factor $(\frac{\sigma_W}{\sigma_L})^{0.8}$.

On the chapter 5.2.3 Dimension of packed columns there is a detailed explanation for the determination of packed columns size.

5.2. Data analysis

5.2.1. Thermal Energy Demand

This section provides an in-depth exploration of data analysis concerning the comprehensive performance and design of a carbon capture system. To commence the discussion on the process's thermal demands, key outcomes derived from existing ship cases that have incorporated a carbon capture system onboard are highlighted. Primarily, the exhaust gas flow serves as a pivotal factor in assessing the system's operational heat requirements, correlating with the type of fuel used in these ship cases, including Heavy Fuel Oil (HFO), LNG, and Diesel.

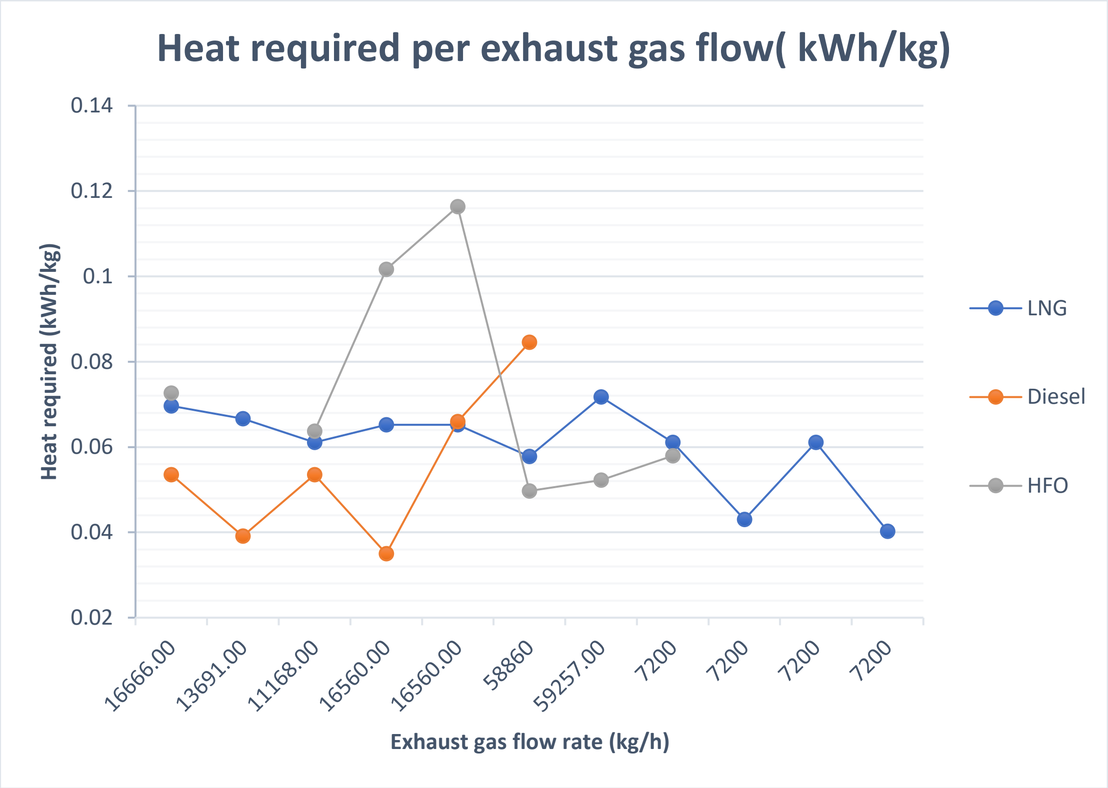


Figure 23:Diagram of Heat required for the Capture of CO_2 per CO_2 captured for different fuels.

Table 19: Heat Demand for CO_2 capture process per exhaust gas flow for maritime case-studies.

Heat Demand per Exhaust gas flow(kWh/kg)			
Fuel	Case	min	max
LNG	Case study number 1	0.061067335	0.069602784
	Case study number 2	0.057764186	0.057764186
	Case study number 3	0.071721484	0.071721484
	Case study number 4	0.040277778	0.061111111
	Total	**0.040277778**	**0.071721484**
	Average	**0.060250839**	
	Deviation	**0.009590608**	
Diesel	Case study number 4	0.034979424	0.053497942
	Case study number 5	0.065976451	0.084516986
	Total	**0.034979424**	**0.084516986**
	Average	**0.055260566**	
	Deviation	**0.016581333**	
HFO	Case study number 6	0.063747052	0.116338369
	Case study number 7	0.049713963	0.057908994
	Total	**0.049713963**	**0.116338369**
	Average	**0.073458929**	
	Deviation	**0.023859252**	

The analysis of the heat demand based on the figure 23 utilizing the exhaust gas flow rate entering the carbon capture system did not yield specific conclusive results. Nonetheless, a primary observation from the figure indicates a consistent increase in heat demand across all main engine fuel types as the exhaust gas flow rate rises throughout the process. Subsequently, the focus shifted to examining the treated CO_2 within the system.

The primary objective was to explore the interaction between the heat duty in the process and the CO_2 generated during carbon capture. Through data gathered from various papers, the relationship between the amount of produced CO_2 and the heat power of the system was established. Specifically, with the use of LNG and Diesel, both the reboiler and stripper heat increased in tandem with the rise in CO_2 production.

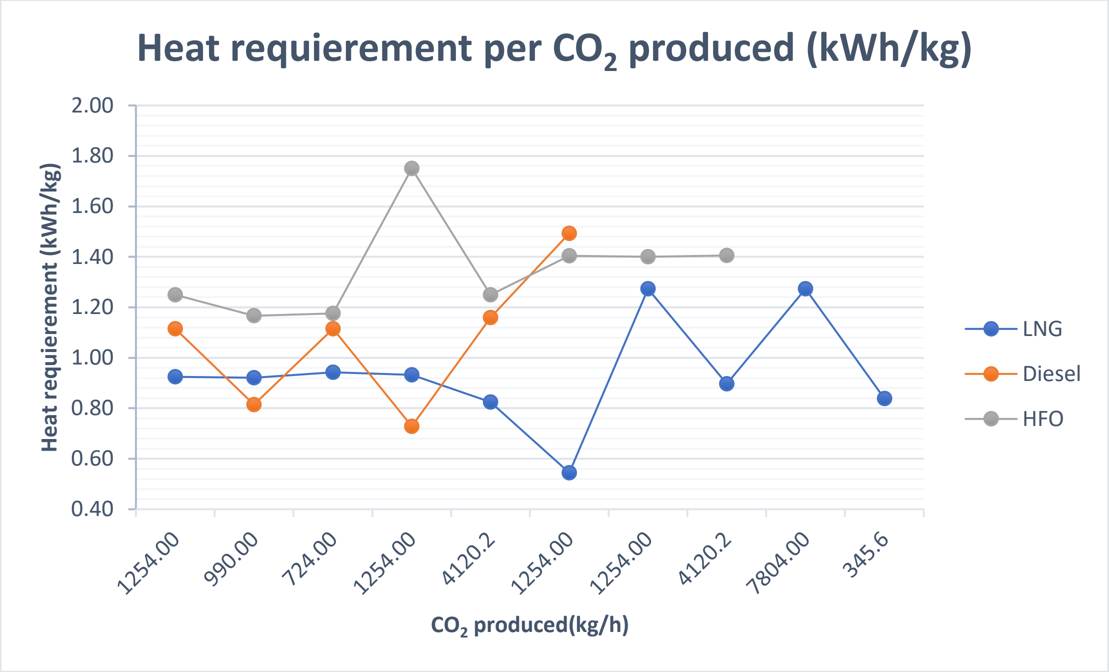


Figure 24: Heat required for CO_2 capture per CO_2 produced.

Another crucial parameter considered in evaluating the heat duty demand for the system was the quantity of captured CO_2. Notably, the heat demand mirrors the treatment of heat demand per unit of CO_2 produced. However, variations in the main engine across different cases, each with its unique power efficiency and exhaust gas flow, necessitated examination. Hence, the CO_2 content within the exhaust gas flow entering the carbon capture system emerged as a pivotal factor requiring scrutiny.

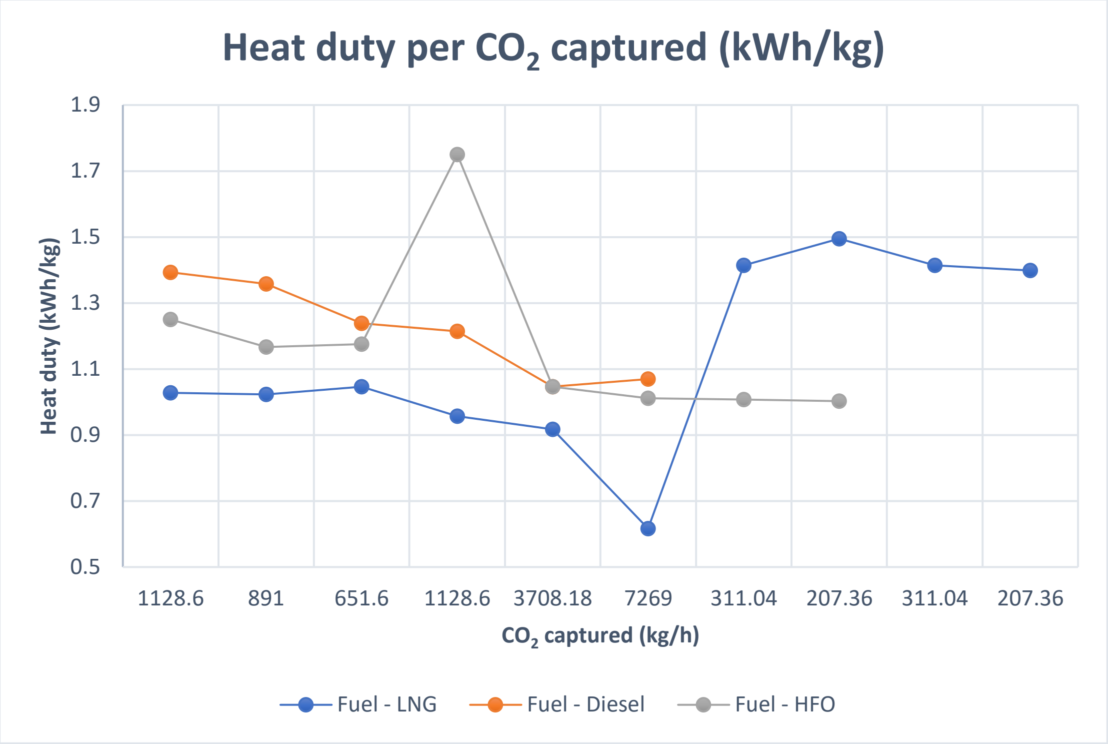


Figure 25: Heat required for CO_2 captured per CO_2 captured.

Despite the CO_2 captured and fuel as main parameters for the heat requirement, the type of solvent which is used is an important factor which has not been considered yet. The next step of the analysis was to examine how monoethanolamine, piperazine and aqueous ammonia affects the energy operation of the process. According to literature the type of solvent provides specific heat duty data which affects the system operation [133].

The subsequent phase of analysis aimed to elucidate the interaction between heat demand, the solvent, and the quantity of captured CO_2. An important observation arose when comparing exhaust gas flow and produced CO_2: the concentration of CO_2 within the gas flow. It was observed that an increase in CO_2 concentration in the exhaust gas flow resulted in decreased heat duty. Specifically, lower CO_2 concentration in the exhaust gas flow necessitates a larger quantity of gas to enter the CCS for the same capture rate. Typically diluted with components like nitrogen, this requires more gas to be treated, subsequently increasing the necessary heat. CO_2 concentrations in various studies ranged from 4.8% wt to 7.5%, with an average concentration of approximately 6.3% wt being selected.

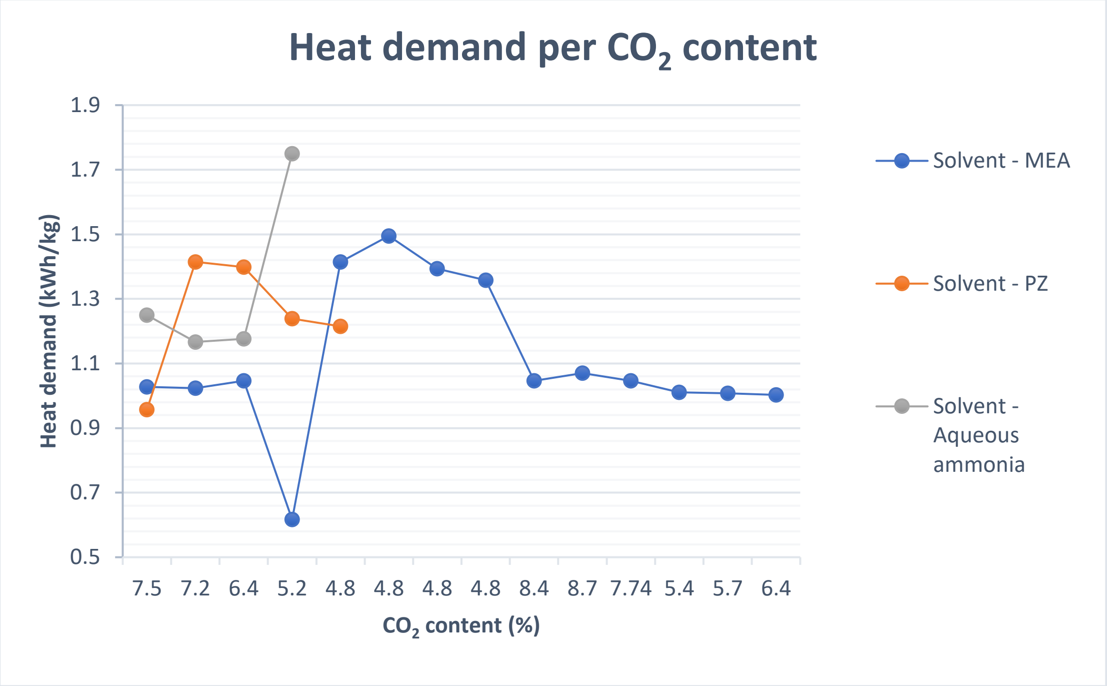


Figure 26: Heat required for CO_2 captured per CO_2 content in exhaust gas flow for different solvents.

For the best analysis of the PCC, the main factors which are selected to describe the thermal energy demand for the system was the amount of CO_2 captured and the CO_2 content in the exhaust gas which flows in the carbon capture system. The irregular treatment of the data which is presented in figure 26 is due to the different units and systems which are used in each study to cover the requirements for each case propose. For this reason, cannot be defined a specific equation to describe the thermal energy demand for the operation of the carbon capture system.

The following table 20 shows the results of the heat requirement with an average price of heat demand for each solvent which is used in studies. For MEA the heat demand ranges from 1.0027 $kWh/kg_{CO2captured}$ to 1.495O $kWh/kg_{CO2captured}$, with an average of 1.1495 $kWh/kg_{CO2captured}$ and a deviation of 0.1801 $kWh/kg_{CO2captured}$. Piperazine (PZ) as solvent seems to have better results for the heat operation of the system as the thermal duty ranges from 0.9569 $kWh/kg_{CO2captured}$ to 1.4146 $kWh/kg_{CO2captured}$, with an average demand of 1.2446 $kWh/kg_{CO2captured}$ and deviation of 0.1651 $kWh/kg_{CO2captured}$. Finally, aqueous ammonia results shows that the fluctuate of heat is from 0.917 $kWh/kg_{CO2captured}$ to 1.75 $kWh/kg_{CO2captured}$, the average thermal duty is around to 1.2519 $kWh/kg_{CO2captured}$, with a deviation of 0.2733 $kWh/kg_{CO2captured}$. The next chapter it is presented energy performance of carbon capture systems which are based on land and a comparation of these with the studies which have been evolved on board.

Table 20: Heat required for CO_2 capture per CO_2 captured for different solvents.

Heat Demand per CO_2 captured(kWh/kg)			
Solvents	Case	min	max
MEA	Case study 1	1.023569024	1.046654389
	Case study 3	-	-
	Case study 4	1.357453132	1.494984568
	Case study 5	1.046698873	1.069926393
	Case study 6	1.046698873	1.046698873
	Case study 7	1.0027	1.011
	Total	**1.0027**	**1.494984568**
	Average	**1.149483998**	
	Deviation	**0.180112973**	
PZ	Case srtudy 1	0.956937799	0.956937799
	Case study 4	1.214563329	1.414609053
	Total	**0.956937799**	**1.414609053**
	Average	**1.244604486**	
	Deviation	**0.165099481**	
Aqueous Ammonia	Case study 2	0.916891845	0.916891845
	Case study 6	1.166666667	1.75
	Total	**0.916891845**	**1.75**
	Average	**1.251867493**	
	Deviation	**0.273275251**	

Stripper's pressure is another important factor which affects the heat requirement for the right operation of the carbon capture system. As the pressure of stripper drops, the more energy is needed for the capture of CO_2. It is due to the power that reboiler needs in order to counterbalance the energy loss of the stripper. Therefore, the heat demand of the system works on the contrary of the pressure operation of the stripper. However, in all studies, strippers' pressure is assumed equal to 2 bar, which is the usual function of this unit.

