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Feasibility Study of Carbon Capture and Storage Process to Implement in Maritime Industry.

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ABSTRACT

The CO_2 emission is considered as one of the main elements for causing the global climatic change. The maritime industry contributes about 2.5% of the worldwide CO_2 gas emission annually. The International Maritime Industry (IMO) has set the target of has set the target of reducing the total annual emission from international shipping to 70% by 2050. So, the carbon capture, utilization, and storage (CCUS) unit are considered as the principal alternative to reduce CO_2 emission by capturing it from vessels. This thesis investigates the various post combustion carbon capture technologies with its advantages and limitations. Also, the possibility of transportation and long-term storage of captured carbon has been figured out.

This thesis performed the technical and economic analysis of installing the carbon capture and storage technology in the specified vessel according with the methodology established. The cryogenic carbon capture technology designed by TECO 2030 has been selected to install on the shuttle ferry named as 'MF Lyngen'. This ferry runs with the LFO fuel and operated by diesel engine with the shaft power of 1040 KW. It is found that carbon capture process equipment is possible to install under the main deck inside the main engine room of the ferry. The equipment can be placed at both side of the main engine beneath the center of gravity of ferry so that it did not disturb the buoyancy of the vessel. The propulsion power of vessel can run vessel smoothly with the added weight of capture equipment whereas the fuel consumption seems to increase slightly. The economic analysis performed shows the CAPEX and OPEX values of $ 5,757,000 and $ 172,710 where the cost of carbon capture is calculated at around $ 229/ton. The captured carbon can be transported through shipping at the rate of around $18/ ton and stored for long term at the site on the west coast of Norway. The result from the analysis shows that it is feasible to install carbon capture and storage system in the vessel.

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS

AnSU	Anti-Sublimation
A3C	Advanced Cryogenic Carbon Capture
CO_2	Carbon dioxide
CCS	Carbon Capture Storage
CFC	Controller Freezing Zone
CAPEX	Capital Expenditure
DHX	Desublimating Heat Exchanger
EEDI	Energy Efficiency Design Index
ECLCCC	External Cooling loop Cryogenic carbon capture
GHG	Greenhouse Gases
HC	Hydrocarbon
IEA	International Energy Agency
ICT	International Council on Clean Transport
IMO	International Maritime Organization
KW	Kilowatt
LFO	Light Fuel Oil
LNG	Liquified Natural Gas

LSFO	Low Sulphur Fuel Oil
MEA	Monoethanoamine
MDO	Marine Diesel Oil
NO_x	Nitrogen Oxide
OPEX	Operating Expenses
pH	Potential of Hydrogen
PM	Particulate Matter
SO_x	Sulphur Oxide
SEEMP	Ship Energy Efficiency Management Plan
TIPC	Total Indirect Plant Cost
TDPC	Total Direct Plant Cost
UN	United Nation
V	Volt

1. Introduction

1.1 Background

The recent worldwide concern is about energy and environment issues. Though, more energy has been developed from the non-fossil energy sources, but large portion of earth is still dependent on the fossils fuel energy sources [1]. The CO_2 gases, one of the important greenhouse gases, generated from the combustion of fossils fuels is considered as the main element for the global climatic change. The much attention has been given on utilizing reasonable amount of fossils fuels to generate the energy efficiently with producing less pollutants to the environment.

The massive increase in the emission of CO_2 began with the beginning of the 3rd industrial revolution. According to the report by Intergovernmental Panel on Climate Change, the mean global temperature will increase approximately by 1.9 °C and average sea level will increase by 3.8 m, 570 ppm of CO_2 may be contained in atmosphere, by the year 2100 [2]. In the last decades, China and United States were the countries with most CO_2 gas emission [3]. The energy generating industry are the dominant sectors on producing massive CO_2 emission. As per data of IEA, the transportation sector contributes as a third largest emitter of CO_2 after the manufacturing industry sector contributing 22% of global emission in 2019 [4] [5].

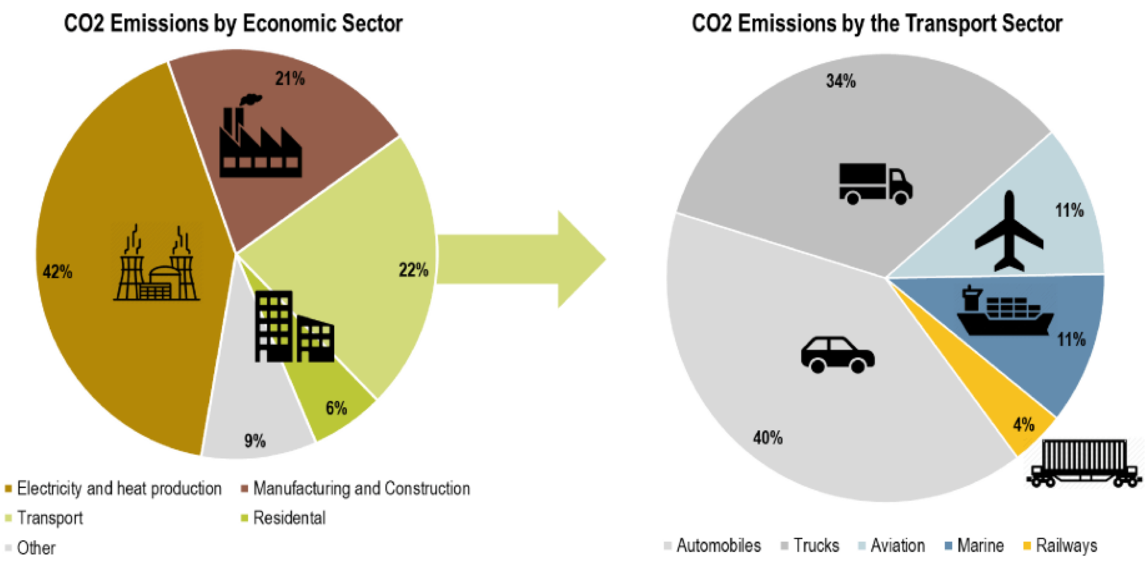

Figure 1: Global CO_2 emission by sectors in 2019[5]

The maritime sector is considered as most energy efficient sectors as compared to other mode of transportation. The CO_2 gas emission from shipping industry contribute about 2.5% of worldwide emissions annually. But the emission from this sector is increasing day by day with the heavy growth in cargo and overall economic development. It is predicted that emission increases between 50% to 250% if no mitigation measures are implemented soon [6].The sharp increase in using the ship as the mode of transportation has been observed for travel and trade purpose with the increase in population and business activities. As per the study by the International Council on Clean Transportation (ICCT), from 2013 to 2015, the overall maritime fuel consumption was increased by 2.4% with 7% increase in shipping transport work. Also, over same period, the CO_2 emissions from global shipping increased from 910 to 932 million tonnes [7]. At the end of 2019, global trade through shipping increased with more than 50% with moving solid and liquid bulk cargo annually across the world's ocean resulting 9.3% growth in the carbon emission where bulk shipping alone accounts for 60% emission of world fleet's emission [8].

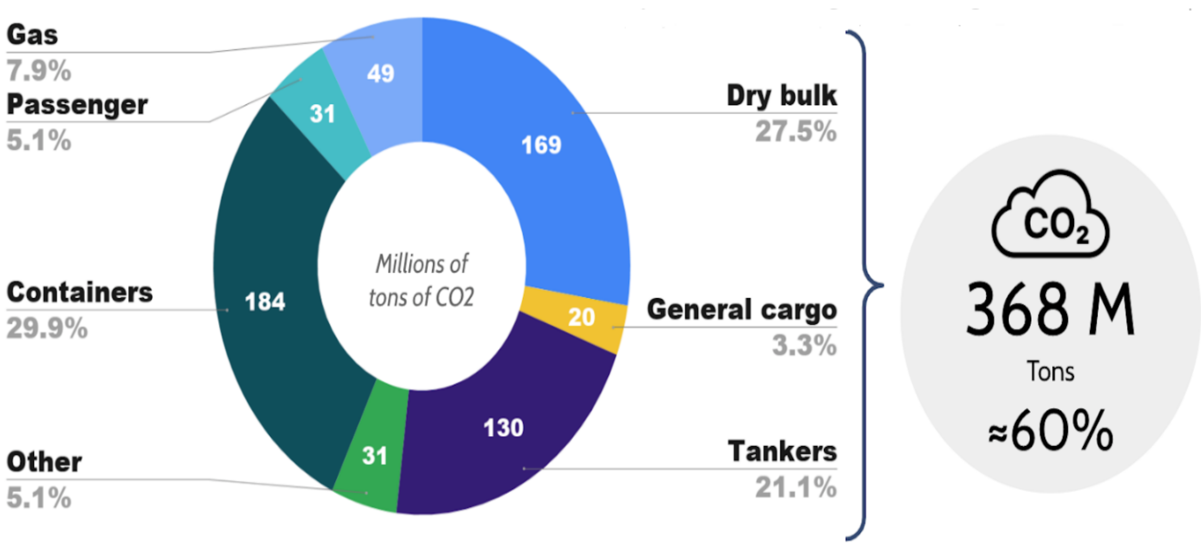

Figure 2: Global CO_2 emission by different ships [8]

The emissions from maritime transport consist of carbon dioxide (CO2) along with other global anthropogenic sulphur oxide (SOx), nitrogen oxide (NOx), and particulate matter (PM). As, more than 50% of shipping emission occurs within 400 km away from the land which has placed the global environment and human health under serious threat [9].

1.2 Decarbonization policies in maritime Industry

It is important to reduce the CO_2 emission from the different manufacturing industries throughout the world to achieve the ambitions of the Paris Agreement's to restrict further increase in the global temperature. In support of the mitigating the emission from the shipping industry, the International Maritime Organization (IMO), the UN specialized agency for maritime industry, has set the target of reducing the total annual emission from international shipping to 70% by 2050 with 2008 as a reference base year. This target should be achieved with every approachable need and overcoming the challenges associated to it which can benefits overall global decarbonization pathways [10]. The IMO had announced their short term, mid-term, and long-term policies for achieving the declared target. In short term (2018-2023) policies, it includes initializing the EEDI, developing the carbon intensity guidelines for the marine fuels, encouraging adoption of low carbon technology and research into innovative technology for zero carbon emission. In mid-term (2023-2030), the policy is to further develop the short-term measures with more effective implement of EEDI. In long term (2030 and further), the policy is to implement zero carbon fuels and market-based emission reduction mechanism [11]. Similarly, the world largest shipping container company 'Maersk' had announced their goal of having carbon neutral vessels commercially viable by 2030 with the adaptation of new innovative technology [12].

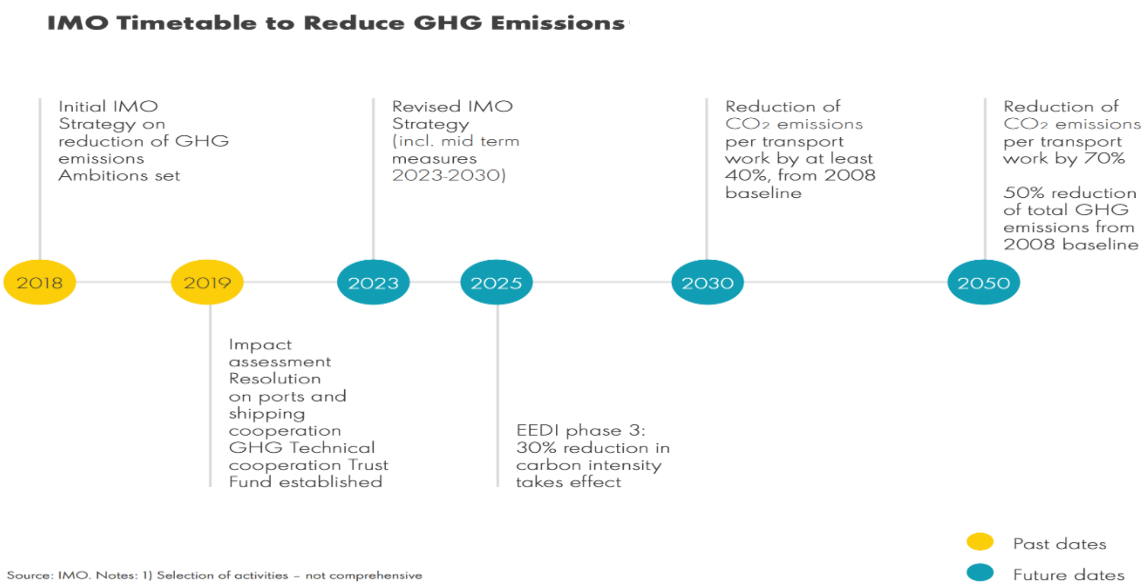

Figure 3 : IMO's long- and short-term plans of reducing CO_2 emission form maritime industry [11]

1.3 Decarbonization option: Carbon capture process

It is globally accepted that a reduction of the GHG emissions is necessary to combat the global climatic change. The various techniques and methods exist to reduce the emissions from different manufacturing sectors. Several options have been suggested from the study, which are lowering the energy consumption with the increase in the efficiency of energy conversion, diverting towards using less carbon contain fuels, and using other renewable energies options. But these options will not be enough to mitigate the global warming problem for long-term [13]. So, the technology of carbon capture, storage and utilization would be able to provides a long-term solution to mitigate the emission while using fossils energy until renewable energy technologies comes into effect. The CO_2 capture, utilization, and storage (CCUS) unit are considered as the principal alternative to reduce CO_2 emission by capturing it from different sector, storing it in porous rock (normally 700m down underground) and reusing it after certain time for different application [14]. This method has been widely researched and accepted by scientists throughout the world, as this unit operates with minimum energy consumption and an optimal capture efficiency. The various choices of CCUS are available but the selection of the suitable capture unit is highly dependent on specific discharge conditions i.e., state of flue gas, including its composition, CO_2 concentration, temperature, pressure, and flow rate [15].

1.4 Scope of the thesis

In this thesis, feasibility study of carbon capture system while installing on the specified vessel has been performed. The case study has been done in specified ferry vessel 'MF Lyngen' where its fuel type, engine type, route followed, and emission parameters has been studied. The feasibility of onboard carbon capture system designed by TECO 2030 has been investigated while installing on the vessel 'MF Lyngen'. The feasibility investigation has been presented based on technical analysis and economic analysis. In technical analysis, the physical properties on equipment placement and vessels capacity to support carbon capture system during start-up and running time has been investigated. Whereas in economic analysis, the cost of captured carbon from the system and the carbon transportation cost has been investigated with much focus. Furthermore, this thesis has also described the long-term storage options for the captured CO_2.