For Case study number 4 it is really important to mention that the big amount of heat demand for the capture of CO_2 is due to the low CO_2 concentration in the exhaust gas flow rate. Specifically, CO_2 concentration in previous studies range from 6% wt to 7.5% wt, while in study 4 is actually 4.8%wt.

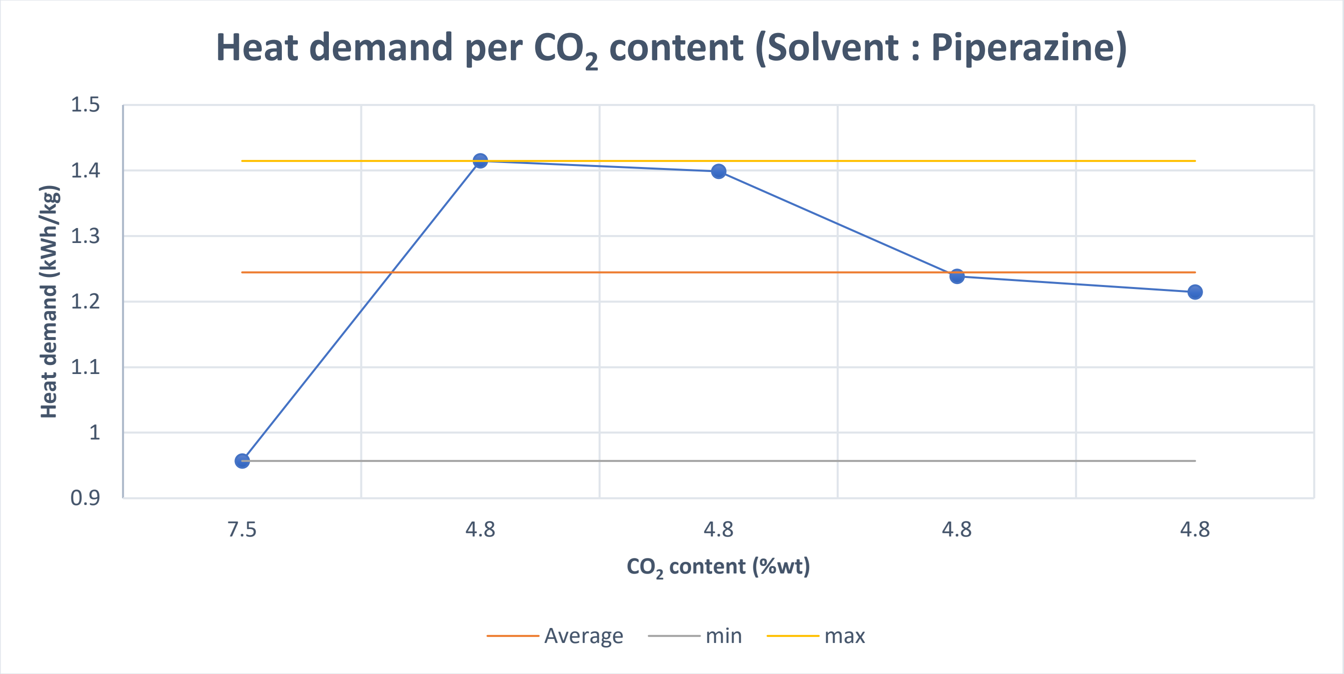


Figure 28: Heat required for CO_2 capture per CO_2 content in exhaust gas flow, using Diesel as fuel in M/E.

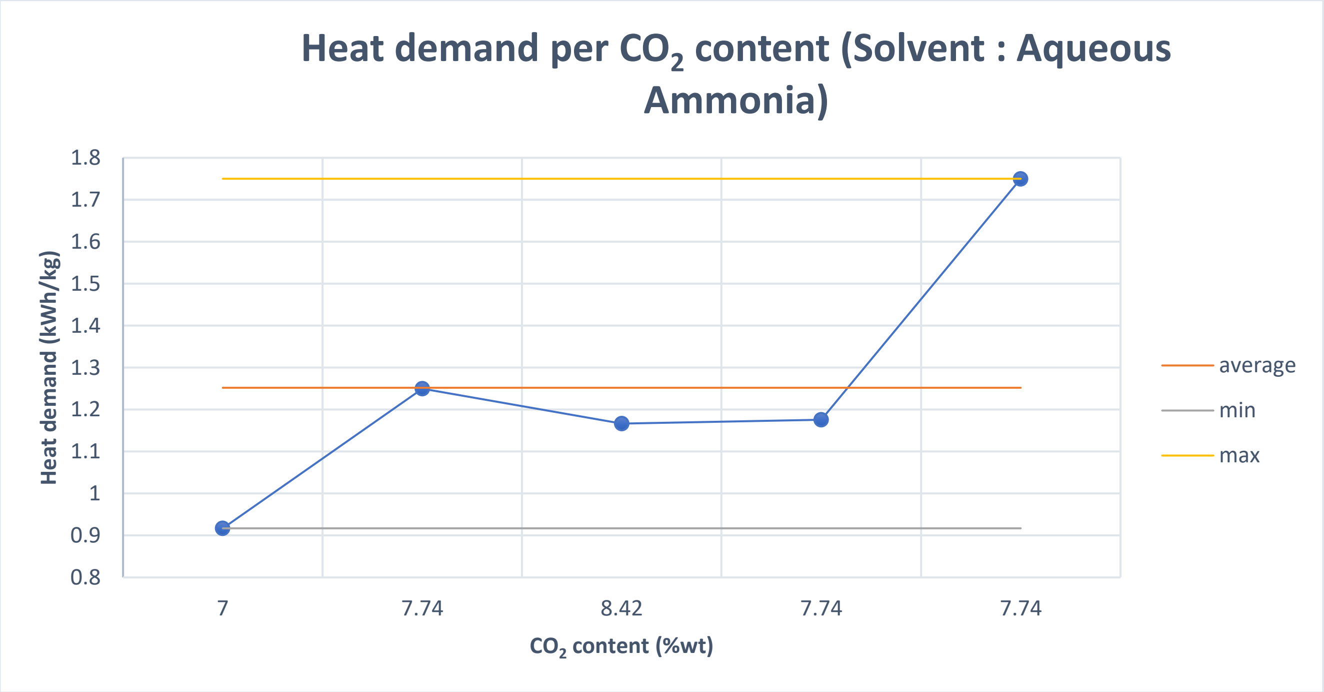


Figure 27: Heat required for CO_2 capture per CO_2 content in exhaust gas flow, using Aqueous Ammonia as fuel in M/E.

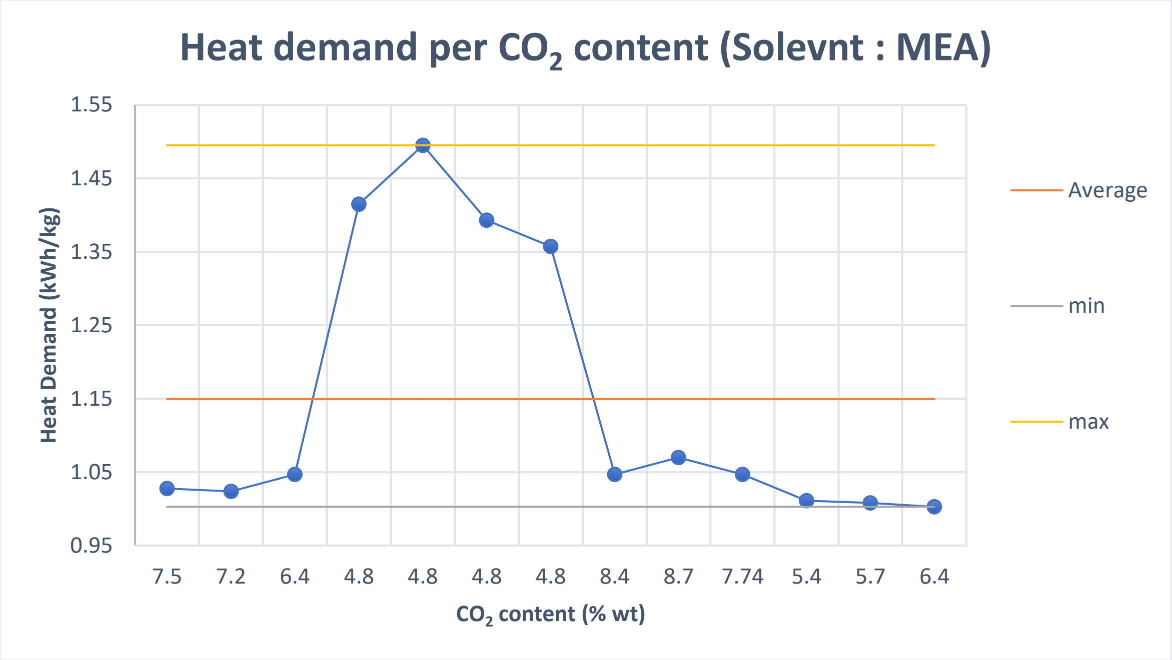


Figure 29: Heat required for CO_2 capture per CO_2 content in exhaust gas flow, using LNG as fuel in M/E.

5.2.2. Electric Energy Demand

Electric power for the operation of the CCS is important for two main reasons. First of all, for the right function of the auxiliary units and secondly for the liquefaction and storage of captured CO_2 under specific conditions. The auxiliary system comprises mainly pumps, fans and the blower. Pumps are used to transport the solvent through the various parts of the CO_2 capture unit and fans are installed to overcome the pressure drop encountered in the absorber [92]. The blower plays a crucial role in transferring gases within the carbon capture system, facilitating the movement of gas streams containing carbon dioxide across various stages of the capture process, including absorption, separation, and compression. In onboard applications studied, the blower is positioned at the system's outset, ensuring the supply of exhaust gases to the absorber at an optimal pressure essential for an effective absorption process.

For the auxiliary units of the system, the most parts have a specific energy demand which is standard in every case. Pumps and fans operate in 30 kW. The functionality of the blower, on the other hand, is affected by the gas flow rate. Specifically, as the gas flow rate increases the energy demand for the blower increases too. This happens in order to overcome the pressure drop across the various components of the carbon capture system (absorber, stripper and piping equipment).

Although the blower plays an essential role in the system's performance, the cases presented in this thesis lack the necessary information to assess the efficiency and functionality of this unit. Instead, an average energy demand is assumed for each case, and only the total electrical demand, encompassing all components of the auxiliary system, is provided.

For the analysis of the auxiliary power demand, at first, the interaction of the exhaust gas flow was selected according to the solvent type (MEA) which is used and a Capture rate of 90%.

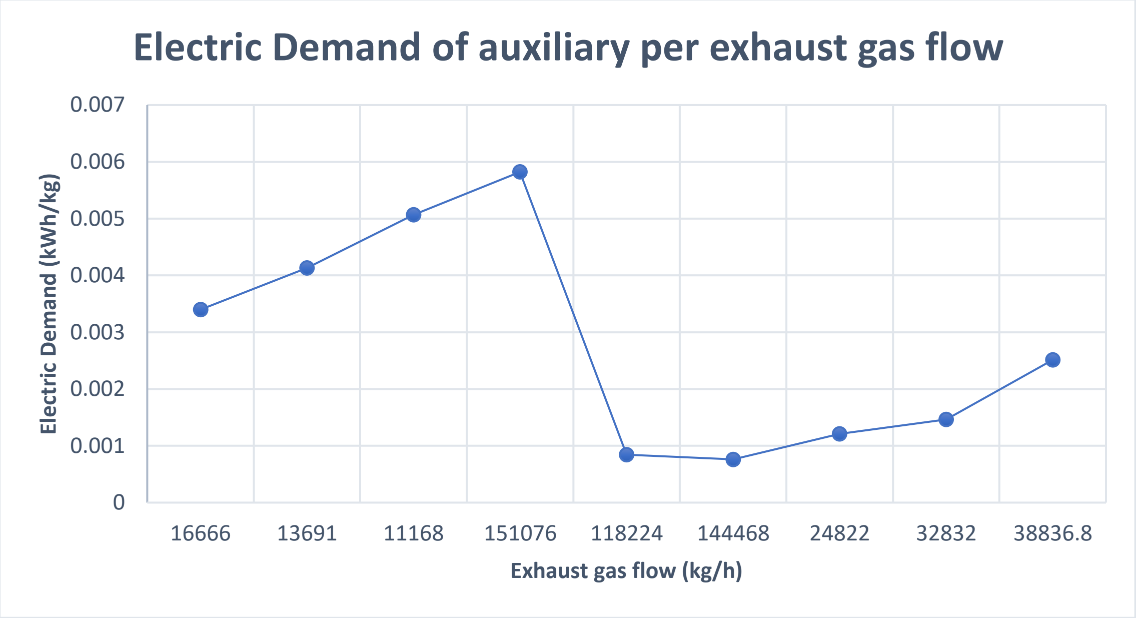


Figure 30: Electric power Demand for carbon capture process of auxiliary per exhaust gas flow.

Figure 30. shows an uncertain allocation of data which cannot provide any specific information about the electric demand. The exhaust gas flow rate, as a factor, may not be the most suitable indicator for estimating the electric demand of the auxiliary units. This is due to the association of electricity primarily with the treatment of captured CO_2, with the blower being the only component directly linked to the exhaust gas flow. Nevertheless, the studies examined do not offer specific information regarding the individual performance of the blower but rather focus on the collective operation of the auxiliary units.

The analysis progressed by examining the correlation between electricity demand and captured CO_2, utilizing the same solvent (MEA) as previously employed, assuming a capture rate of 90%. The accompanying figure 31 illustrates that an increase in captured CO_2 corresponds to a decrease in electricity demand. The rationale behind focusing the analysis of electric demand on the amount of CO_2 captured stems from the specific role of the blower in the auxiliary units' energy demand, while other components maintain a standard energy requirement. Additionally, the concentration of CO_2 in the exhaust gas defines both the amount of exhaust gas entering the CCS and the CO_2 concentration in the gas flow. Essentially, a higher exhaust gas flow in the capture system implies a lower concentration of CO_2 in the gas flow. Given the direct connection between the blower and the exhaust gas flow, higher CO_2 capture results in increased CO_2 concentration in the exhaust gas flow rate, subsequently reducing the amount of exhaust gas entering the system.

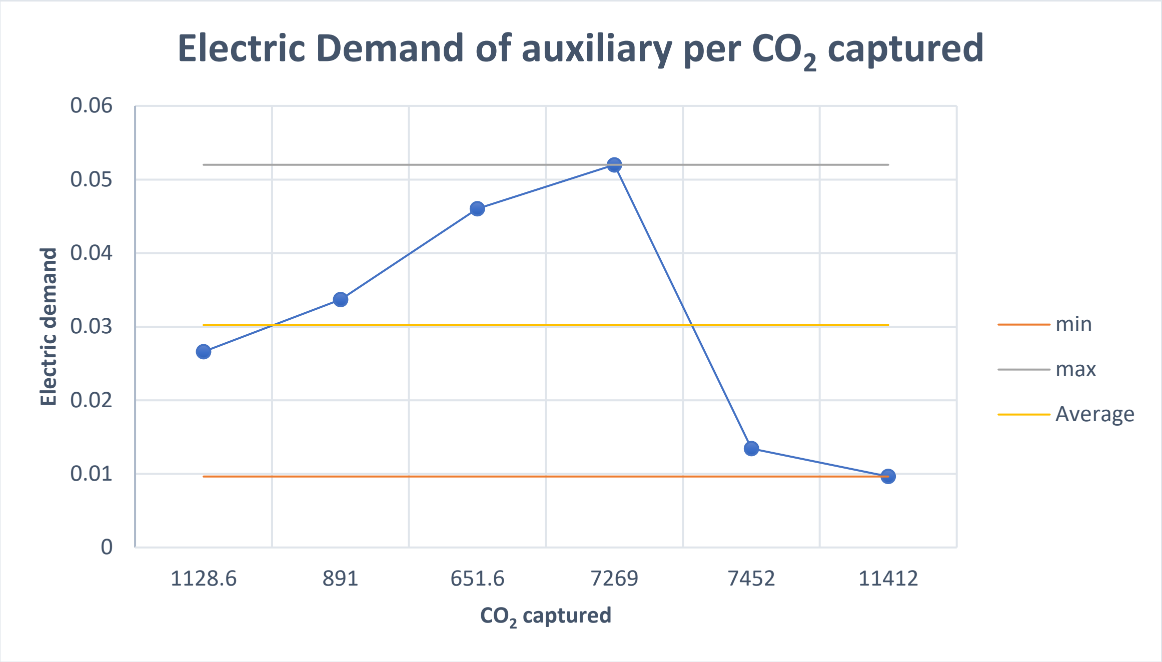


Figure 31: Electric power for carbon capture process of auxiliary per CO_2 captured.

Table 21: Electric Demand for carbon capture process of auxiliary per CO_2 captured.

Electric Demand of AUX per CO_2 captured(kWh/kg)			
Fuel	Case	min	max
MEA	Case study 1	0.026581606	0.005068052
	Case study 3	0.052	0.052
	Case study 5	0.009638977	0.013419216
	Case study 7		
	Total	**0.009638977**	**0.052**
	Average	**0.030225058**	
	Deviation	**0.015575849**	

The subsequent phase of the electric requirement analysis involves determining the power demand necessary for the liquefaction of the captured CO_2. The primary factor chosen for examining this process was the quantity of captured CO_2. However, it's crucial to consider the specific conditions required for the storage and transportation of carbon dioxide.

Initially, it's important to note that lower target liquefaction temperatures and higher target pressures necessitate increased electric power for the process. Moreover, a decrease in storage temperature correlates with an increase in electricity power requirements. Typically, common storage conditions involve maintaining CO_2 in a liquid phase close to its triple point. The studies forming the basis of this thesis encompass a range of CO_2 storage conditions, each tailored to specific ship characteristics and requirements.

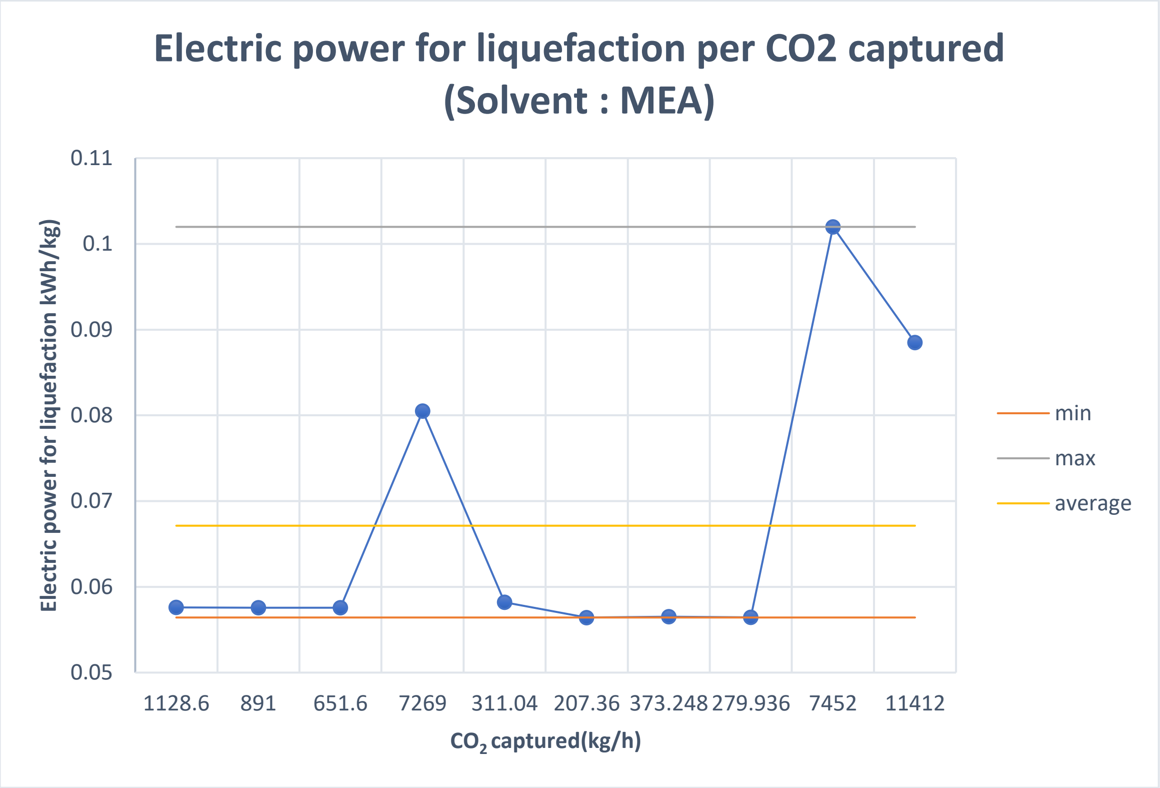


Figure 32: Electric power for liquefaction of CO_2 captured per CO_2 captured.

In case number 5, the storage conditions are extremely high in contrast to other cases and this is the reason why the energy demand is two times higher. Specifically, in all cases the storage conditions range from 6.5 bar to 22 bar pressure and temperature from -16°C to -51°C. For case number 5, the storage conditions of the CO_2 are 73 bar pressure and 31°C. It is an important difference which have a serious impact on electricity demand. For storage conditions of pressure from 6.5 bar to 22 bar and temperature from -16°C to -51°C an average electric power of 0.06 $kWh/kg_{CO2captured}$ is required according to studies. However, the table 22 presents an overall performance of electric demand for liquefaction of CO_2 using MEA with a capture rate of 90%.

Table 22: Electric Demand for Liquefaction of CO_2 captured per CO_2 captured.

Electric Demand for liquefaction per CO2 captured(kWh/kg)			
Fuel	Case	min	max
MEA	Case study 1	0.057573074	0.057593479
	Case study 3	0.0805	0.0805
	Case study 4	0.056423611	0.058191872
	Case study 5	0.08850333	0.101986044
	Total	**0.056423611**	**0.101986044**
	Average	**0.067131673**	
	Deviation	**0.015953808**	

For the cases with piperazine solvent, the results are different. However, the storage conditions are the same, pressure equal to 11 bar and temperature around to -36°C or pressure 22 bar with a temperature of -16°C. As the CO_2 capture increases the electric power for liquefaction decreases as it seems in figure 32. Both electric power for liquefaction/storage and of auxiliary units have a same treatment. While the amount of CO_2 captured increases, the electric demand decreases.

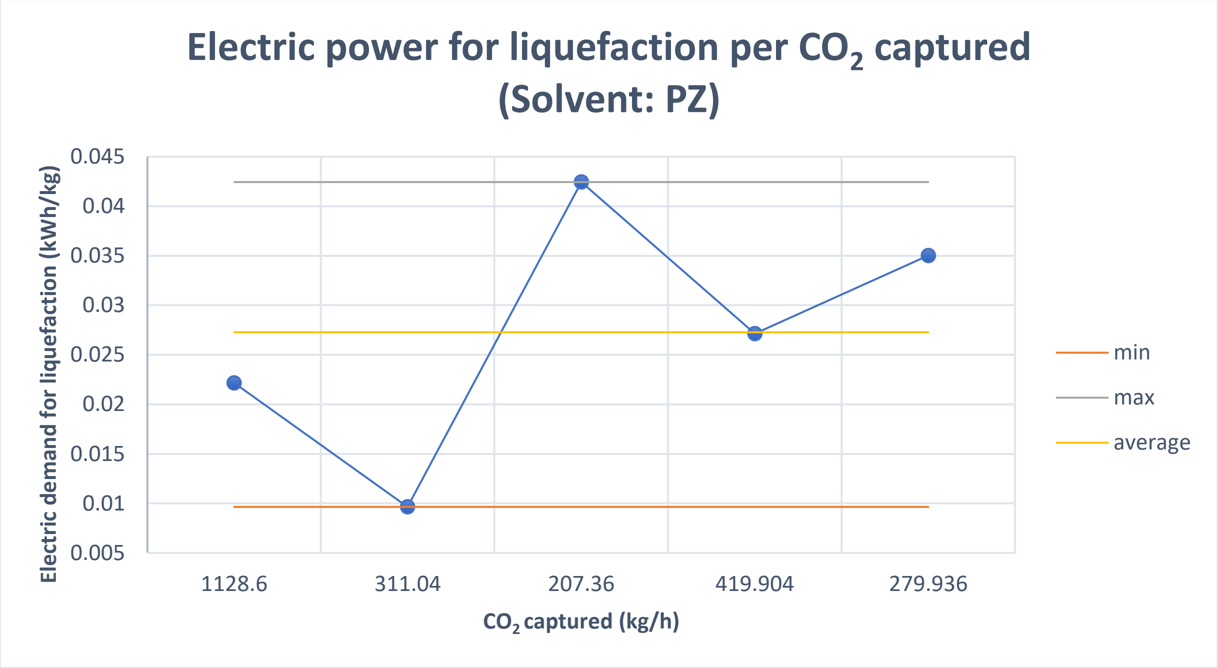


Figure 33: Electric power for Liquefaction of CO_2 captured per CO_2 captured, using piperazine as solvent.

Table 23: Electric power for Liquefaction of CO_2 captured per CO_2 captured, using piperazine as solvent.

Electric Demand for liquefaction per CO2 captured(kWh/kg)			
PZ	Case study 1	0.022151338	0.022151338
	Case study 4	0.009645062	0.042438272
	Total	**0.009645062**	**0.042438272**
	Average	**0.027278347**	
	Deviation	**0.011196487**	

Having estimated the partial electric energy demand for the system, the next step is to determine the total energy demand for the electric power of the CCS. Studies provide information about the electric demand for all different types of solvent apart from piperazine (PZ). For all cases, except from the last one (case 7), the total electric energy requirement decreases while the CO_2 captured increases. In case study 7 the exact opposite happens.

In the case study number 5, the decrease in electric demand despite the increase in captured CO_2 can be attributed to the utilization of a gas turbine. Initially, the first scenario relied solely on the ship's auxiliary parts to meet the electricity demand within the system, resulting in a lower amount of CO_2 captured compared to the second scenario. In the second scenario, a gas turbine was integrated into the system to fulfill the electric demand for the carbon capture operation, contributing to a higher capture of CO_2. The introduction of the gas turbine aimed to enhance the overall energy performance of the system. The treatment with a gas turbine in case 1 was replicated in case 5 to improve the system's operation, elucidating the decrease in power demand with an increase in captured CO_2. Interestingly, when using aqueous ammonia as a solvent, the total electric demand followed a similar trend to case study number 1 and 5, which employed MEA. Figure 34 and figure 35 shows the previous observations, table 24 and table 25 present the data for electric requirement according to the type of solvent which is used.

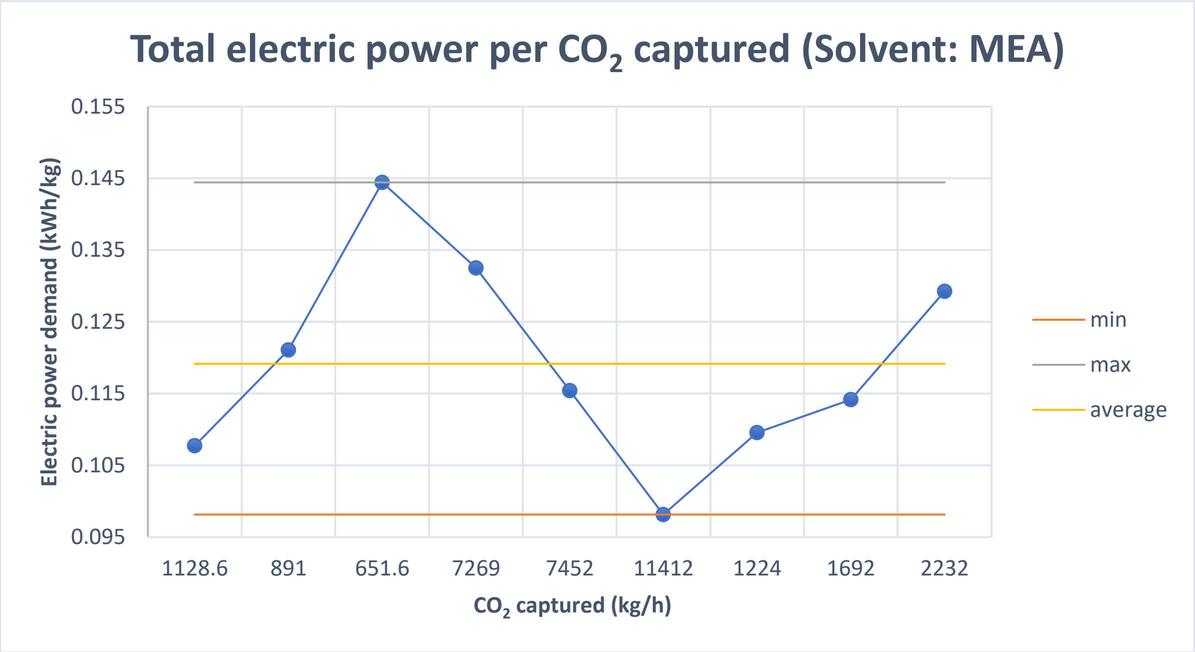


Figure 34: Total Electric power for carbon capture process per CO_2 captured, using MEA as solvent.

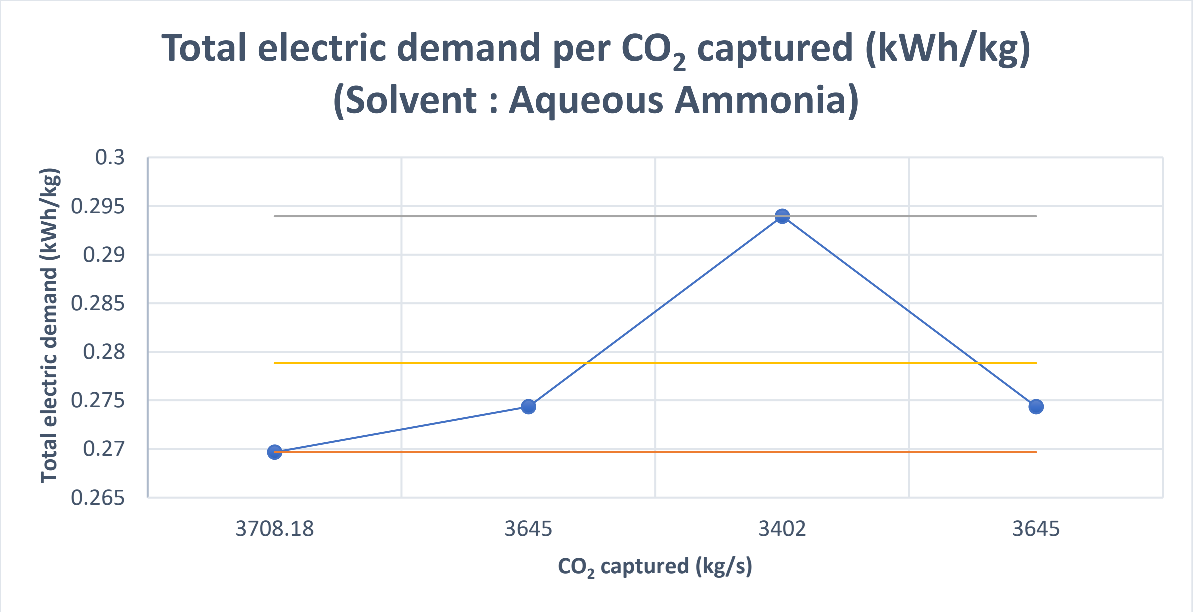


Figure 35: Total electric power for carbon capture process per CO_2 captured, using aqueous ammonia as solvent.

Table 24: Total electric power for carbon capture process per CO_2 captured, using MEA as solvent.

Total Electric Demand per CO_2 captured(kWh/kg)			
Fuel	Case	min	max
MEA	Case study 1	0.107744108	0.14443618
	Case study 3	0.1325	0.1325
	Case study 5	0.098142306	0.11540526
	Case study 7	0.109558824	0.129256272
	Total	**0.098142306**	**0.14443618**
	Average	**0.119147172**	
	Deviation	**0.064675746**	

Table 25: Total electric power for carbon capture process per CO_2 captured, using Aqueous Ammonia as solvent.

Total Electric Demand per CO_2 captured(kWh/kg)			
Fuel	Case	min	max
Aqueous Ammonia	Case study 2	0.269674072	0.269674072
	Case study 6	0.274348422	0.293944738
	Total	**0.269674072**	**0.293944738**
	Average	**0.278836095**	
	Deviation	**0.008504885**	

5.2.3. Dimensions of packed columns

Before applying the equations of Cornell's method in order to calculate the dimension of carbon capture units, it is really important to determine the number of stages (N_{OG}) of packed columns. Parameter N_{OG} depends on the factor $m\frac{G_m}{L_m}$ and $\frac{y_1}{y_2}$(partial pressure drop), where:

- $m = \frac{mole\ fraction\ in\ vapor}{mole\ fraction\ in\ liquid}$.
- G_m = molar gas flow rate per unit cross-sectional area.
- L_m= molar liquid flow rate per unit cross-sectional area.
- y_1,y_2 = the mol fractions of the solute in the gas at the bottom and top of the column, respectively.

The figure 36 shows the number of transfer units as a function of $\frac{y_1}{y_2}$ (partial pressure drop) with $m\frac{G_m}{L_m}$ as parameter.