1.5 Objectives:

The main objective of this thesis is:

- Conduct the literature survey of various carbon capture technologies available along with the carbon transport and permanent storage feasibility.
- Development of methodology for performing the feasibility study (i.e., technical, economical and storage) of cryogenic carbon capture process installing on the specified vessels.
- Perform the detail study of specified vessel with its emission details and specified cryogenic carbon capture process.
- Finding the possibility of installing the CCS system in the specified vessels according with the developed methodology.
- Preparing the final report of the work performed.

1.6 Structure of Thesis

This thesis is organized in 6 chapter

- Chapter 1 provides the background information about the CO_2 emission from the various sectors with some fact and figures. It also consists of the scenario of carbon emission from the maritime industry with decarbonizing strategic plans and solution methods. The scope of this thesis work is also described in this section.
- Chapter 2 includes the literature survey done in the various carbon capture technologies available with some real-life applications. It also includes survey on several carbon transportation and permanent storage options.
- Chapter 3 consist of methodology part. In this section, how the technical analysis, economic analysis and selecting the storage feasibility are performed in this thesis is shown in detail.
- Chapter 4 describes the case study part. The detail study of the specified vessels with its engine characteristics, fuel used, routes used with the emission details has been done. The process of cryogenic carbon capture system to be used in this thesis has been briefly described. Furthermore, the possibility of the installation of that

typical CCS system in the specified vessel has been shown with the technical and economical assessment.

- Chapter 5 shows the discussion part where the results and findings of the thesis work has been presented in detail.
- Chapter 6 presents the conclusion part with some further recommendation for the future works.

2 Literature Survey

In this chapter, the literature survey has been done on several carbon capture and storage technologies with some real-life applications. Also, literature study has been performed on carbon transportation and long-term storage options for captured carbon.

2.1 Existing CO_2 capture strategy

The CO_2 capture strategy has been divided into three categories. The choices of the CO_2 capture strategy depend upon concentration of CO_2 in the flue gas, operating conditions of flue gas and pressure of the gas stream.

2.1.1 Pre-combustion CO_2 capture strategy

The pre-combustion CO_2 capture method is mostly applicable for coal gasification in an gasification combined cycle. In this method, the reaction occurs between fuel, O_2 and H_2O by which the carbon present in the fuel is converted to CO_2 and CO, and H_2 simultaneously. Then, CO is converted to CO_2, resulting approximately 20-40% CO_2 which can be compressed and stored for further use, after the water-gas shift reaction [16]. This capture strategy is commercial applied in some industrial sectors because this method doesn't produce waste gas but only generates the water which can be applicable for different purposes in various sector (battery manufacturing industries, aerospace industry, automobile industry, etc.).

2.1.2 Oxy-fuel combustion CO_2 capture strategy

In this capture strategy, the combustion of fuel takes place in pure O_2, resulting the higher level of CO_2 concentration (approx. 80-90%) in the flue gas. With application of this method, the content of NO_x in the flue gas gets minimized and purification process of CO_2 also gets easier as compared to other strategies. The temperature regulation in the combustor is performed by the recirculation of flue gas as opposed to air supply. This strategy is usually associated with pulverized coal combustion process. The advantage of this strategy is lower capital cost and initial low investment of boiler and other equipment [17].

2.1.3 Post-fuel Combustion CO_2 capture strategy

In this strategy, the CO_2 is captured after the combustion of fuel takes place in air. In this method, CO_2 concentration in flue gas is considered as quite low, i.e., for natural gases range from 3-4% and for coal-fired power plant range from 12-15%. [18]. This method can be considered as the simpler method than pre-combustion and oxy-fuel combustion for adding to the existing power plant with some retrofitting process. This strategy has been also built in some small-scale sites. The increment in the exhaust CO_2 concentration seems possible with exhaust gas re-circulation and availability of much energy and equipment.

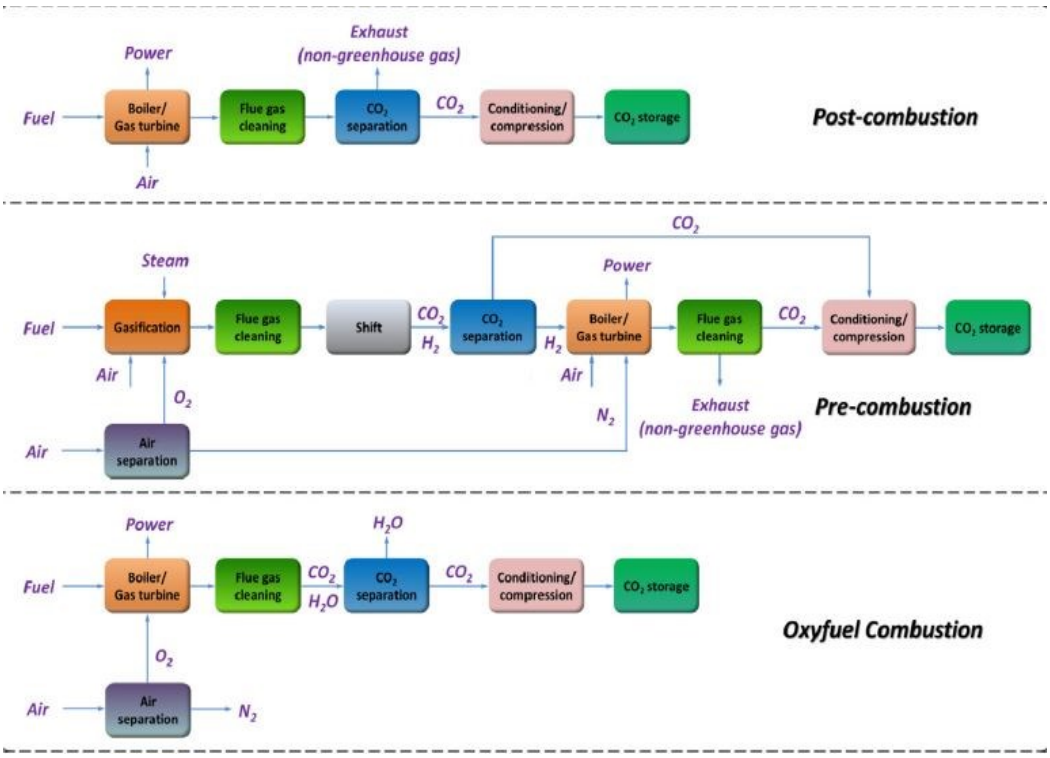

Figure 4: The existing CO_2 mitigation strategies [19]

2.2 Existing CO_2 capture technologies

2.2.1 Absorption

This method, commonly known as Monoethanolamine (MEA) absorption, is widely used technology for post-combustion CO_2 capture. It has capacity of capturing CO_2 at higher level (85-90%) from flue gas by application of strong physical and chemical reactions. It consists of two sections i.e., absorption and desorption. In absorption section, the flue gas is passed through the absorption tower where it gets mixed with amine solution. Then, the gas with low content of CO_2 will get released from the top of the tower whereas rich content of CO_2 with amine solution are released from the bottom to get heated in the heat exchanger. The heated gas and solution are sent to the stripper tower of desorption section. The high amount of CO_2 is captured from the top of stripper tower whereas the amine solution is recycled back to the absorption section for continuous regeneration [20]. Though, this method is most likely technology due to application of chemical solvents, it has some limitations i.e., corrosion, solvent degradation, and solvent regeneration efficiency [21], which needed to be solved out for high getting high efficiency output.