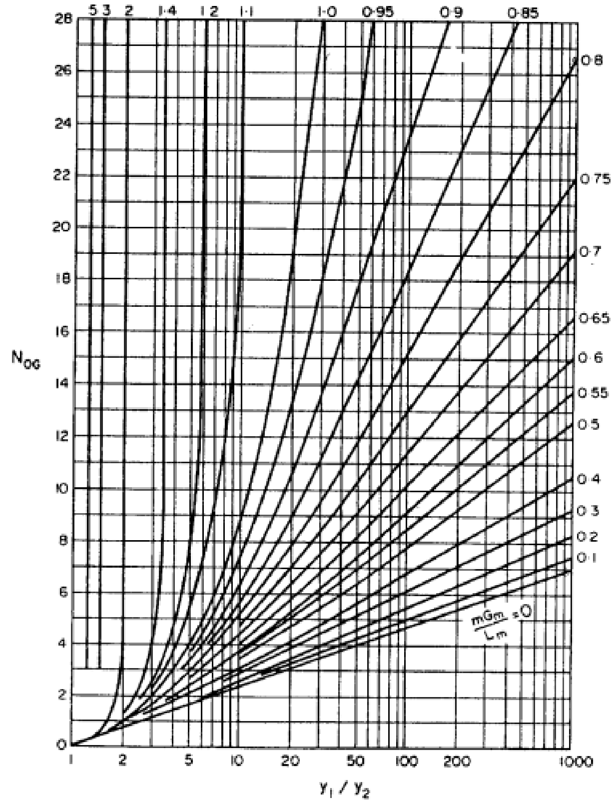


Figure 36: Number of transfer units N_{OG} as a function y_1/y_2 with mG_m/L_m as parameter [134].

5.2.3.1. Diameter of the packed column

The capacity of a packed column is determined by its cross-sectional area. Normally, the column will be designed to operate at the highest economical pressure drop, to ensure good liquid and gas distribution.

First step of the analysis is to estimate the gas flow rate (kg/s) into the packed columns and the liquid flow rate (kg/s). The liquid is the type of solvent which is used in the absorption process. The operation temperature of the absorber is 40°C. At this temperature it is estimated the gas density and the liquid (solvent) density in kg/m^3, while the solvent viscosity in Ns/m^2.

Secondly, it is needed to determine the pressure drop and the factor $\frac{L_{\dot{W}}}{V_{\dot{W}}}\sqrt{\frac{\rho_v}{\rho_L}}$ in order to estimate the factor K_4 and the factor K_4 at flooding from figure 22, calculating the percentage flooding. Furthermore, the factor K_4 it is used to calculate the solvent-liquid flow rate in kg/m^{2}s.

$$V_{\dot{W}} = \sqrt{\frac{K_4 * \rho_v * (\rho_L - \rho_v)}{13.1 * F_p * (\frac{\mu_L}{\rho_L})^{0.1}}}.$$

Where:

- F_p= packing factor, charactreristic of the size and type.
- ρ_v= liquid density, kg/m^3.
- ρ_L= vapour density, kg/m^3.
- μ_L= liquid viscosity, Ns/m^2.

The percentage of flooding is estimated equal to $\sqrt{\frac{K_{4\_estimated}}{K_{4\_flooding}}} * 100$

After calculating the solvent liquid flow rate in kg/m^{2}s, it can be estimated the column area required in m^2 by dividing the gas flow rate with the solvent liquid. The diameter of the packed column is calculated with the following equation:

$$\text{Diameter}=\sqrt{\frac{4}{\pi} * column\ area\ required}.$$

The correct column area is then calculated:

$$Column\ area = \frac{\pi}{4} * diameter^2$$

Finally for the height of the packed column according to Cornell's method it is necessary to estimate the percentage flooding at selected diameter using the following equation:

$$\text{Percentage flooding at selected diameter} = \frac{Column\ area\ required}{Column\ area} * \%\ flooding.$$

5.2.3.2. Height of the packed column

The height of packing column is given by the following equation:

$$Z = \frac{G_m}{K_G a P} \int_{y_2}^{y_1} \frac{dy}{y - y_e}.$$

Or,

$$Z = \frac{L_m}{K_L a P} \int_{X_2}^{X_1} \frac{dx}{x_e - x}.$$

The equation. is in terms of the overall gas phase mass transfer coefficient K_L and the liquid composition, while the equation. is in terms of the overall liquid phase mass transfer coefficient K_L and the liquid composition.

Where,

- G_m= molar gas flowrate per unit cross-sectional area.
- L_m= molar liquid flowrate per unit cross-sectional area.
- α= interfacial surface area per unit volume.
- P=total pressure.
- C_t= total molar concentration.
- y_1 and y_2= the mol fraction of the solute in the gas at the bottom and top of the column respectively.

- x_1 and x_2= the mol fraction of the solute in the liquid at the bottom and top of the column respectively.
- x_e=the concentration in the liquid that would be in equilibrium with the gas concentration at any point.
- y_e=the concentration in the gas that would be in equilibrium with the liquid concentration at any point.

For design purposes, it is convenient to write the equations in terms of “transfer units” (HTU), where the value of integral is the number of transfer units and the group in front of the integral sign which has units of length, is the height of a transfer unit.

$$Z = H_{OG} N_{OG}.$$

$$Z = H_{OL} N_{OL}.$$

Where,

- $H_{OG} = \frac{G_m}{K_G a P}$, is the height of an overall gas-phase transfer unit.
- $N_{OG} = \int_{y_2}^{y_1} \frac{dy}{y - y_e}$, is the number of overall gas-phase transfer units.
- $H_{OL} = \frac{L_m}{K_L a C_t}$, is the height of an overall liquid-phase transfer unit.
- $N_{OL} = \int_{x_2}^{x_1} \frac{dx}{x_e - x}$, is the number of overall liquid-phase transfer unit.

The number of overall gas-phase transfer units is often more conveniently expressed in terms of the partial pressure drop of the solute gas.

The relationship between the overall height of a transfer unit and the individual film transfer units H_L and H_G, which are based on concentration driving force across the liquid and gas films is given by:

$$H_{OG} = H_G + m \frac{G_m}{L_m} H_L.$$

$$H_{OL} = H_L + \frac{L_m}{m G_m} H_G.$$

Cornell’s method is used in order to estimate the H_G and H_L. From chapter 5.1 “Important metrics” the equations of Cornell’s method are the following:

- $$H_G = \frac{0.011 \psi_h (Sc)_v^{0.5} (\frac{D_C}{0.305})^{1.11} (\frac{Z}{3.05})^{0.33}}{(L_{\dot{W}} f_1 f_2 f_3)^{0.5}}.$$
- $$H_L = 0.305 \varphi_h (Sc)_L^{0.5} K_3 (\frac{Z}{3.05})^{0.15}.$$

Where,

- H_G= Height of a gas-phase transfer unit, m.
- H_L= Height of a liquid-phase transfer unit, m.
- $(Sc)_v$=gas Schmidt number =$(\frac{\mu_v}{\rho_v * D_v})$.
- $(Sc)_L$= liquid Schmidt number =$(\frac{\mu_L}{\rho_L * D_L})$.
- $L_{\dot{W}}$=Liquid mass flowrate per unit area column cross-sectional area, kg/m^{2}s.
- Z= column height, m.
- D_c=column diameter, m.

- K_3= percentage flooding correction factor, from figure 37.
- ψ_h= H_G factor from figure 38.
- ψ_L= H_L factor from figure 39.
- f_1= liquid viscosity correction factor = $(\frac{\mu_L}{\mu_w})^{0.16}$.
- f_2= liquid density correction factor=$(\frac{\rho_W}{\rho_L})^{1.25}$.
- f_3= surface tension correction factor=$(\frac{\sigma_w}{\sigma_L})^{0.8}$.

At first it is needed to determine the mass diffusion of the exhaust gas (D_V) and the solvent (D_L) respectively. From Chemical Engineering Design “Principles, Practice and Process Design”, the mass diffusion for gas and liquid is given by the following equations:

- $D_v = \frac{1.013*10^{-7}T^{1.75}*\sqrt{\frac{1}{M_a}+\frac{1}{M_b}}}{P*(\sqrt[3]{\sum_a v_i}+\sqrt[3]{\sum_b v_i})^2}$, for gases

- $D_L = \frac{1.173*10^{-13}*(\varphi M)^{0.5}*T}{\mu*V_m^{0.6}}$, for liquid

Where,

- T= temperature, K
- M_a, M_b= molecular masses of components a and b
- P= total pressure, bar
- $\sum_a v_i$, $\sum_b v_i$= the summation of the special diffusion volume coefficients.
- φ= an association factor for the solvent
  = 2.6 for water
  = 1.9 for methanol
  = 1.5 for ethanol
  = 1.0 for unassociated solvents
- M =molecular mass of solvent
- μ= viscosity of solvent , Ns/m^2
- V_m= molar volume of the solute at its boiling point, m^3/ kmol. This can be estimated from the group contributions given in table 26.

Πίνακας 26: Molecular Volumes m3/kmol.

Molecular Volumes m^3/kmol	
Air	0.0299
CO_2	0.034
CO	0.0307
H_2	0.0143
NH_3	0.0258
C	0.0148
H	0.0037
F	0.0087
P	0.027
Br	0.027
Cr	0.0274
primary amines	0.0105

Having calculated the mass diffusion and estimated the viscosity of gas (from the data of the studies which are examined in this thesis) and solvent (from literature), it can be determined the gas and liquid Schmidt number respectively.

Next step is to estimate the Liquid mass flowrate per unit area column cross-sectional area $(L_{\dot{W}})$. From the method which was used for the calculation of the diameter of the column, it has already been determined the column area in m^2, and the liquid mass flowrate in kg/s. The simple deviation of liquid mass flow rate with the column area is providing the $L_{\dot{W}}$ in kg/s m^2.

$$L_{\dot{W}} = \frac{Liquid\ mass\ flow-rate\ in\ kg/s}{Column\ area}.$$

Having calculated the $L_{\dot{W}}$, it can be estimated the factor for H_L, for Berl Saddles from figure 37.

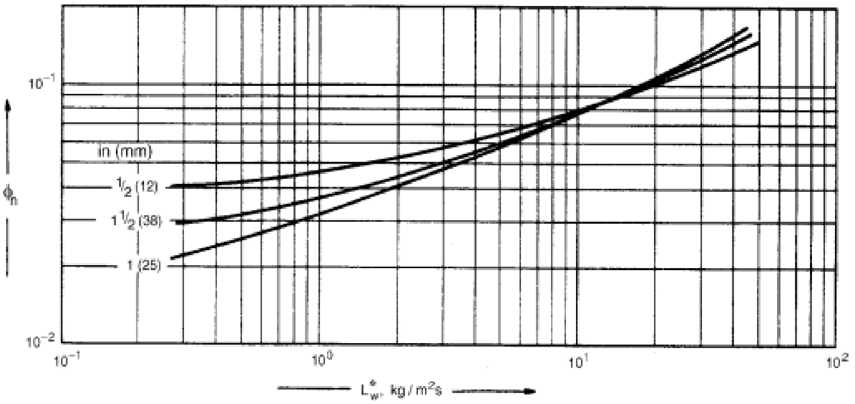


Figure 37: Factor for HL for Berl saddles.

From the percentage flooding which has been estimated in the calculation method of the packed column diameter, it can be determined the percentage flooding correction factor K_3 by the figure 38 and the factor for H_G (ψ_n) by the figure 39, for Berl Saddles.

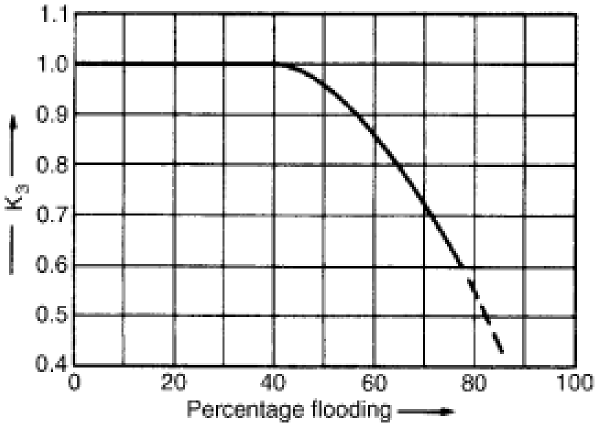


Figure 38: Percentage flooding correction factor.

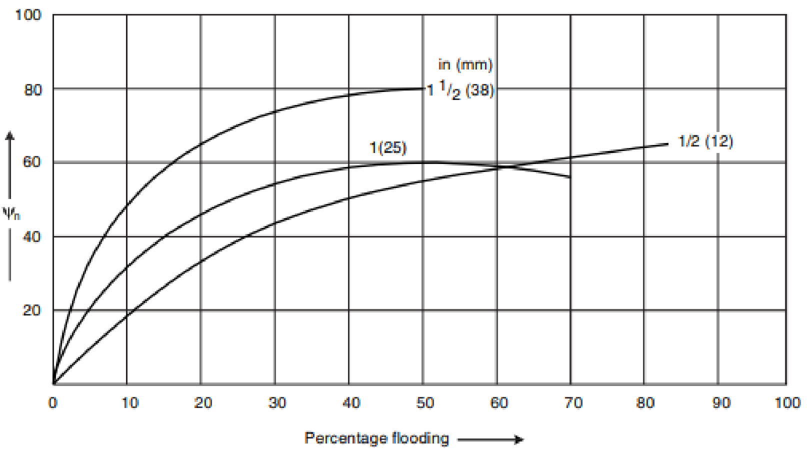


Figure 39: Factor for HL for Berl saddles.

Next step for the calculation of the height of the packed column is to determine the factors f_1,f_2,f_3 according to the viscosity , the density and the surface tension of the water and the solvent which is used. Specifically:

- $f_1 = (\frac{\mu_L}{\mu_w})^{0.16}$.
- $f_2 = (\frac{\rho_w}{\rho_L})^{1.25}$.
- $f_3 = (\frac{\sigma_w}{\sigma_L})^{0.8}$.

Finally, a first estimation of the height Z is needed for the use of the equations.

5.2.4. Technoeconomic model

A preliminary cost estimation considering all machinery required for the CC system follows the Chemical Engineering Design [134] provides functions and parameters for different equipment that calculates the cost of each part. Multiplying the capital cost with the installation factors proposed by Hand, a total economic overview of the CC system is given.

To begin with, the total capital cost (including engineering cost) is given by the following equation.

$$\mathrm{C} = \mathrm{F} \sum \mathrm{C_F}$$

Where,

- F= an installation factor (Table 27)
- $\sum C_F$= total delivered cost of all the major equipment items: reactors, tanks, columns, heat exchangers, furnaces etc.

Table 27: Installation factor F.

Equipment Type	Installation Factors
Compressors	2.5
Distillation columns	4
Fired heaters	2
Heat exchangers	3.5
Instruments	4
Miscellaneous equipment	2.5
Pressure vessels	4
Pumps	4

Another factor which has to be considered is the material cost factor (Table 28).

Table 28: Material cost factor Fm.

Material	fm
Carbon Steel	1
Aluminium and Bronze	1.07
Cast steel	1.1
304 stainless steel	1.3
316 stainless steel	1.3
321 stainless steel	1.5
Hastelloy C	1.55
Monel	1.65
Nickel and Inconel	1.7

In this thesis, the cost evaluation is based on engineers who lack access to reliable cost data or estimating software. For this reason, the table 28 below shows the correlations which are formed by the following equation

$$C_e = a + bS^n$$

Where,

- C_e= purchased equipment
- α,b= cost constants (Table 29)
- S=size parameter (Table 29)
- n=exponent for that type of equipment

Table 29: Purchased Equipment Cost for Common Plant Equipment.

Equipment	Units for size, S	Slower	Supper	a	b	n
Boilers						
Packaged, 15 to 40 bar	kg/h steam	5000	200000	4600	62	0.8
Field erected, 10 to 70 bar	kg/h steam	20000	800000	-90000	93	0.8
Compressors						
Blower	m3/h	200	5000	4200	27	0.8
Centrifugal	driver power, kW	132	29000	8400	3100	0.6
Reciprocating	driver power, kW	100	16000	240000	1.33	1.5
Distillation columns						
See pressure vessels, packing and trays	-	-	-	-	-	-
Exchangers						
U-tube shell and tube	area, m2	10	1000	10000	88	1
Floating head shell and tube	area, m2	10	1000	11000	115	1
Double pipe	area, m2	1	80	500	1100	1
Thermosyihon reboiler	area, m2	10	500	13000	95	1
U-tube Kettle reboiler	area, m2	10	500	14000	83	1
Plate and frame	area, m2	1	180	1100	850	0.4
Packings						
304 ss Raching rings	m3	-	-	0	3700	1
Ceramic intalox saddles	m3	-	-	0	930	1
304 ss Pall rings	m3	-	-	0	4000	1
PVC structured packing	m3	-	-	0	250	1
304 ss structured packing	m3	-	-	0	3200	1

Equipment	Units for size, S	Slower	Supper	a	b	N
Pressure Vessels						
Vertical, cs	shell mass, kg	150	69200	-400	230	0.6
Horizontal, cs	shell mass, kg	250	69200	-2500	200	0.6
Vertical, 304 ss	shell mass, kg	90	124200	-10000	600	0.6
Horizontal, 304 ss	shell mass, kg	170	114000	-15000	560	0.6
Pumps and drivers						
Single-stage centrifugal	flow Litters/s	0.2	500	3300	48	1.2
Explosion-proof motor	power, kW	1	2500	920	600	0.7
Condensing steam turbine	power, kW	100	20000	-19000	820	0.8
Trays						
Sieve trays	diameter, m	0.5	5	100	120	2
Valve trays	diameter, m	0.5	5	130	146	2
Bubble cap trays	diameter, m	0.5	5	200	240	2
Utilities						
Cooling tower & pumps	flow liters/s	100	10000	61000	650	0.9
Packaged mechanical refrigerator	evaporator duty, kW	50	1500	4900	720	0.9
Water ion exchange plant	flow m3/h	1	50	6200	4300	0.9

Table 28 doesn't provide data information for the size parameter for distillation columns. The distillation column can be costed as a combination of a vertical pressure vessel and internals. It is necessary to determine the wall thickness as it is given in equation:

$$t_W = \frac{P * D}{2 * S * E - 1.2 * P}$$

Where,

- P: Design pressure
- D: Diameter
- S: Allowable stress, (table 29)
- E: Welded-joint efficiency

Next step to estimate the C_e is to calculate the shell mass using the following equation:

$$Shell\ mass = \pi * D_c * L_c * t_w * \rho$$

Where,

- D_c= Diameter of Column
- L_c= Length of Column
- t_w=thickness of column
- ρ=Density of the column's material

The final step is to estimate the installation cost, following the Hand's method, multiplying the cost with the installation factor proposed by Hand.

$$C = f * C_e$$

5.3. Analysis / Compare with land

This section aims to compare Maritime carbon capture systems with the land-based projects previously discussed in Chapter 3. Land-based projects typically involve large-scale facilities, where the costs associated with system establishment and sizing significantly differ from their maritime counterparts. Therefore, when evaluating their equivalence in maritime applications, these specific cost considerations are not taken into account for comparison purposes.

However, the energy demand of the land-based systems for the system is an important parameter that can be considered to examine the operations of marine projects. Most studies analyzed have used monomethylamine (MEA) and aqueous ammonia as solvents. According to literature, the heat demand for capturing CO_2 using MEA as a solvent is estimated to be around 1-1.1 kWh/$kg_{CO2captured}$, while using aqueous ammonia as a solvent demands approximately 0.5556-0.6944 kWh/$kg_{CO2captured}$ [133].

Table 30: Heat required for carbon capture process using MEA and Aqueous Ammonia in Land-Based case studies.

Case studies	Heat requiered per CO_2 captured
MEA	
1	0.7778
9	0.9833
3	1.1
4	1.19
5	1.42
6	1.334983217
10	1.01
10	1.013
10	1.016
10	1.027
10	1.027
11	1.044
12	1.041
13	1.04166375
13	1.06110814
13	1.07777476
13	1.16110786
13	1.269444409
Average	1.08862123
Deviation	0.141160567
Aqueous ammonia	
2	0.81111
7	0.777
8	0.709664387
Average	0.765924796
Deviation	0.051621683

Table 30 shows the results of the analysis for land-based studies for MEA and aqueous ammonia. The overall energy performance of the system employing monomethylamine as a solvent, aligns with the corresponding literature data. However, utilizing aqueous ammonia as a solvent appears to exhibit differences. Specifically, there seems to be a deviation in the energy performance compared to the literature data derived from land-based projects, estimated at 0.070452.

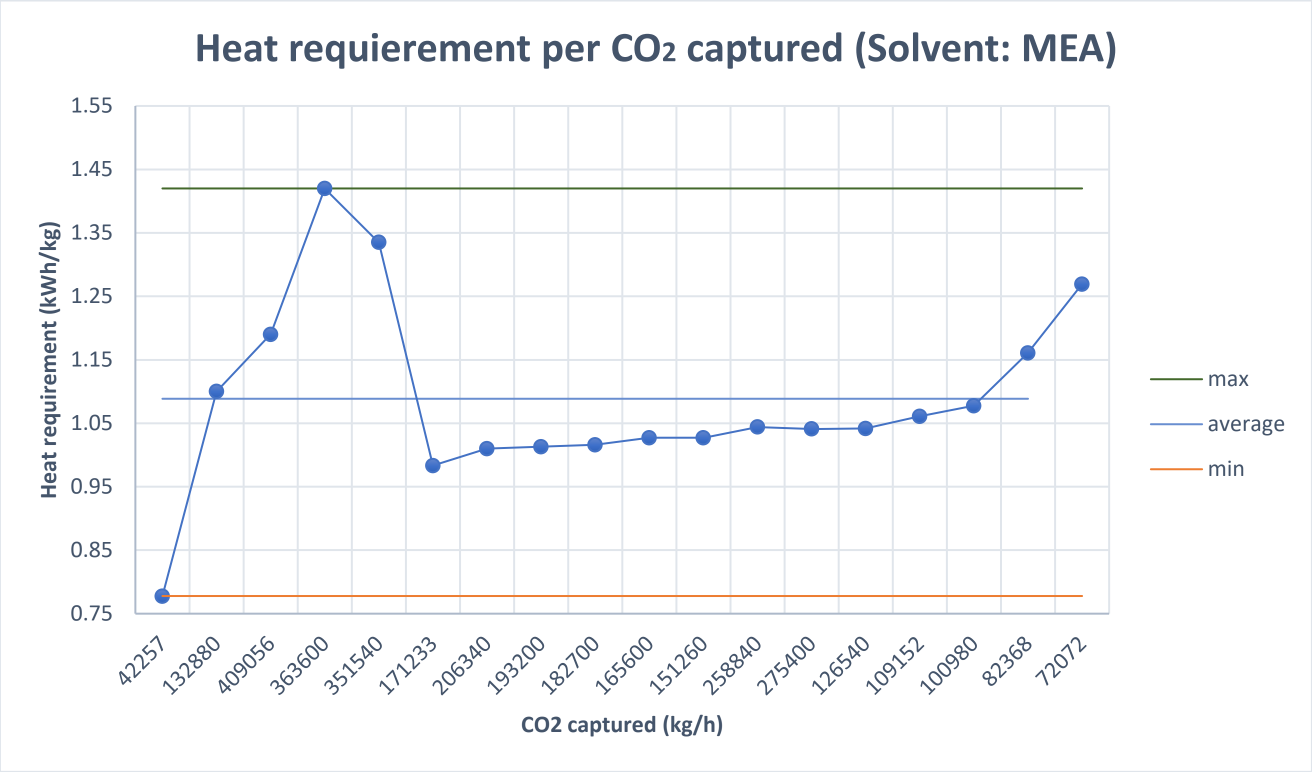


Figure 40: Heat required for the carbon capture process per CO2 captured, using MEA as solvent (Land-based case studies).

The table 31 and table 32 below compares the heat demand using MEA for both maritime applications and land-based projects. In most marine studies, there's a general alignment with the corresponding data from land-based projects, showing a deviation of approximately 0.03043. However, in the case of maritime case study number 4, the heat demand exceeds the energy requirement. Conversely, when utilizing aqueous ammonia, there's a considerable difference in heat power between maritime applications and land-based projects. In conclusion, the use of MEA as a solvent in the shipping industry for implementing a carbon capture system onboard appears to be the most reliable option compared to other solvents, which exhibit lagging data and operational performance.

Table 31: Compare land-based studies with maritime applications of energy demand using MEA.

MEA		
	Land-based	Maritime application
Min	0.7778	1.0027
Max	1.42	1.494984568
Average	1.08862123	1.149483998
Deviation	0.030431384	

Table 32: Compare Land-Based studiez with maritime application of energy demand, using Aqueous Ammonia.

Aqueous ammonia		
	Land-based	Maritime application
Min	0.709664387	0.916891845
Max	0.81111	1.75
Average	0.765924796	1.251867493
Deviation	0.242971349	

6. Carbon Capture Technology Application study

In this Chapter, we will explore the application of a carbon capture system on various types of ships. Based on the analysis of maritime case studies presented in Chapter 5, we will provide an overview of the overall energy performance. Additionally, we will delve into determining the dimensions of the CCS components, and finally, propose a cost evaluation.

First step of the application study is to determine the ship in which the CCS will be implemented. Specifically, the reference ship is a Very Large Crude Oil Tanker (VLCC) with a total capacity of 300.000 DWT. The vessel specifications, drawings and performance data were provided by Euronoav Ship Management LTD. The vessel has one Wartsila 16V46F main engine with an Engine output 19200kW x 600 rpm [155]. She also supplies 3 Hyundai-Himsen 9MELOAD1/32 auxiliary engines with a total output of 4590kW x 900 rpm. The fuel consumed by the engines is Heavy Fuel Oil. The specific characteristics of crude oil carrier are presented on the table 33.

Table 33: Characteristics of the Ship-reference

Ship type	Length O.A. (m)	Length B.P. (m)	Breadth (m)	Depth (m)	Design Draught (m)	Scantling Draught (m)	Engine MCR (kW)
Crude oil Carrier (VLCC)	333.08	322	60	29.4	20.5	21.6	16320

The power of the engine is examined at the load of 85% ME (MCR). Specifically, according to technical data of this engine [155], the exhaust gas flow (kg/s) and the fuel consumption at 85% are given below:

- Exhaust gas flow: 32 kg/s.
- Fuel Consumption: 178.1 g/kWh.

As it is already mentioned in Chapter 5, the most important parameter which were used in this thesis in order to estimate the energy demand of the system is the CO_2 in the exhaust mass flow. For the determination of the exhaust mass gas flow, the following equation were used [156]:

$$CO_{2emissions} = Fuel\ Consumption * Fuel\ emission\ conversion\ factor.$$

The fuel consumption is influenced by both the engine's technical specifications and fuel consumption data [155], with the fuel emission conversion factor from ISO 8217 IMO (Cf=3.114) [157]. Subsequently, the calculation of CO_2 emissions yields a value of 2.51 kg/s. Consequently, the CO_2 content in the exhaust gas flow is estimated to be 7.84%. The capture rate is approximated at around 90%, aligning with the prevalent trend observed in most studies conducted, which have consistently utilized a capture rate of 90%. The captured CO_2 is then estimated to be 2.259 kg/s.

Table 34: Technical Data of ME.

Description	Units	
Exhaust gas flow	32	kg/s
Fuel consumption	178.1	g/kWh
CO_2 content in Exhaust	7.84	(%w/w)
CO_2 production	2.51	kg/s

Generally, a specific amount of exhaust gases are entering the CCS carbon capture system. In this analysis is considered that the 100% of exhaust gases enter the CCS. For the implementation of the carbon capture system on the ship, it is important to present the General Arrangement. The carbon capture units are about to be established in the space between the wheelhouse and the LNG-tank.

6.1. Energy Performance of CCS.

From chapter 5 "Maritime Carbon Capture System Analysis", the data and metrics will be used for the determination of the energy demand. Specifically, the maritime case studies of the Chapter 4 "Maritime Carbon Capture System" shows that the heat requirement range from 1.0027kWh/kg$_{CO2captured}$ to 1.4948 kWh/kg$_{CO2captured}$ using monothelamine as solvent. For piperazine, the heat demand fluctuates from 0.9569 kWh/kg$_{CO2captured}$ to 1.4146 kWh/kg$_{CO2captured}$. Finally, the use of Aqueous Ammonia as solvent requires a heat energy for capture equal to 0.9169 kWh/kg$_{CO2captured}$ – 1.75 kWh/kg$_{CO2captured}$.

As previously mentioned in Chapter 5, the primary factor influencing the heat demand in the capture process is the choice of solvent. In this section, an examination of three different scenarios involving the same reference ship is undertaken, employing MEA, piperazine, and Aqueous Ammonia as solvents, respectively. Among these, monothelamine (MEA) stands out as the most widely utilized. The range of engines employed in maritime applications spans from 1280 kW to 33250 kW, with the corresponding exhaust gas flow estimated to range from 7200 kg/h to 151076 kg/h, averaging at 41731.91 kg/h.

The key parameters for assessing the Energy Demand of the carbon capture system are h_1 (representing thermal energy) and e_1 (indicating electric power), as detailed in Chapter 5. It is crucial to highlight that the most dependable solvent for this purpose is monothelamine (MEA). This preference is grounded in the thorough analysis of energy demands, encompassing both thermal and electric aspects specific to maritime applications. The consistency with established studies in Land-based projects and alignment with literature-reviewed data further affirm MEA as a reliable choice for solvent use in this context.

For all three solvents the average power demand is used in order to calculate the energy requirement for the carbon capture system as it shown in Table 35.

Table 35: Energy Demand for the application CCS

Energy Demand for the application CCS				
Solvent	Analysis Data for heat demand per CO_2 captured (kWh/kg$_{CO2}$)	Analysis Demand for electric power per CO_2 captured (kWh/kg$_{CO2}$)	Heat Demand for the application CCS (kW)	Electric Demand for the application CCS (kW)
MEA	1.14	0.1191	9270.936	968.56884
Piperazine	1.24	-	10084.176	-
Aqeuous Ammonia	1.25	0.2781	10165.5	2261.62044

In the context of heat demand, when utilizing MEA, there is a deviation of 18%, whereas the use of piperazine and aqueous ammonia yields estimated deviations of 16% and 27%, respectively. The electric power requirement is eliminated when piperazine is used as a solvent. Conversely, for monothelamine and aqueous ammonia, the deviations in electric power are 1.3% and 0.92%, respectively. Notably, both in terms of electric and thermal power, the utilization of MEA as a solvent proves to be more energy-efficient for the capture and liquefaction-storage of CO_2 compared to the other two solvents, namely Aqueous ammonia and Piperazine.

6.2. Dimension and sizing of CCS

As it is already mentioned the method which is used for the sizing of the CCS according to to chapter 5 is Onda's and Cornell Method. The most important units which need to been determined for the CCS is the absorption column and the stripper respectively. The rest of units such as the pumps, the boiler, the condensers, the compressors, blower (if it is existed) and tanks of CO_2 captured have specific dimension. The dimensions of absorption and stripper column are exactly the same [108], so the determination of only the absorption column is required. It is important to be mentioned that the next analysis of dimensions of units and the techno economical model are use only the case of monomethylamine as solvent.

6.2.1. Diameter

In subchapter 5.2.3.1 the method of diameter of packed column is been described. The first step is to determine the exhaust gas flow and liquid flow rate. The exhaust gas flow rate has been already determined and the solvent rate results from the case studies which have been already investigated.

- Gas flow rate= 32kg/s
- Liquid flow rate= 186.47 kg/s

The gas density is estimated of around 1.05kg/m^3 at a temperature of 40°C, where the absorber column is operated, and a gas viscosity of μ=0.00003996 Ns/m^3. The density and viscosity of exhaust gas of HFO is estimated according to the data analysis of the maritime case studies. For MEA the viscosity is equal to 0.003Ns/m^3 and the density is estimated to 10053.39 kg/m^3[159]. This physical properties of MEA are the most common for the use in CCS.

Then is needed to estimate factor K_4, using the following parameter F_{LV}:

$$\frac{L_{\dot{w}}}{V_{\dot{W}}}\sqrt{\frac{\rho_v}{\rho_L}} = \frac{186.47}{32}\sqrt{\frac{1.05}{1053.3}} = 0.1840$$

The design is assumed to be at a pressure drop of 50mm H_2O/m packing because the recommended value of liquid pressure drop is between 15-50mm H_2O per meter packed area[108].

From figure 22, the K_4 is equal to 1.8 and 3.5 at flooding line.

The percentage flooding = $\sqrt{\frac{1.8}{3.5}} * 100 = 72\%$

Next step is to estimate the gas flow rate in kg/m^2s using the following equation:

$$V_{\dot{W}} = \sqrt{\frac{K_4 * \rho_v * (\rho_L - \rho_v)}{13.1 * F_p * (\frac{\mu_L}{\rho_L})^{0.1}}} = 3.73 kg/m^2 s$$

The Fp factor is the packing factor. The most common in use and selected for this application is the Mellapak 250Y and Berl saddles. Typical price of packing factor for a Berl Saddle is Fp=39m^{-1} [159].

Following the column area required:

$$Column\ area\ required = \frac{Gas\ flow\ rate(\frac{kg}{s})}{V_{\dot{W}}(\frac{kg}{m^2 s})} = \frac{32}{3.73} = 8.57m^2$$

The diameter of the packed column is calculated with the following equation:

$$\text{Diameter=}\sqrt{\frac{4}{\pi} * column\ area\ required} = 3.3m$$

Round off to **D=3.5m.**

The column are is given:

$$Column\ area = \frac{\pi}{4} * diameter^2 = \mathbf{9.61m^2}$$

$$\text{Percentage flooding at selected diameter} = \frac{Column\ area\ required}{Column\ area} * \%flooding = \mathbf{64}\%$$

6.2.2. Height

For the determination of the height of the packed columns it is really important to estimate the mass diffusion of the exhaust gas (D_v) and of the liquid (D_L) respectively according to the following equations as they have been already mentioned in chapter 5.