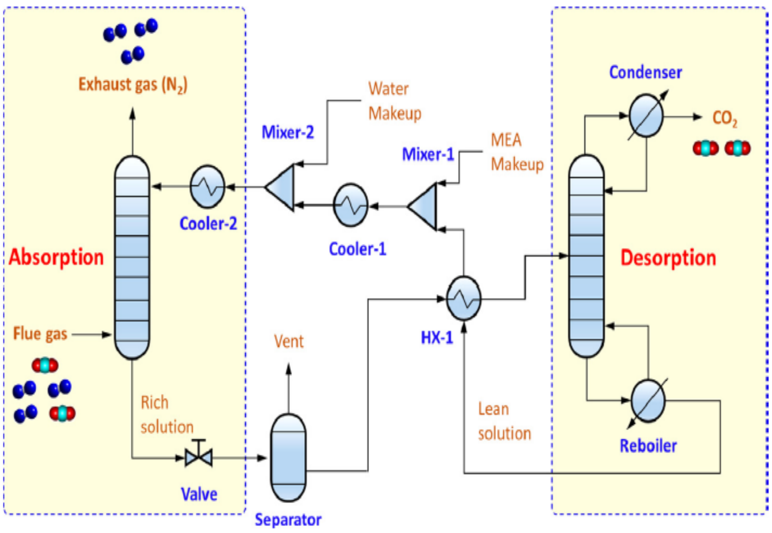

Figure 5: Absorption process (chemical) for capturing CO_2[20]

2.2.2 Adsorption

This method has the wide range of selectiveness and low energy consumption which make it much attractive techniques of post-combustion carbon capture strategy. In this method, flue gases are passed through pretreatment stage before processes through adsorption chambers [22]. Normally, it consists of two or three adsorption chambers filled with a solid adsorbent (i.e., activated carbon and zeolite) for accomplish the whole process. While operating this technique, one chamber acts as feed, second one acts as a desorbing unit for the captured CO_2, and the final one acts as a reserve chamber so that the system can operate without breakdown. This technique can be carried out in different manners i.e., Pressure swing adsorption, Temperature swing adsorption and Electrical swing adsorption. The limitation of this method is having a reserve capacity for available absorbent and adsorbent regeneration efficiency [23].

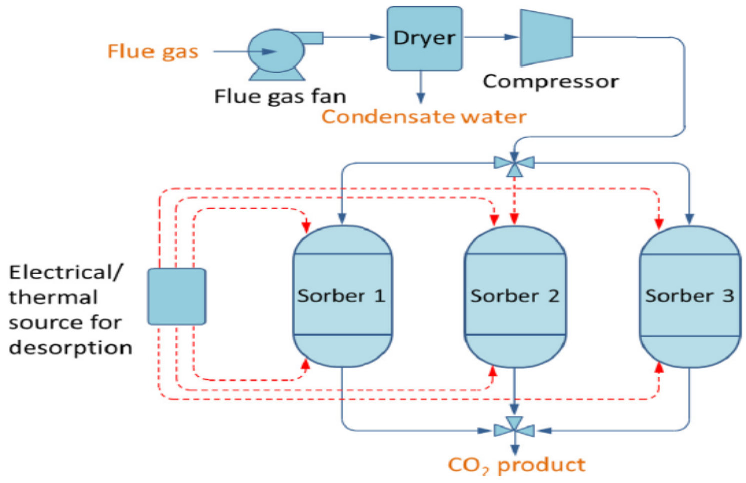

Figure 6: Adsorption process flow diagram for capturing CO_2 [23]

2.2.3 Membranes

This method is relatively new concept of separation technology by implementing membranes to separate CO_2 from a flue gas, gas stream or natural gas. Membranes are semi-permeable barriers which can separate substances by using various mechanism with the availability in different material types. The two methods of membranes i.e., gas separation membranes and gas absorption membranes has been explored in recent years. In gas separation method, the flue gas stream is released at high pressure into the one side of hollow separator membranes arranged in parallel. The CO_2 permeates through the membrane and remain in another side of membrane with the reduced pressure. In gas absorption method, the flue gas is released from one side of the micro porous solid membrane, then CO_2 gas diffuses through membrane and remain as liquid absorbent in the other side of membrane. This process also has limitation of low removal efficiency and capturing of low purity CO_2 [24].

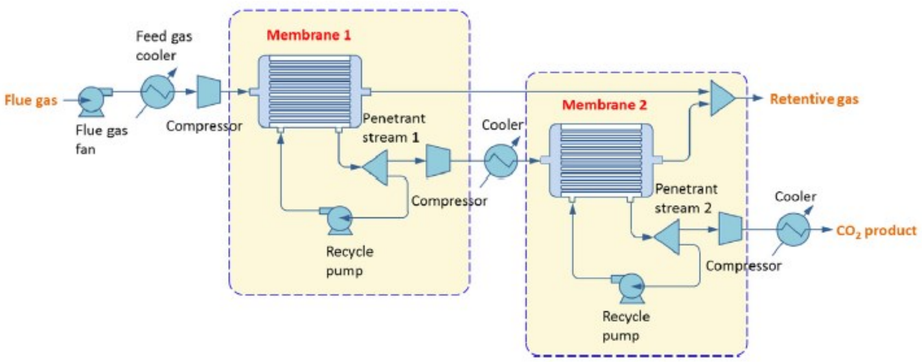

Figure 7: Carbon capture through Membrane's process [24]

2.2.4 Chemical Looping cycle

In this process, the combustion is performed by intermediate oxidation and reduction reactions which are carried out separately as a form of metal oxide in solid phase between the two sections. The metal oxide, such as copper, nickel, cobalt, iron, etc. are considered as good oxygen carrier. This process work uses two reactors, air reactors and fuel reactors. When the gaseous fuel is fed, the carrier is oxidized by oxygen in air reactor whereas in fuel reactor, carrier is reduced by the fuel and produces the CO_2 and water vapor. By condensing water vapor, the CO_2 can be sequestrated out and can be applicable for further process [24]. The insufficient stability of the oxygen carrier and slow kinetics can be considered as basic problem of this process.

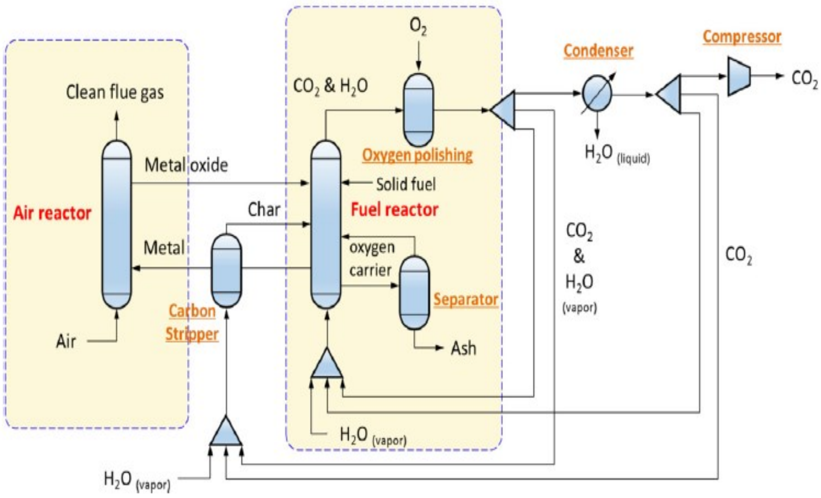

Figure 8: Chemical looping process flow diagram [24]

2.2.5 Microalgae

The various physical and chemical method has been discovered until now to mitigate the CO_2 from flue gas. This method adopts the biological method of using of algae, bacteria, and plants for CO_2 removal process. Currently, bio-fixation via microalgae is becoming more popular due to its high photosynthesis rate and environmentally sustainable method which perform high CO_2 mitigation effectively than by terrestrial plant [25].