- $D_v = \frac{1.013*10^{-7}T^{1.75}*\sqrt{\frac{1}{M_a}+\frac{1}{M_b}}}{P*(\sqrt[3]{\sum_a v_i}+\sqrt[3]{\sum_b v_i})^2}$, for gases
- $D_L = \frac{1.173*10^{-13}*(\varphi M)^{0.5}*T}{\mu * V_m^{0.6}}$, for liquid

The summation of the special diffusion volume coefficients and the molecular masses of components are given the table 36 and table 37 respectively below [134].

Table 36: Diffusion Volume

Difussion Volume				
CO_2	SO_2	N_2	O_2	air
18.9	41.1	17.9	16.6	20.1

Table 37: Molecular masses

Molecular Masses	
Exhaust gas	Air
28.91	29

The molar volume of the solute is given on the following table 38 [134].

Table 38: Molar Volume of the solute

molar volume of the solute		
C	H	NO
0.0148	0.0037	0.0236

The total molar volume of MEA (C_2H_7NO) is given by multiplying the atomic molar volume with the number of the atoms in the MEA (Table 39).

Table 39: Total Molar Volume of MEA

MEA		
C2	H7	NO
0.0296	0.0259	0.0236
0.0791		

Table 40: Characteristics of exhaust gas flow and of the solvent

Characteristics of the exhaust gas flow and of the solvent				
Temperature of Exhaust gas flow (K)	Pressure of Exhaust gas flow (bar)	ϕ	μ of solvent (Ns/m)	Molecular mass of MEA(g/mol)
316	0.045	1	0.002	61.08

According to previous data and the equation of the mass diffusion the final results are:

- $D_v=2.67 *10^{-5}$
- $D_L=4.42 *10^{-7}$

Having estimated the mass diffusion, the next step for the calculation of the packed height is to determine the gas and liquid Schmidt number respectively, while the solvent flow rate in kg/sm^3.

- $(Sc)_v = \left(\frac{\mu_v}{\rho_v * D_v}\right) = 1.4215$
- $(Sc)_L = \left(\frac{\mu_L}{\rho_L * D_L}\right) = 6.43$
- $L_{\dot{W}} = \left(\frac{L_w}{Column\ area}\right) = 19.4\ kg/sm^2$
- From figure 38, at 64% flooding, K_3=0.78
- From figure 39, at 64% flooding, ψ_h=80
- From figure 37, at $L_{\dot{W}}$=19.4, ϕ_h=0.1

Next step is to determine the factors f_1,f_2,f_3.

- $f_1 = (\frac{\mu_L}{\mu_w})^{0.16} = 1.28$
- $f_2 = (\frac{\rho_w}{\rho_L})^{1.25} = 0.928$
- $f_3 = (\frac{\sigma_w}{\sigma_L})^{0.8} = 1$

The calculation of Height of the packed columns continues with the estimation of the height of the gas-phase transfer unit (H_G) and the height of the liquid-phase transfer unit (H_L). In order to determine the previous parameters, a random prediction of the height of the packed column is needed, Z=12m. Finally, according to Onda's method [134], the diameter correction term will be taken as 2.3 due to the fact that the column diameter is greater than 0.6m.

- $H_G = \frac{0.011\psi_h(Sc)_v^{0.5}(\frac{Dc}{0.305})^{1.11}(\frac{Z}{3.05})^{0.33}}{(L_{\dot{W}}f_1f_2f_3)^{0.5}} = 0.8$

- $H_L = 0.305\varphi_h(Sc)_L^{0.5}K_3(\frac{Z}{3.05})^{0.15} = 0.07$

The final step is to determine the number of transfer units into the packed column. For this purpose, the use of $m\frac{G_m}{L_m}$ is necessary. According to figure 36 it can be seen that the "optimum" rate of the parameter $m\frac{G_m}{L_m}$ will be between 0.6 and 0.8. Below 0.6 there is only a small decrease in the number of stages required with increasing the liquid rate, and above 0.8 the number of stages increases rapidly with decreasing liquid rate [134]. In this application of CCS the use of $m\frac{G_m}{L_m} = 0.8$ is applied.

For the pressure drop value for the absorber, it is recommended as ideal values to be 15 and 50mm H_2O [160]. For this application the pressure drop of absorber and stripper is selected to be 40mm H_2O/m of packing. According to previous parameters and the figure 36, the number of transfer units into the packed columns is estimated to be N_{OG}=13.

As a result, the concentration driving force across the liquid and gas films is given by:

$$H_{OG} = H_G + m\frac{G_m}{L_m}H_L = 0.8 + 0.8 * 0.07 = 0.856$$

Finaly, The height of packed columns is given by:

$$Z = N_{OG} * H_{OG} = 11m$$

The value of final height of packed columns (11m) is close enough to the first estimated value (12m). On the following table 41 are shown the final dimension of absorber and stripper

Table 41: Dimension of packed columns

Dimensions of packed columns		
Units	Diameter (m)	Height (m)
Absorber	3.5	11
Stripper	3.5	11

6.3. Technoeconomical model

In this subsection, a technoeconomical model of the CCS is presented. For this goal, a typical plan of CCS components needs to be specified. Table 42 shows all the units which are used in this application of carbon capture system.

Table 42: Carbon Capture Components of the system

Equipment	Number
Absorber	1
Stripper	1
Cooler	2
Pumps	3
Boiler	1
Heat exchanger	1
Tank	1
Blower	1
Dryer	1
Condenser	1
Compressor	2

As it is already be mentioned in Chapter 5, for the cost evaluation of the carbon capture system it is needed to specify the a,b constants , the exponent for the type of the equipment (n), the installation factor (f) and the size parameter S.

For the determination of the cost evaluation it is need to be calculated the size parameter S. According to case studies which were investigated and the Krammer cooler catalog, the cooler duty for the amine is estimated, as an average value for 90% capture rate, of 928.1 kW. This value corresponds to size parameter for the cooler. For the absorber and stripper, the size parameter S corresponds to the volume of each component. In this case of application, both stripper and absorber have the same dimension and consequently, the same volumes. For blower, the parameter S was estimated (according to case studies) 111500.37 m^3/h. The tank volume, for an average value of 2762.256 kg/h for carbon which is captured, is estimated 1132m^3. The size parameter S for pumps was estimated as an average price from table 29, equal to 250 L/s. Finally for the heat exchanger, a typical value of S is estimated of 1150.5m^2. For the liquefaction system of the carbon capture process an average value of 2,298,347$ is estimated according to typical price value of condensers and compressors which have been investigated [161]. Most of the components expect from the absorber and the stripper have standard values of size parameter S, which were mentioned before.

On the following table 43 the total amount of the installation of CCS is estimated.

Equipment	Number	S		a	b	n	installation factor	Cost	
Absorber	1	105.7788	m^3	0	3200	1	4	£	1,353,968.00
Stripper	1	105.7788	m^3	0	3200	1	4	£	1,353,968.00
Cooler	2	928.1	kW	4900	720	0.9	0.9	£	308,085.88
Pumps	3	250	L/s	3300	48	1.2	1.2	£	47,406.07
Boiler	1	5400	kg/h steam	4600	62	0.8	0.8	£	51,697.18
Heat exchanger	1	1150.5	m^2	1000	88	1	1	£	102,244.00
Blower	1	111500.4	m^3/h	4200	27	0.8	1	£	298,767.49
Tank	1	1132	m^3	5300	2400	0.6	0.6	£	101,054.68
Liquefaction procees								£	2,298,347.00
Total								£	5,915,538.30

7. Conclusion

In summary, there has never been a more pressing need to put carbon capture systems into place if we are to lessen the effects of climate change. The need for practical solutions is critical, as shown by the rising levels of greenhouse gas emissions. This thesis has examined numerous techniques used in carbon capture systems, demonstrating their versatility and suitability for a range of industrial contexts.

Notwithstanding the advancements, there are still significant obstacles in the way of widespread adoption, from financial and technological constraints to problems with public acceptance and policy. However, the advantages of carbon capture systems are indisputable since they offer the possibility of sustainable industrial practices in addition to a significant decrease in CO_2 emissions.

According to analysis of the carbon capture system it can be seen that MEA seems to present better performance from the other three solutions, because of the fact that the experiments that have already been conducted. Specifically, Heat demand for the capture of CO2 using MEA is estimated to 1.14kWh/$kg_{CO2captured}$, while the use of piperazine and aqueous ammonia require 1.24kWh/$kg_{CO2captured}$ and 1.25kWh/$kg_{CO2captured}$ respectively. Furthermore, similar treatment follows the electric power, as 0.1191kWh/$kg_{CO2captured}$ of electric power need for the capture process using MEA, in contrast to aqueous ammonia which demands 0.2788kWh/$kg_{CO2captured}$.

The main conclusions of the thesis ar listed below:

1. Use of MEA seems to provide more reliably results from the other two solvents (Piperazine and Aqueous ammonia).
2. The energy demand for the good efficiency of the system is based on the CO_2 content in the exhaust gas flow, which enters the CCS.
3. Heat demand for capture, using MEA, is estimated to 1.14kWh/$kg_{CO2captured}$.
4. Heat demand for capture, using Piperazine, is estimated to 1.24kWh/$kg_{CO2captured}$.
5. Heat demand for capture, using aqueous ammonia, is estimated to 1.25kWh/$kg_{CO2captured}$.
6. Total Electric demand for capture, using MEA, is estimated to 0.1191kWh/$kg_{CO2captured}$.
7. Total electric demand for capture, using aqueous ammonia, is estimated to 0.2788kWh/$kg_{CO2captured}$.
8. Electric demand for liquefaction, using MEA, is estimated to 0.067kWh/$kg_{CO2captured}$.
9. Electric demand for liquefaction, using piperazine, is estimated to 0.067kWh/$kg_{CO2captured}$.
10. Electric demand of auxiliary, using MEA, is estimated to 0.03023 kWh/$kg_{CO2captured}$.
11. For a VLCC with a DWT of 300000 tons and Wartsila 16V46F main engine the heat power of CCS is calculated 9270.936 kW (For MEA), 10084.176kW (for Piperazine), 10165.5 kW (for Aqueous Ammonia)
12. For a VLCC with a DWT of 300000 tons and Wartsila 16V46F main engine the electric power of CCS is calculated 968.6 kW (For MEA), 2261.62 kW(for Aqueous Ammonia).
13. The cost of the implementation of the CCS on the VLCC reference-ship is estimated equal to 5.9 million $.

8. References

[1] IMO. (2020). Fourth Greenhouse Gas Study 2020. International Maritime Organization

[2] Porwal, R. (2023, December 5). Insights into the Shipping Industry | ShipFinex. Shipfinex. https://www.shipfinex.com/blog/shipping-industry.

[3] Wan, Z., el Makhloufi, A., Chen, Y., & Tang, J. (2018, January). Decarbonizing the international shipping industry: Solutions and policy recommendations. Marine Pollution Bulletin, 126, 428–435. https://doi.org/10.1016/j.marpolbul.2017.11.064.

[4] Dong, J., Zeng, J., Yang, Y., & Wang, H. (2022, November 22). A review of law and policy on decarbonization of shipping. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.1076352.

[5] IMO. (2022).Improving the energy efficiency of ships. International Maritime Organization.

[6] Annex IV 2014 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships. (n.d.). (C) Copyright 2005. https://www.imorules.com/GUID-507FC12C-452D-4925-8D8E-052333B40148.html.

[7] Inal, O. B., Zincir, B., & Deniz, C. (2022, May). Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. International Journal of Hydrogen Energy, 47(45), 19888–19900. https://doi.org/10.1016/j.ijhydene.2022.01.189.

[8] IMO (2012). EEDI – rational, safe and effective. International Maritime Organization.

[9] Emission Reduction Targets for International Aviation and Shipping | Think Tank | European Parliament. (n.d.). https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2015)569964.

[10] Hub, I. S. K. (n.d.). UNEP Announces Climate Neutral Network | News | SDG Knowledge Hub | IISD. https://sdg.iisd.org/news/unep-announces-climate-neutral-network/.

[11] IMO. (2011). International Convention for the Prevention of Pollution from Ships (MARPOL). International Maritime Organization.

[12] Mazzetti, M. J., Skagestad, R., Mathisen, A., & Eldrup, N. H. (2014). CO_2 from Natural Gas Sweetening to Kick-start EOR in the North Sea. Energy Procedia, 63, 7280–7289. https://doi.org/10.1016/j.egypro.2014.11.764.

[13] Olabi, A., Obaideen, K., Elsaid, K., Wilberforce, T., Sayed, E. T., Maghrabie, H. M., & Abdelkareem, M. A. (2022, January). Assessment of the pre-combustion carbon capture contribution into sustainable development goals SDGs using novel indicators. Renewable and Sustainable Energy Reviews, 153, 111710. https://doi.org/10.1016/j.rser.2021.111710.

[14] Cann, D., Willson, P., & Font Palma, C. (2019). Experimental Exploration of CO_2 Capture Using a Cryogenic Moving Packed Bed. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3366196.

[15] Ming, Z., Shaojie, O., Yingjie, Z., & Hui, S. (2014, November). CCS technology development in China: Status, problems and countermeasures—Based on SWOT analysis. Renewable and Sustainable Energy Reviews, 39, 604–616. https://doi.org/10.1016/j.rser.2014.07.037.

[16] Kanniche, M., Gros-Bonnivard, R., Jaud, P., Valle-Marcos, J., Amann, J. M., & Bouallou, C. (2010, January). Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO_2 capture. Applied Thermal Engineering, 30(1), 53–62. https://doi.org/10.1016/j.applthermaleng.2009.05.005.

[17] Dziejarski, B., Krzyżyńska, R., & Andersson, K. (2023, June). Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel, 342, 127776. https://doi.org/10.1016/j.fuel.2023.127776.

[18] Miller. (2016, September). Carbon Dioxide Emissions Reduction and Storage. In Clean coal engineering design (2nd ed., Vol. 13).

[19] Zheng, L. (2011, February 26). Oxy-Fuel Combustion for Power Generation and Carbon Dioxide (CO_2) Capture. Elsevier. http://books.google.ie/books?id=_3dwAgAAQBAJ&printsec=frontcover&dq=Oxy-Fuel+Combustion+for+Power+Generation+and+Carbon+Dioxide+(CO_2)+Capture&hl=&cd=1&source=gbs_api.

[20] Nemitallah, M. A., Habib, M. A., Badr, H. M., Said, S. A., Jamal, A., Ben-Mansour, R., Mokheimer, E. M. A., & Mezghani, K. (2017, February 8). Oxy-fuel combustion technology: current status, applications, and trends. International Journal of Energy Research, 41(12), 1670–1708. https://doi.org/10.1002/er.3722.

[21] Mondal, M. K., Balsora, H. K., & Varshney, P. (2012, October). Progress and trends in CO_2 capture/separation technologies: A review. Energy, 46(1), 431–441. https://doi.org/10.1016/j.energy.2012.08.006.

[22] Manabendra , & Bassam B. (2022). Solid fuels flameless combustion. In Fundamentals of Low Emission Flameless Combustion and Its Applications (Vol. 16).

[23] Wall, T. F., Gupta, R. P., Sheng, C. D., Elliott, L. K., & Buhre, B. J. P. (2005). Oxy-fuel combustion technology for coal-fired power generation. In Progress in Energy and Combustion Science (Vol. 31).

[24] Habib, M. A., Badr, H. M., Ahmed, S. F., Ben-Mansour, R., Mezghani, K., Imashuku, S., la O', G. J., Shao-Horn, Y., Mancini, N. D., Mitsos, A., Kirchen, P., & Ghoneim, A. F. (2010, December 13). A review of recent developments in carbon capture utilizing oxy-fuel combustion in conventional and ion transport membrane systems. International Journal of Energy Research, 35(9), 741–764. https://doi.org/10.1002/er.1798.

[25] Wu, F., Argyle, M. D., Dellenback, P. A., & Fan, M. (2018, July). Progress in O2 separation for oxy-fuel combustion–A promising way for cost-effective CO_2 capture: A review. Progress in Energy and Combustion Science, 67, 188–205. https://doi.org/10.1016/j.pecs.2018.01.004.

[26] Darabkhani, H. G., Varasteh, H., & Bazooyar, B. (2022, September 24). Carbon Capture Technologies for Gas-Turbine-Based Power Plants. Elsevier. http://books.google.ie/books?id=VGJjEAAAQBAJ&printsec=frontcover&dq=Carbon+Capture+Technologies+for+Gas-Turbine-Based+Power+Plants&hl=&cd=1&source=gbs_api.

[27] Carbon Capture Storage/ Utilisation (CCUS) Technology & Market From a Maritime Point of View. (2021, November). George Dimopoulos. Retrieved January 9, 2024, from https://conference18.newsfront.gr/images/presentations/Chara_Georgopoulou.pdf.

[28] Abass A. (2010, June). CO_2 capture and separation technologies for end-of-pipe applications- A review . In Energy (Vol. 35).

[29] I. (2005, December 19). Carbon Dioxide Capture and Storage. Cambridge University Press. http://books.google.ie/books?id=HWgRvPUgyvQC&printsec=frontcover&dq=IPCC+Special+Report+on+Carbon+Dioxide+Capture+and+Storage&hl=&cd=1&source=gbs_api.

[30] Romano, M. C., Chiesa, P., & Lozza, G. (2010, September). Pre-combustion CO_2 capture from natural gas power plants, with ATR and MDEA processes. International Journal of Greenhouse Gas Control, 4(5), 785–797. https://doi.org/10.1016/j.ijggc.2010.04.015.

[31] Terry F. (2007, January). Combustion processes for carbon capture. In Proceedings of the Combustion Institute (Vol. 31).

[32] Xinli Zhu, Trung Hoang, Lance L. Lobban, & Richard G. Mallinson . (2010, February). Low CO content hydrogen production from bio-ethanol using a combined plasma reforming–catalytic water gas shift reactor. In Applied Catalysis B: Enviromental (Vol. 94).

[33] Jansen, D., Gazzani, M., Manzolini, G., Van Dijk, E., & Carbo, M. (2015, September 1). Pre-combustion CO_2 capture. International Journal of Greenhouse Gas Control. https://doi.org/10.1016/j.ijggc.2015.05.028.

[34] Lau, H. C., Ramakrishna, S., Zhang, K., & Radhamani, A. V. (2021, April 7). The Role of Carbon Capture and Storage in the Energy Transition. Energy & Fuels. https://doi.org/10.1021/acs.energyfuels.1c00032.

[35] Dziejarski, B., Krzyżyńska, R., & Andersson, K. (2023, June 1). Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel. https://doi.org/10.1016/j.fuel.2023.127776.

[36] Feron, P. (2016, May 27). Absorption-Based Post-Combustion Capture of Carbon Dioxide. Woodhead Publishing. http://books.google.ie/books?id=X5PBCQAAQBAJ&printsec=frontcover&dq=Absorption-Based+Post-Combustion+Capture+of+Carbon+Dioxide&hl=&cd=1&source=gbs_api.

[37] Carde, Thomsen , Stenby, & van Well. (2011). CO_2 capture using aqueous ammonia: kinetic study and process simulation. In Energy Procedia (Vol. 4).

[38] Spigarelli, B. P., & Kawatra, S. K. (2013, June). Opportunities and challenges in carbon dioxide capture. Journal of CO_2 Utilization, 1, 69–87. https://doi.org/10.1016/j.jcou.2013.03.002.

[39] Chen, Z., Deng, S., Wei, H., Wang, B., Huang, J., Yu, G., 2013. Activated carbons and amine-modified materials for carbon dioxide capture – a review. Front. Environ. Sci. Eng. 7, 326–340. https://doi.org/10.1007/s11783-013-0510-7.

[40] Hornbostel, M.D., Bao, J., Krishnan, G., Nagar, A., Jayaweera, I., Kobayashi, T., Sanjurjo, A., Sweeney, J., Carruthers, D., Petruska, M.A., Dubois, L., 2013. Characteristics of an advanced carbon sorbent for CO_2 capture. Carbon N. Y. 56, 77–85. https://doi.org/10.1016/j.carbon.2012.12.08

[41] Linga, P., Kumar, R., Englezos, P., 2007. The clathrate hydrate process for post and pre-combustion capture of carbon dioxide. J. Hazard. Mater. 149, 625–629. https://doi.org/10.1016/j.jhazmat.2007.06.086

[42] Soares, C. (2014, January 1). Gas Turbines, 2nd Edition. http://books.google.ie/books?id=0rBRzQEACAAJ&dq=Gas+Turbines+A+Handbook+of+Air,+Land+and+Sea+Applications&hl=&cd=2&source=gbs_api.

[43] Hai Yu, Paul Feron, Leigh Wardhaugh, Graeme Puxty. (n.d.). Retrieved 2013, from https://www.globalccsinstitute.com/archive/hub/publications/169123/development-ammonia-based-pcc-technology-australian-conditions-technical-report-2.pdf.

[44] Membrane technology for carbon dioxide (CO_2) capture in power plants. (2011). In Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications (Vol. 5).

[45] Zincir, B. A. (2020, June 1). COMPARISON OF THE CARBON CAPTURE SYSTEMS FOR ONBOARD APPLICATION AND VOYAGE PERFORMANCE INVESTIGATION BY A. . . ResearchGate. https://www.researchgate.net/publication/361506871_COMPARISON_OF_THE_CARBON_CAPTURE_SYSTEMS_FOR_ONBOARD_APPLICATION_AND_VOYAGE_PERFORMANCE_INVESTIGATION_BY_A_CASE_STUDY.

[46] Mittal, G., Dhand, V., Rhee, K. Y., Park, S. J., & Lee, W. R. (2015, January). A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites. Journal of Industrial and Engineering Chemistry, 21, 11–25. https://doi.org/10.1016/j.jiec.2014.03.022.

[47] Ben-Mansour, R., Habib, M., Bamidele, O., Basha, M., Qasem, N., Peedikakkal, A., Laoui, T., & Ali, M. (2016, January). Carbon capture by physical adsorption: Materials, experimental investigations and numerical modeling and simulations – A review. Applied Energy, 161, 225–255. https://doi.org/10.1016/j.apenergy.2015.10.011.

[48] Bonaventura, D., Chacartegui, R., Valverde, J., Becerra, J., & Verda, V. (2017, October). Carbon capture and utilization for sodium bicarbonate production assisted by solar thermal power. Energy Conversion and Management, 149, 860–874. https://doi.org/10.1016/j.enconman.2017.03.042.

[49] Rashidi, N. A., & Yusup, S. (2016, March). An overview of activated carbons utilization for the post-combustion carbon dioxide capture. Journal of CO_2 Utilization, 13, 1–16. https://doi.org/10.1016/j.jcou.2015.11.002.

[50] Home - Global CCS Institute. (2023, August 4). Global CCS Institute. https://www.globalccsinstitute.com/.

[51] Shafiq, I., Shabeer, S., Uzbeck, M. H., Zoumot, Z., Abuzakouk, M., & Wahla, A. S. (2021, July 14). Genetic and Clinical Demographics of Adult Cystic Fibrosis Patients in a Middle Eastern Population. Turkish Thoracic Journal, 22(4), 279–283. https://doi.org/10.5152/turkthoracj.2021.20121.

[52] Gal, E. (2004, August 6). WO2006022885A1 - Ultra cleaning of combustion gas including the removal of CO_2 - Google Patents. https://patents.google.com/patent/WO2006022885A1/en.

[53] Lindstad, E., & Sandaas, I. (2016, November 1). Emission and Fuel Reduction for Offshore Support Vessels through Hybrid Technology. Journal of Ship Production and Design. https://doi.org/10.5957/jspd.32.4.150006.

[54] Plaza, M., Pevida, C., & Rubiera, F. (2016, January 1). Ongoing Activity on CO_2 Capture in the Power Sector: Review of the Demonstration Projects Worldwide. Elsevier eBooks. https://doi.org/10.1016/b978-0-12-409547-2.11129-1.

[55] Sreenivasulu, B., Gayatri, D., Sreedhar, I., & Raghavan, K. (2015, January). A journey into the process and engineering aspects of carbon capture technologies. Renewable and Sustainable Energy Reviews, 41, 1324–1350. https://doi.org/10.1016/j.rser.2014.09.029.

[56] Koroneos, C. J., M, K., & Th, G. (2010, November 1). Thermodynamic, Economic and Environmental Analysis of a Lignite Power Plant with Carbon Sequestration. ResearchGate. https://www.researchgate.net/publication/229069775_Thermodynamic_Economic_and_Environmental_Analysis_of_a_Lignite_Power_Plant_with_Carbon_Sequestration.

[57] ECOS 2010 : Proceedings of the 23rd International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems, Lausanne, Switzerland, June 14-17, 2010 | WorldCat.org. (2011). https://search.worldcat.org/title/ecos-2010-proceedings-of-the-23rd-international-conference-on-efficiency-cost-optimization-simulation-and-environmental-impact-of-energy-systems-lausanne-switzerland-june-14-17-2010/oclc/748091300.

[58] Gao, J., Wang, J., An, Q., Zhang, F., Hu, Z., Xu, C., Zhang, X., & Zhang, F. (2019, November 11). Over 16.7% efficiency of ternary organic photovoltaics by employing extra PC71BM as morphology regulator. Science China Chemistry. https://doi.org/10.1007/s11426-019-9634-5.

[59] MacDowell, N., Florin, N., Buchard, A., Hallett, J., Galindo, A., Jackson, G., Adjiman, C.S., Williams, C.K., Shah, N., Fennell, P., 2010. An overview of CO_2 capture technologies. Energ. Environ. Sci. 3, 1645–1669.

[60] Rochelle, G., Chen, E., Freeman, S., Van Wagener, D., Xu, Q., & Voice, A. (2011, July). Aqueous piperazine as the new standard for CO_2 capture technology. Chemical Engineering Journal, 171(3), 725–733. https://doi.org/10.1016/j.cej.2011.02.011.

[61] Figueroa, J. D., Fout, T., Plasynski, S., McIlvried, H., & Srivastava, R. D. (2008, January). Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program. International Journal of Greenhouse Gas Control, 2(1), 9–20. https://doi.org/10.1016/s1750-5836(07)00094-1.

[62] Zhang, Y., & Chen, C. C. (2013). Modeling CO_2 Absorption and Desorption by Aqueous Monoethanolamine Solution with Aspen Rate-based Model. Energy Procedia, 37, 1584–1596. https://doi.org/10.1016/j.egypro.2013.06.034.

[63] Yusof, S. M. M., Sharif, A. M., Horng, T. W., Mustafa, F. A., & Keong, L. K. (2021). Effect of Monoethanolamine Concentration on CO_2 Removal using Continuous High Frequency Ultrasonic Reactor. E3S Web of Conferences, 287, 01001. https://doi.org/10.1051/e3sconf/202128701001.

[64] Engineers, A. I. O. C. (2010, September 14). *AIChE Equipment Testing Procedure - Tray Distillation Columns*. John Wiley & Sons. http://books.google.ie/books?id=qz-triGHFggC&printsec=frontcover&dq=AIChE+Equipment+Testing+Procedure+-+Tray+Distillation+Columns:+A+Guide+to+Performance+Evaluation,+2nd+Edition&hl=&cd=1&source=gbs_api.

[65] Artioli. (2008). Adsorption . In Encyclopedia of Ecology.

[66] Brunetti, A., Scura, F., Barbieri, G., & Drioli, E. (2010, September). Membrane technologies for CO_2 separation. Journal of Membrane Science, 359(1–2), 115–125. https://doi.org/10.1016/j.memsci.2009.11.040.

[67] Gupta, M., Coyle, I., & Thambimuthu, K. (2003, January 1). CO_2 Capture Technologies and Opportunities in Canada. "Strawman Document for CO_2 capture and Storage. . . ResearchGate. https://www.researchgate.net/publication/302996814_CO2_Capture_Technologies_and_Opportunities_in_Canada_Strawman_Document_for_CO2_capture_and_Storage_CCS_Technology_Roadmap.

[68] Burdyny, T., & Struchtrup, H. (2010, May). Hybrid membrane/cryogenic separation of oxygen from air for use in the oxy-fuel process. Energy, 35(5), 1884–1897. https://doi.org/10.1016/j.energy.2009.12.033.

[69] Spitoni, M., Pierantozzi, M., Comodi, G., Polonara, F., & Arteconi, A. (2019, February). Theoretical evaluation and optimization of a cryogenic technology for carbon dioxide separation and methane liquefaction from biogas. Journal of Natural Gas Science and Engineering, 62, 132–143. https://doi.org/10.1016/j.jngse.2018.12.007.

[70] Ghasem. (2020). CO_2 removal from natural gas. In Advances in Carbon Capture.

[71] Association, G. G. P. S. (1998, January 1). Engineering Data Book. http://books.google.ie/books?id=TlHBXwAACAAJ&dq=GPSA+Gas+Processors+Suppliers+Association+Engineering+Data+Book&hl=&cd=1&source=gbs_api.

[72] Li Xie, Jun Xu, Yidie Zhang, & Yingying He. (2020). Biogras upgrading. In Advances in Bioenergy (Vol. 5).

[73] Cann, D., Willson, P., & Font-Palma, C. (2019, January 1). Experimental Exploration of CO_2 Capture Using a Cryogenic Moving Packed Bed. Social Science Research Network. https://doi.org/10.2139/ssrn.3366196.

[74] Understanding carbon capture and storage - British Geological Survey. (2022, November 16). British Geological Survey. https://www.bgs.ac.uk/discovering-geology/climate-change/carbon-capture-and-storage/.

[75] CO_2 Capture and Utilisation - Energy System - IEA. (n.d.). IEA. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-capture-and-utilisation.

[76] Turkenburg, W. C. (1997, January). Sustainable development, climate change, and carbon dioxide removal (CDR). Energy Conversion and Management, 38, S3–S12. https://doi.org/10.1016/s0196-8904(96)00237-3.

[77] Metz, B., Davidson, O., De Coninck, H., & Meyer, L. (2005, January 1). IPCC Special Report on Carbon dioxide Capture and Storage. ResearchGate. https://www.researchgate.net/publication/239877190_IPCC_Special_Report_on_Carbon_dioxide_Capture_and_Storage.

[78] Holloway, S., & Savage, D. (1993, September 1). The potential for aquifer disposal of carbon dioxide in the UK. Energy Conversion and Management. https://doi.org/10.1016/0196-8904(93)90038-c.

[79] Jessen, K. (2021, October 21). Increasing CO_2 storage in oil recovery. www.academia.edu. https://www.academia.edu/59330864/Increasing_CO2_storage_in_oil_recovery.

[80] Bachu, S. (2000, June 1). Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change. Energy Conversion and Management. https://doi.org/10.1016/s0196-8904(99)00149-1.

[81] Bachu, S. (1994). Aquifer disposal of CO_2: Hydrodynamic and mineral trapping. https://www.semanticscholar.org/paper/Aquifer-disposal-of-CO2%3A-Hydrodynamic-and-mineral-Bachu-Gunter/471aef268a6ab703b7b59c153f096e2b13c3624e.

[82] Gunter WD, Gentzis T, Rottenfusser BA, Richardson RJH (1997) Deep coalbed methane in Alberta, Canada: a fuel resource with the potential of zero greenhouse emissions. Energy Convers Manage

[83] Stevens, S. H., Kuuskraa, V. A., Spector, D., & Riemer, P. (1999, August 1). CO{sub 2} sequestration in deep coal seams: pilot results and worldwide potential. https://www.osti.gov/etdeweb/biblio/363765.

[84] Greenhouse gas control technologies : proceedings of the 4th International Conference on Greenhouse Gas Control Technologies, 30 August-2 September 1998, Interlaken, Switzerland | WorldCat.org. (1999). https://search.worldcat.org/title/greenhouse-gas-control-technologies-proceedings-of-the-4th-international-conference-on-greenhouse-gas-control-technologies-30-august-2-september-1998-interlaken-switzerland/oclc/40954002.

[85] Home - GeoScienceWorld. (2023, December 29). GeoScienceWorld. https://community.geoscienceworld.org/.

[86] Garg, G., Gómez, M., Masdeu-Bultó, A. M., & Medina González, Y. (2023, November). Compressed carbon dioxide as a medium in catalytic hydrogenations: Engineering and

chemistry. Journal of CO_2 Utilization, 77, 102605. https://doi.org/10.1016/j.jcou.2023.102605.

[87] Home - Underground Energy Storage Technologies - UEST. (2023, November 27). Underground Energy Storage Technologies - UEST. https://underground.energy/?gad_source=1&gclid=CjwKCAiAxreqBhAxEiwAfGfndF3EupIUZVh2aZGiHd_p_zAAVPl6P1bRLL5fkSjZUSuKYt1D4rzgERoCqGYQAvD_BwE.

[88] CO_2 Capture and Utilisation - Energy System - IEA. (n.d.). IEA. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-capture-and-utilisation.

[89] Gabrielli, P., Campos, J., Becattini, V., Mazzotti, M., & Sansavini, G. (2022, December 1). Optimization and assessment of carbon capture, transport and storage supply chains for industrial sectors: The cost of resilience. International Journal of Greenhouse Gas Control. https://doi.org/10.1016/j.ijggc.2022.103797.

[90] Morales Mora, M., Vergara, C. P., Leiva, M., Martínez Delgadillo, S., & Rosa-Domínguez, E. (2016, December). Life cycle assessment of carbon capture and utilization from ammonia process in Mexico. Journal of Environmental Management, 183, 998–1008. https://doi.org/10.1016/j.jenvman.2016.09.048.

[91] Petrescu, L., Bonalumi, D., Valenti, G., Cormos, A. M., & Cormos, C. C. (2017, July). Life Cycle Assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage. Journal of Cleaner Production, 157, 10–21. https://doi.org/10.1016/j.jclepro.2017.03.225.