2.3 Low temperature CO_2 capture technology

The low temperature CO_2 capture technogies are commonly called as cryogenic carbon capture technology. This method mainly depends upon phase change, capturing the CO_2 gas in the form of solid or liquid by implementing condensation and desublimation properties [26]. The word 'cryogenic' means the process that occurs below temperature 120K, which simply resembles the low temperature separation as defined by terminology from the IIR (International Dictionary) [27]. But the cryogenic temperature as defined by the IIR doesn't work for the CO_2 capture process because the scope of working of this process is above temperature 120K. This system implies the physical separation process depending on the boiling points and desublimation properties of the components present in the gas. It is possible to obtain higher level recovery of CO_2 and purity (99 %) by implementing this technology, so it is gaining considerably more attention. This technology restricts the use of chemical absorbent as other method and deliver the high purity dry CO_2 in solid form which have higher density and more compact size than gas and liquid CO_2 and will be beneficial for the transportation and storage. The main advantages of cryogenic CO_2 capture process are it optimizes the further purification and compression process, costs of transportation and reduce the consumption of supplementary energy for further processing, high purity product resulting with high range of CO_2 product without any toxic chemicals which can be easily transported, stored, or utilized. [28].

Although, the cryogenic based CO_2 capture system has more potential application, several challenges still exist to overcome. The high energy consumption for cryogenic condition to realizing CO_2 separation, high capturing cost, presence of several impurities in flue gas and maintaining the efficiency has provided some space of improvement. Due to high CO_2 recovery rate and purity, there has been an increase in attention for the combining cryogenic capture methods with other conventional process for creating the hybrid process (i.e., cryogenic-adsorption, cryogenic membrane, cryogenic-adsorption, and cryogenic-hydrate, etc.).

2.3.1 Cryogenic packed Bed

This cryogenic CO_2 capture process operated with the packed beds where the packing materials is of steel monolith structure. It includes three consecutive processes i.e., cooling, capture, and recovery. Firstly, before feeding the flue gas into the refrigerator packed bed, the bed temperature is reduced below -120°C for cooling. The flue gas gets cooled down resulting the heating of packing materials and condensing of water at the packing material will happen until reaching of equilibrium temperature of water. After condensation of all remained water, the further cooling of flue gas will take place, until the desublimation of CO_2 starts at the packing surface up to an equilibrium temperature of CO_2 is reached. The slowly movement of two fronts of condensing water and desublimating CO_2 throughout the packed bed will occur. But, at the same moment, the hot incoming flue gas will heat up the inlet of packing bed and evaporates the moving front of previously condensed water and sublimates the moving front of CO_2. When CO_2 breakthrough is observed, the bed is shifted towards the recovery step at the outlet. In the recovery step, a recycle flow of pure CO_2 will occur through the bed at same inlet initial temperature. Then, initially present CO_2 begins to desublimate due to pressure differences between recovery step and capture step. Also, the condensed water and desublimated CO_2 from the inlet zone continue to move towards recovery step resulting the pure CO_2 at the outlet part. The unwanted impurities are removed from obtained CO_2 and compressed for further application. It is essential to run all steps in parallel for the continuous operation of the process [29].

The method can separate the water and CO_2 simultaneously from the flue gas because of the differences of the dew and sublimation points. Also, the pressure drop issues and clogging issues can be neglected in the cryogenic packed bed. As, the cold energy stored in the packing materials helps to determine the amount of accumulated frosted CO_2 which abolish the requirement of chemical absorbent [30]. The cost of this technology depends heavily on the CO_2 concentration on the flue gas and initial bed temperatures. This technology can be utilized effectively with much deposition of CO_2 per unit volume of bed by lowering the initial temperatures as a result a much cold energy is stored in bed so that it works more efficiently.

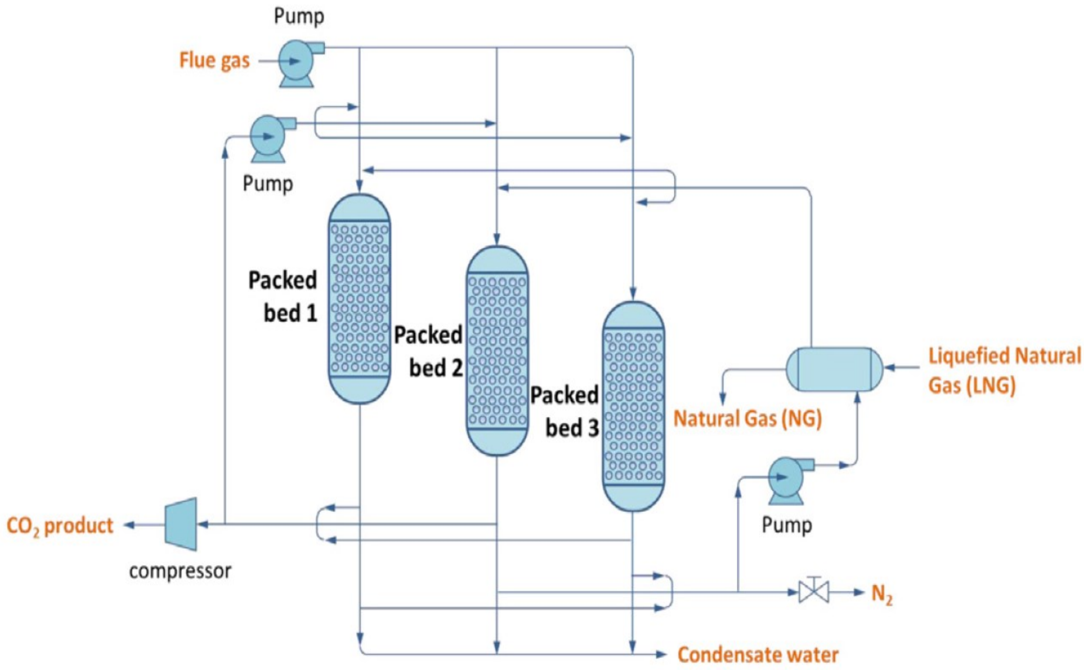

Figure 9: The schematic flow diagram for CO_2 capture by using cryogenic packed bed [29].

2.3.2 External cooling loop cryogenic carbon capture (ECLCCC)

This process comes with the approach of reducing the energy consumption by utilizing waste cold energy from the industries sources by an external cooling loop or thermal swing process. At first, the flue gas is fed into the flue gas system for drying and cooling process. Then, the flue gas is processed for compression and cooling up to the temperature slightly above where gaseous CO_2 transformed into solid form. It is processed for further cooling so that the desired amount of CO_2 in solid form can be obtained at certain temperature. Then, the CO_2 is much pressurized by compressor and several cycle of heating action takes place at heat-exchanger. Finally, the liquid CO_2 is obtained through the liquid pump as output product where the N_2 rich gas stream is discharged. This process has overcome the challenges of high energy load by storing energy in the form of LNG (Liquified Natural gas). In addition, it manages the loss of energy implementing stored refrigerant, so it drives the process during high demand whereas in low demand regenerating the refrigerant [31].