[92] Koornneef, J., van Keulen, T., Faaij, A., & Turkenburg, W. (2008, October). Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. International Journal of Greenhouse Gas Control, 2(4), 448–467. https://doi.org/10.1016/j.ijggc.2008.06.008.

[93] Clarens, F., Espí, J. J., Giraldi, M. R., Rovira, M., & Vega, L. F. (2016, March). Life cycle assessment of CaO looping versus amine-based absorption for capturing CO_2 in a subcritical coal power plant. International Journal of Greenhouse Gas Control, 46, 18–27. https://doi.org/10.1016/j.ijggc.2015.12.031.

[94] Ferrara, G., Lanzini, A., Leone, P., Ho, M., & Wiley, D. (2017, July). Exergetic and exergoeconomic analysis of post-combustion CO 2 capture using MEA-solvent chemical absorption. Energy, 130, 113–128. https://doi.org/10.1016/j.energy.2017.04.096.

[95] Hanak, D. P., Kolios, A. J., & Manovic, V. (2016, June). Comparison of probabilistic performance of calcium looping and chemical solvent scrubbing retrofits for CO_2 capture from coal-fired power plant. Applied Energy, 172, 323–336. https://doi.org/10.1016/j.apenergy.2016.03.102.

[96] Gaspar, J., Arshad, M. W., Blaker, E. A., Langseth, B., Hansen, T., Thomsen, K., von Solms, N., & Fosbøl, P. L. (2014). A Low Energy Aqueous Ammonia CO_2 Capture Process. Energy Procedia, 63, 614–623. https://doi.org/10.1016/j.egypro.2014.11.066.

[97] Kim, Y., Lim, S. R., Jung, K. A., & Park, J. M. (2019, August). Process-based life cycle CO_2 assessment of an ammonia-based carbon capture and storage system. Journal of Industrial and Engineering Chemistry, 76, 223–232. https://doi.org/10.1016/j.jiec.2019.03.044.

[98] Wang, J., Zhao, J., Wang, Y., Deng, S., Sun, T., & Li, K. (2017, June). Application potential of solar-assisted post-combustion carbon capture and storage (CCS) in China: A life cycle approach. Journal of Cleaner Production, 154, 541–552. https://doi.org/10.1016/j.jclepro.2017.04.021.

[99] Rezazadeh, F., Gale, W. F., Hughes, K. J., & Pourkashanian, M. (2015, August). Performance viability of a natural gas fired combined cycle power plant integrated with post-combustion CO_2 capture at part-load and temporary non-capture operations. International Journal of Greenhouse Gas Control, 39, 397–406. https://doi.org/10.1016/j.ijggc.2015.06.003.

[100] Díaz-Herrera, P. R., Alcaraz-Calderón, A. M., González-Díaz, M. O., & González-Díaz, A. (2020, February). Capture level design for a natural gas combined cycle with post-combustion CO_2 capture using novel configurations. Energy, 193, 116769. https://doi.org/10.1016/j.energy.2019.116769.

[101] Herraiz, L., Fernández, E. S., Palfi, E., & Lucquiaud, M. (2018, April). Selective exhaust gas recirculation in combined cycle gas turbine power plants with post-combustion CO2 capture. International Journal of Greenhouse Gas Control, 71, 303–321. https://doi.org/10.1016/j.ijggc.2018.01.017.

[102] Apan-Ortiz, J. I., Sanchez-Fernández, E., & González-Díaz, A. (2018, December). Use of steam jet booster as an integration strategy to operate a natural gas combined cycle with post-combustion CO_2 capture at part-load. Energy, 165, 126–139. https://doi.org/10.1016/j.energy.2018.09.148.

[103] Onboard carbon capture and storage on ships - DNV. (n.d.). DNV. https://www.dnv.com/focus-areas/ccs/onboard-carbon-capture-and-storage-on-ships.html.

[104] Baroudi, H. A., Awoyomi, A., Patchigolla, K., & Anthony, E. (2021, February 13). A review of large-scale CO_2 shipping and marine emissions management for carbon capture, utilisation and. . . ResearchGate. https://www.researchgate.net/publication/350632154_A_review_of_large-scale_CO2_shipping_and_marine_emissions_management_for_carbon_capture_utilisation_and_storage.

[105] Leiss, W. (2009, July 1). Risk Management of Carbon Capture and Storage: Overview and Future Steps. ResearchGate. https://www.researchgate.net/publication/228954377_Risk_Management_of_Carbon_Capture_and_Storage_Overview_and_Future_Steps.

[106] Paltrinieri, N., Wilday, J., Farret, R., & Breedveld, L. (2011, April 11). Carbon Capture and storage: A case study of emerging risk issues in the iNTeg-Risk project. ResearchGate.

https://www.researchgate.net/publication/266436912_Carbon_Capture_and_storage_A_case_study_of_emerging_risk_issues_in_the_iNTeg-Risk_project.

[107] Wilday, J., Wardman, M., Johnson, M., & Haines, M. (2011, November). Hazards from carbon dioxide capture, transport and storage. Process Safety and Environmental Protection, 89(6), 482–491. https://doi.org/10.1016/j.psep.2011.09.002.

[108] Mokhatab, S., Poe, W. A., & Mak, J. Y. (2018, October 16). Handbook of Natural Gas Transmission and Processing. Gulf Professional Publishing. http://books.google.ie/books?id=buRyDwAAQBAJ&printsec=frontcover&dq=Handbook+of+Natural+Gas+Transmission+and+Processing+Principles+and+Practices&hl=&cd=1&source=gbs_api.

[109] Kohl, A. L., & Nielsen, R. (1997, August 28). Gas Purification. Elsevier. http://books.google.ie/books?id=rpzrIZW-OcEC&printsec=frontcover&dq=Gas+Purification&hl=&cd=1&source=gbs_api.

[110] Bullin, J.A., (2003). Optimization of Amine Sweetening Units

[111] Feenstra, M., Monteiro, J., van den Akker, J. T., Abu-Zahra, M. R., Gilling, E., & Goetheer, E. (2019, June). Ship-based carbon capture onboard of diesel or LNG-fuelled ships. International Journal of Greenhouse Gas Control, 85, 1–10. https://doi.org/10.1016/j.ijggc.2019.03.008.

[112] CO_2 Transport and Storage - Energy System - IEA. (n.d.). IEA. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage.

[113] Knowledge sharing report. CO_2 liquid logistics shipping concept (LLSC): overall supply chain optimization - Global CCS Institute. (2023, January 23). Global CCS Institute. https://www.globalccsinstitute.com/resources/publications-reports-research/knowledge-sharing-report-co2-liquid-logistics-shipping-concept-llsc-overall-supply-chain-optimization/.

[114] Ansaloni, L., Alcock, B., & Peters, T. (2021). CO_2 EPOC project: effect of CO_2 on the polymeric materials within the CO_2 transport chain. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3816726.

[115] Craig, J. (2020, July 28). New IEAGHG Report: The Status and Challenges of CO_2 Shipping Infrastructures. IEAGHG. https://ieaghg.org/ccs-resources/blog/new-ieaghg-report-the-status-and-challenges-of-co2-shipping-infrastructures.

[116] Seo, Y., Huh, C., Lee, S., & Chang, D. (2016, September 1). Comparison of CO 2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain. International Journal of Greenhouse Gas Control. https://doi.org/10.1016/j.ijggc.2016.06.011.

[117] Neele, F., De Kler, R., Nienoord, M., Brownsort, P., Koornneef, J., Belfroid, S., Peters, L., Van Wijhe, A., & Loeve, D. (2017, July 1). CO_2 Transport by Ship: The Way Forward in Europe. Energy Procedia. https://doi.org/10.1016/j.egypro.2017.03.1813.

[118] Aspelund, A., & Jordal, K. (2007, July 1). Gas conditioning—The interface between CO_2 capture and transport. International Journal of Greenhouse Gas Control. https://doi.org/10.1016/s1750-5836(07)00040-0.

[119] The costs of CO_2 transport: post-demonstration CCS in the EU - Global CCS Institute. (2023, January 23). Global CCS Institute. https://www.globalccsinstitute.com/resources/publications-reports-research/the-costs-of-co2-transport-post-demonstration-ccs-in-the-eu/.

[120] De Kler, R. C., Neele, F., Nienoord, M., & Loeve, D. (2015, November 25). Transportation and unloading of CO_2 by ship - a comparative assessment. ResearchGate. https://www.researchgate.net/publication/303034150_Transportation_and_unloading_of_CO2_by_ship_-_a_comparative_assessment.

[121] Yoo, B., Choi, D., Kim, H., Moon, Y., Na, H., & Lee, S. G. (2013, January 1). Development of CO_2 terminal and CO_2 carrier for future commercialized CCS market. International Journal of Greenhouse Gas Control. https://doi.org/10.1016/j.ijggc.2012.11.008.

[122] Joan, V. D. A. (2017). Carbon capture onboard LNG-fueled vessels: A feasibility study. https://repository.tudelft.nl/islandora/object/uuid%3Aa94741f3-c7cb-4970-80d1-bceebff4e423.

[123] Awoyomi, A., Patchigolla, K., & Anthony, E. J. (2019, November 27). Process and Economic Evaluation of an Onboard Capture System for LNG-Fueled CO_2 Carriers. Industrial & Engineering Chemistry Research, 59(15), 6951–6960. https://doi.org/10.1021/acs.iecr.9b04659.

[124] Ciferno, J. (2005). An Economic Scoping Study for CO 2 Capture Using Aqueous Ammonia. https://www.semanticscholar.org/paper/An-Economic-Scoping-Study-for-CO-2-Capture-Using-Ciferno-Dipietro/6aec9dbb8f17f687a0e36b58e756e088122a3dca.

[125] Feenstra, M., Monteiro, J., van den Akker, J. T., Abu-Zahra, M. R., Gilling, E., & Goetheer, E. (2019, June). Ship-based carbon capture onboard of diesel or LNG-fuelled ships. International Journal of Greenhouse Gas Control, 85, 1–10. https://doi.org/10.1016/j.ijggc.2019.03.008.

[126] Idem, R., Supap, T., Shi, H., Gelowitz, D., Ball, M., Campbell, C., & Tontiwachwuthikul, P. (2015, September). Practical experience in post-combustion CO_2 capture using reactive solvents in large pilot and demonstration plants. International Journal of Greenhouse Gas Control, 40, 6–25. https://doi.org/10.1016/j.ijggc.2015.06.005.

[127] Zong, L., & Chen, C. C. (2011, July). Thermodynamic modeling of CO_2 and H2S solubilities in aqueous DIPA solution, aqueous sulfolane–DIPA solution, and aqueous sulfolane–MDEA solution with electrolyte NRTL model. Fluid Phase Equilibria, 306(2), 190–203. https://doi.org/10.1016/j.fluid.2011.04.007.

[128] Zhang, Y., Sachde, D., Chen, E., & Rochelle, G. (2017, September). Modeling of absorber pilot plant performance for CO_2 capture with aqueous piperazine. International Journal of Greenhouse Gas Control, 64, 300–313. https://doi.org/10.1016/j.ijggc.2017.08.004.

[129] Luo, X., & Wang, M. (2017, June). Study of solvent-based carbon capture for cargo ships through process modelling and simulation. Applied Energy, 195, 402–413. https://doi.org/10.1016/j.apenergy.2017.03.027.

[130] Awoyomi, A., Patchigolla, K., & Anthony, E. J. (2018). CO$_2$/SO$_2$ Emission Reduction in CO$_2$ Shipping Infrastructure. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3365623.

[131] Stec, M., Tatarczuk, A., Iluk, T., & Szul, M. (2021, June). Reducing the energy efficiency design index for ships through a post-combustion carbon capture process. International Journal of Greenhouse Gas Control, 108, 103333. https://doi.org/10.1016/j.ijggc.2021.103333.

[132] LNGC With Onboard Carbon Capture. (2021, December 21). Chara Georgopoulou , George Dimopoulos.

[133] Green, D. W., & Southard, M. Z. (2018, July 13). Perry's Chemical Engineers' Handbook, 9th Edition. McGraw Hill Professional. http://books.google.ie/books?id=WZJnDwAAQBAJ&printsec=frontcover&dq=Perry%E2%80%99s+chemical+engineers+handbook&hl=&cd=1&source=gbs_api.

[134] Towler, G., & Sinnott, R. (2012, January 25). Chemical Engineering Design. Elsevier. http://books.google.ie/books?id=IG5jsDMbcP0C&printsec=frontcover&dq=CHEMICAL+ENGINEERING+DESIGN+Principles,+Practice+and+Economics+of+Plant+and+Process+Design&hl=&cd=1&source=gbs_api.

[135] Pérez, J. R., & Reusser, C. A. (2020, March 20). Optimization of the Emissions Profile of a Marine Propulsion System Using a Shaft Generator with Optimum Tracking-Based Control Scheme. Journal of Marine Science and Engineering. https://doi.org/10.3390/jmse8030221.

[136] Emissions from planes and ships: facts and figures (infographic) | News | European Parliament. (2019, May 12). https://www.europarl.europa.eu/news/en/headlines/society/20191129STO67756/emissions-from-planes-and-ships-facts-and-figures-infographic.

[137] CII - Carbon Intensity Indicator - DNV. (n.d.). DNV. https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/index.html.

[138] Damartzis, T., Asimakopoulou, A., Koutsonikolas, D., Skevis, G., Georgopoulou, C., Dimopoulos, G. G., Nikolopoulos, L. A. A., Bougiouris, K., Richter, H., Lubenau, U., Economopoulos, S. P., Perinu, C., Hopkinson, D., & Panagakos, G. (2022, June 15). Solvents for Membrane-Based Post-Combustion CO$_2$ Capture for Potential Application in the Marine Environment. Applied Sciences. https://doi.org/10.3390/app12126100.

[139] Orr, F. M. (2009, September 25). Onshore Geologic Storage of CO 2. Science, 325(5948), 1656–1658. https://doi.org/10.1126/science.1175677.

[140] What is needed from CO$_2$ transport, an essential element of the CCUS value chain? | Blog | Energy Transition MITSUBISHI HEAVY INDUSTRIES GROUP. (n.d.). Energy Transition MITSUBISHI HEAVY INDUSTRIES GROUP. https://solutions.mhi.com/blog/what-is-needed-from-co2-transport-an-essential-element-of-the-ccus-value-chain/.

[141] What is needed from CO_2 transport, an essential element of the CCUS value chain? | Blog | Energy Transition MITSUBISHI HEAVY INDUSTRIES GROUP. (n.d.). Energy Transition MITSUBISHI HEAVY INDUSTRIES GROUP. https://solutions.mhi.com/blog/what-is-needed-from-co2-transport-an-essential-element-of-the-ccus-value-chain/.

[142] Prevljak, N. H., & Prevljak, N. H. (2023, June 7). EverLoNG ship-based carbon capture project wins EU funding. Offshore Energy. https://www.offshore-energy.biz/everlong-ship-based-carbon-capture-project-wins-eu-funding/.

[143] C. A. (2021, February 26). Closing the Carbon Loop. Conoship International Ship Design. https://www.conoship.com/2020/06/10/researching-a-closed-carbon-loop/.

[144] Answered: Use the phase diagram for CO_2 to answer. . . | bartleby. (2022, May 23). https://www.bartleby.com/questions-and-answers/use-the-phase-diagram-for-co2-to-answer-the-following.-2.-at-what-temperature-does-sublimation-at-1-/23de2551-d4b1-46ca-adcf-d6547332a05a.

[155] Find your ideal ship engine - Online configurator - Wärtsilä. (n.d.). Wartsila.com. https://www.wartsila.com/marine/engine-configurator.

[156] RightShip. (2013). Calculating and Comparing CO2 Emissions from the Global Maritime Fleet.

[157] IMO. (17 C.E., August 19). GUIDELINES FOR VOLUNTARY USE OF THE SHIP ENERGY EFFICIENCY OPERATIONAL INDICATOR (EEOI) . In https://www.classnk.or.jp/hp/pdf/activities/statutory/eedi/mepc_1-circ_684.pdf.

[158] Arachchige, Arya, Eimer, & Melaae. (2013). Viscosities of Pure and Aqueous Solutions of Monoethanolamine (MEA), Diethanolamine (DEA) and N-Methyldiethanolamine (MDEA) .

[159] Ji, C., Yuan, S., Huffman, M., El-Halwagi, M. M., & Wang, Q. (2021, September). Post-combustion carbon capture for tank to propeller via process modeling and simulation. Journal of CO2 Utilization, 51, 101655. https://doi.org/10.1016/j.jcou.2021.101655.

[160] Sinnott, R. K. (1999). Chemical engineering design. CiNii Research. https://cir.nii.ac.jp/crid/1130282271998021376.

[161] Compressed Air Systems 2023 List Price Sheet. (2023, January 1). Retrieved January 18, 2024, from https://www.compressed-air-systems.com/assets/downloads/marketing/pricing-sales/current-price.pdf.