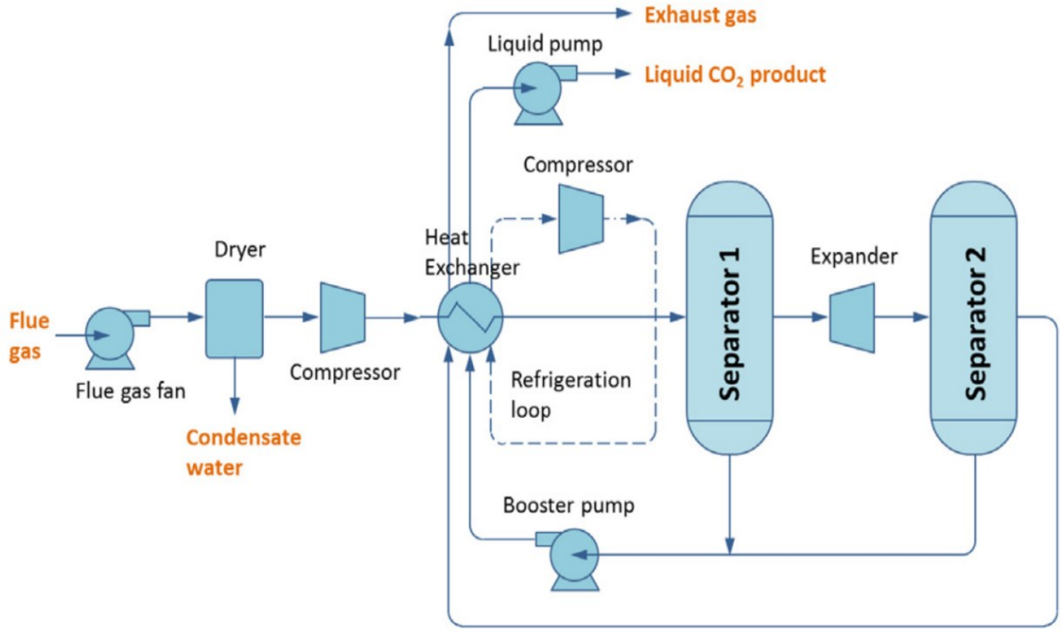

Figure 10: The schematic flow diagram for CO_2 by using external cooling loop [31].

2.3.3 Anti-Sublimation (AnSU)

Clodic and Younes had designed and proposed an anti-sublimation process to capture CO_2. [32]. This process is comprised of five sub-system.

1. Hot flue gases are passes through series of three condensing unit for cooling purposes whereas cold flue gases weak in CO_2 concentration are passed through three evaporating units and then cooled from each respective condensing unit.
2. To recover the coldness of cold flue gases before processing through freezing unit, the heat exchanger is placed between the hot flue gases coming from third cooling chamber and cold flue gas going to third evaporating chamber.
3. Integrated cascade refrigeration system is installed for working as low temperature freezers.
4. The freezing heat exchangers are installed for operating the defrosting process so that the liquid and gas phase of CO_2 are recovered at end.
5. The CO_2 gas is further process for treatment so that captured CO_2 reaches 99.9% purity [33].

This process shows the higher efficiency than amine-absorption process when retrofitted in the built power plant. In this process, the liquid blend of refrigerants occurs due to the defrosting of CO_2 on the heat exchanger surface which is considered as the advantageous part of this method [34].Hence, the wise selection of material for making heat exchanger, prevention from clogging and maintaining the rise in the pressure during the operation can affect in the efficiency of the process.

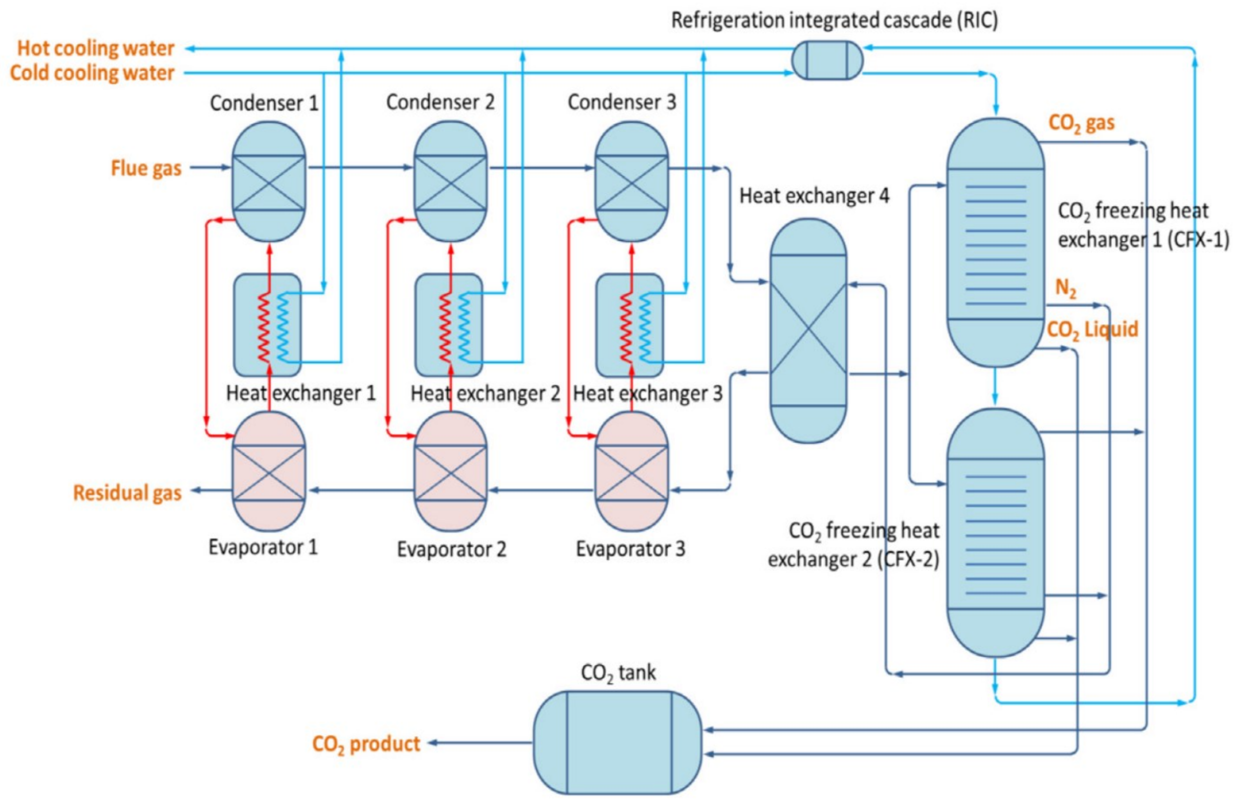

Figure 11: The Schematic flow diagram of CO_2 capture by Anti-sublimation [33].

2.3.4 Cryogenic Distillation

This method is one of the commonly used separation processes for purification of natural gas. In this process, the gas is fed into the precooler for cooling and further chilled by heat exchanger to low temperature. Then, the fed gas is transferred to the distillation column made of trays or packing materials. The steam component after the treatment from the distillation column gets separated into upper and lower part. The separated methane is collected from the top part via a partial condenser whereas the condensed CO_2 is collected from the bottom part. Some percentage of separated CO_2 is recycled through the reboiler for providing vaporization heat and other part are further separated to get the pure purified CO_2 product [35]. This process has the potential of energy storage and water storage with simultaneous removal of pollutant. Though, it has major industrial use, but also has the limitation of high installation cost and capital cost for pressure difference.

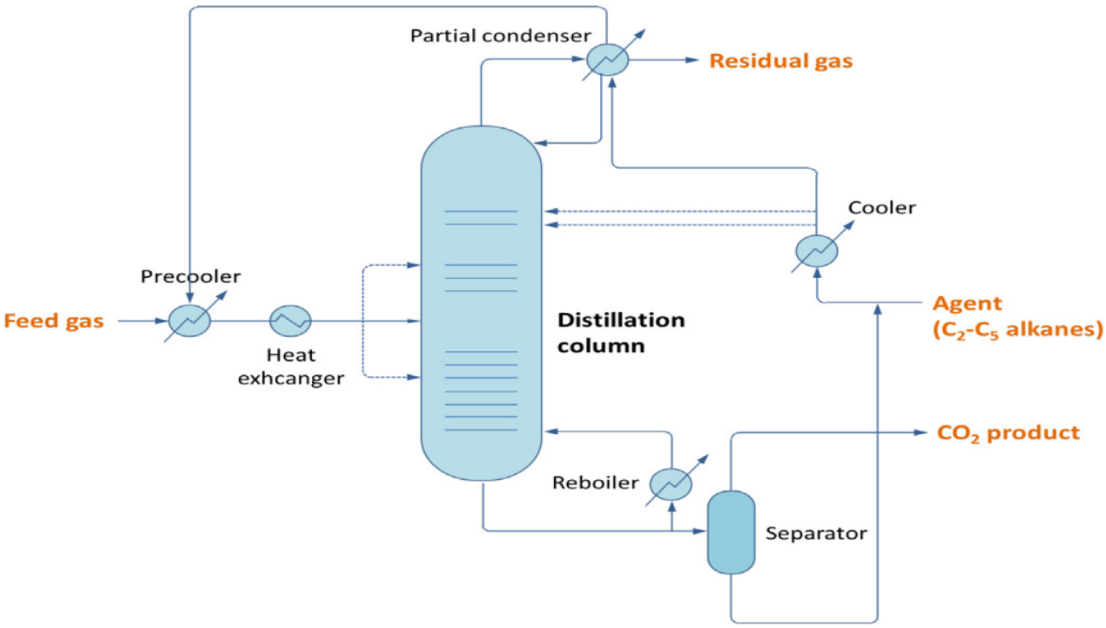

Figure 12: The Schematic flow diagram of CO_2 capture by Cryogenic distillation [35].

2.3.5 Cryocell process

This process is highly advantageous as it doesn't require the process heating system and is mainly suitable for the high CO_2 concentration than 20%. Here, the feed gas is passed through dehydrator to remove the water content of the gas and make it dry. Then, the dry gas is processed to heat exchanger and further to the cooler for cooling purpose of CO_2 to its freezing point. It is further processed to Joule-Thomson valve for expansion before entering to Cryogenic separator. The CO_2 in the solid form is collected from the bottom of separator and heated by reboiler to received it in liquid form [36].

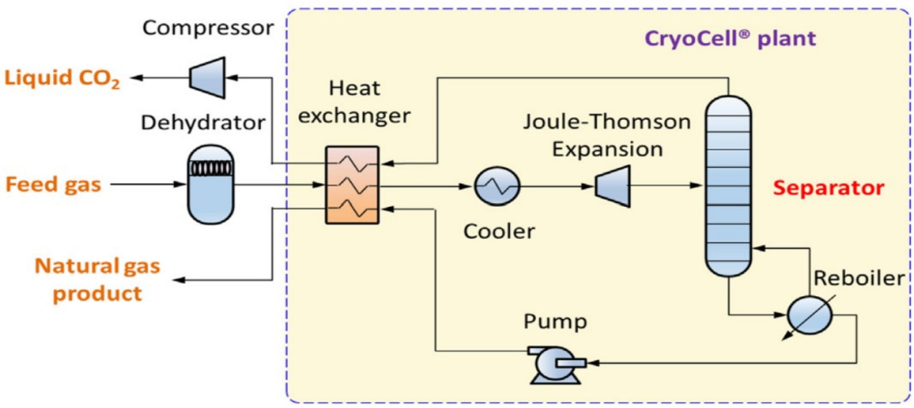

Figure 13: The Schematic flow diagram of CO_2 capture by Cryocell Process [36].

2.3.6 Stirling cooler system

Stirling cooler system consist of three parts i.e., pre-freezing tower, main freezing tower, and storage tower, where free-piston Stirling chiller is placed for chilling each part. The water is separated from the flue gas by condensation process in the pre-freezing tower. The dry gas is moved towards main freezing tower for further cooling purpose until the temperature is lowered down to capture CO_2 by anti-sublimation process. Finally, the frosted CO_2 is captured at the storage tower and on the other hand, residual gas exhaust from the gas outlet. This novel cryogenic system avoids the regeneration of solvent and pressure differences as in other technology. This system has provided the large extent of scope in the industrial application because of its small size, high reliability and high efficiency but has only been demonstrated on the laboratory scale till now [37].

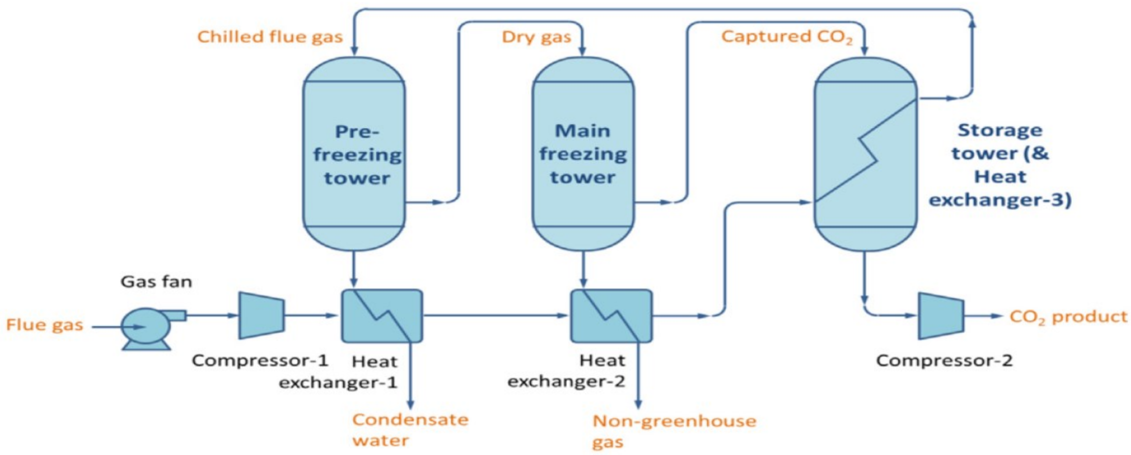

Figure 14:The Schematic flow diagram of CO_2 capture by Stirling Cooling System [37].

2.3.7 Advanced Cryogenic Carbon Capture Process (A3C Process)

It is a newly developed low-cost process of capturing CO_2 by consuming less amount of energy and utilizing the reduced equipment size. This process resulted with high purity form of CO_2, without utilizing any chemical process, which can be utilized for storage and transportation purpose. In this process, a moving bed of metallic beads has been utilized for heat transfer medium and frost capturing surface eliminating the use of multiple beds so that the process equipment size has been reduced with the minimum energy consumption.

This process consists of two steps i.e., cooling-drier step and CO_2-seperator step, each step is filled with 2-5 mm diameter metallic beads. The raw gas is passed through the chiller for condensing the water vapor to 274K. At the cold end of the first circulating packed bed, the residual water content is removed as a frost. The water ice decomposition is 0.1% of the rate of bed mass flow. The gas is further cooled to 174K to eliminate water content in the gas, and cold dry gas is transferred to the CO_2-separator step. Whereas the frost bearing bed is taken out of the stream of raw gas, slightly warm until to melt the ice and shifted to other part where it moves in the opposite direction to lean gas coming out of the desublimation process. The moist beading bed is dried and cooled by the cold dry lean gas stream and placed in its initial position. In another step, the dry gas is passed to the desublimer unit, where it flows opposite to the cooler bed forming the frost CO_2 on the bed material. The collected frozen CO_2 mass is around 1% of the flow rate of bed. The bed transferred the frosted CO_2 to the gas inlet end of the bed, and it carries into the sublimer heat exchanger for heating to recover the CO_2 in liquid form [38].

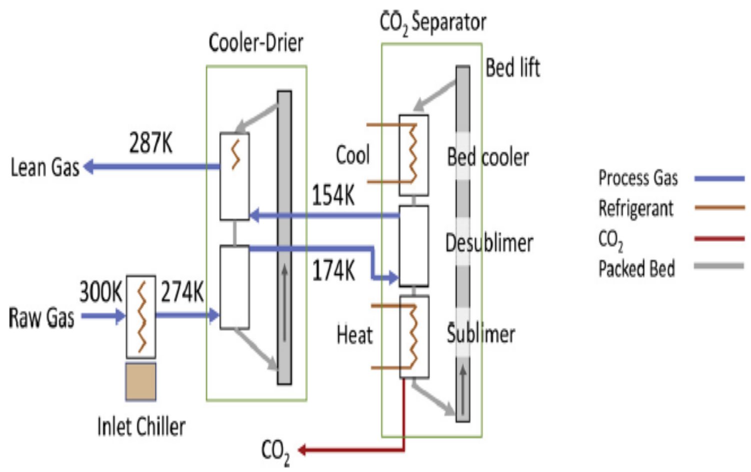

Figure 15:The Schematic flow diagram of CO_2 capture by A3C separation process [38].

The economic and technical analysis of A3C method has been conducted through modelling by Wilson [39], where it was compared against the amine-based CO_2 capture process for some potential applications. The observation from that analysis shows that the recuperative A3C process optimizes the energy demand than the amine-based method which shows the specific energy consumption of 263 kWh/ton for the upgrading of biogas applications [39].

2.3.8 Other Process

There is other several cryogenic methods which are available for some applications. Cryogenic carbon capture with compressed flue gas (CCC-CFG) system compresses the flue gas to 5-7 bar before processing to the heat exchanger where the flue gas gets expanded and desublimate to deliver the frozen CO_2 [40].This process utilizes the dryer system for removal of water content from the flue gas and heat exchanger for desublimation of CO_2.Another process named 'Controlled Freezing Zone (CFZ)'is used for removal of impurities (CO_2 and H_2S) from the natural gas. The sour impurity in raw natural gas varies from 20% to 70% according to the geographical region [41]. This whole system is composed of three sections; an upper distillation section, controlled freezing zone and lower distillation section. This process has been successfully demonstrated by ExxonMobil Upstream Research company in Wyoming which adds the economic benefits by reserving sour natural gas [42].Comparison of various cryogenic carbon capture process is shown in table 1.

Table 1: Table showing different cryogenic carbon capture process with their features

Cryogenic Processes	**Gas sources**	**CO_2 Recovery**	**Cold energy source**	**Energy Consumption**	**Phase**
Cryogenic packed bed	Coal-fired power plants	99.0%	LNG	1.8 $MJ_{electrical}$/kg CO_2	liquid
CCC-ECL	Raw Natural gas	95.6% mol		1.401 KWh/kg CO_2	liquid
AnSU	Coal-fired power plants	90%	LNG	1.18 $MJ_{electrical}$/kg CO_2	liquid
Cryogenic Distillation			Compressor and Cooler		liquid
Cryocell process	Raw natural gas		Chiller		liquid
Stirling Cooler System	Coal-fired power plant	85%	Stirling cooler	3.4 $MJ_{thermal}$/kg	solid
A3C Process	Raw Natural gas	99.9%			liquid

2.4 Decarbonization in Maritime Industry

According to the survey from the International Maritime Organization (IMO), the emissions from the maritime industry contribute about 2.5% of global greenhouse gas (GHG) emissions. In 2018, IMO sets the vision of their strategy of fighting against the climatic change by reducing the greenhouse gases from the shipping industry. As per strategy, it is committed to reduce the emissions of carbon intensity from international shipping at least to 40% by 2030, pushing same effort towards to 70% by 2050. This strategy is a part of ambition of Paris Agreement temperature goals of reducing CO_2. The definite measures that IMO has adopted as per strategy includes mandatory implementing the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP). IMO is also implementing global technical cooperation projects to supporting the states, mainly developing states for supporting and executing the energy efficiency in the shipping sector [43].

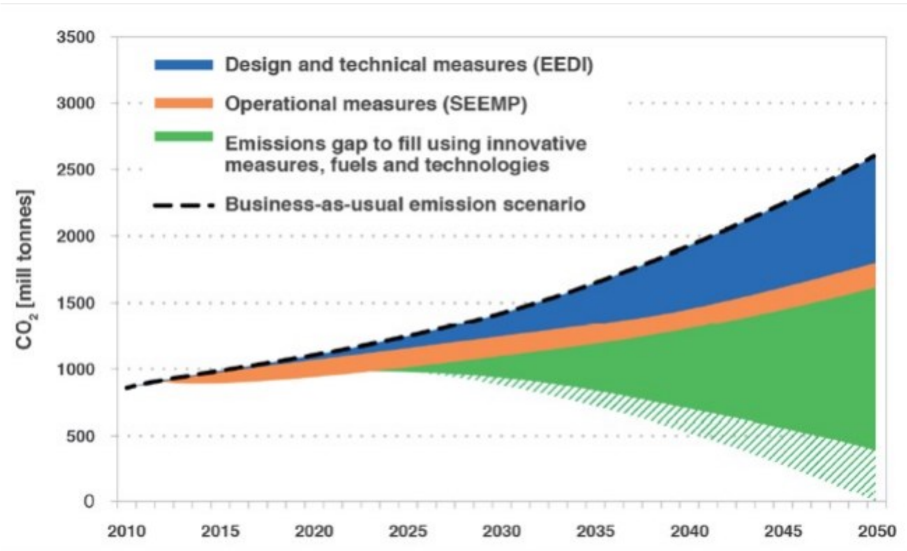

Figure 16: Overall GHG reduction pathway to achieve the initial IMO strategy [43].

About 80% of the global trade has been possible with the international shipping, but now a major technological shift is needed for following the new regulations set for greenhouse gas (GHG) emissions. The emission differs from one ship to other ships in terms of fuels and efficiencies. Different fuels have varying composition of CO_2, SOx, NO_x and methane emissions, and inefficient ships consume more fuels. Among 75% of ships in maritime industry consume the residual fuels (e.g., heavy fuel oil HFO), 23-24% consume the distillates (e.g., marine diesel oil MHO) and almost 1-2% consume liquified natural gas (LNG) [44]. The marine diesel oil (MDO) and heavy fuel oil (HFO) contains less sulphur, whereas enrich in GHG and

NO_x content, whose emission increases with the high temperature combustion [45]. The burning of heavy fuel oil results the marine black carbon, which is a solid fine particle with a short lifespan of 1 week, have a huge impact in global climatic change and human health [46].

In support of long-term decarbonization in maritime industry, liquified natural gas (LNG) as a fuel can be utilized as one of the best alternatives to heavy fuel and marine diesel. To produce LNG fuel, the natural gas is liquified and cooled up to -162^{o} C and required minimum space for storing and transportation purpose. LNG does not contain sulphur in it, could provide the reduction in CO_2 emissions with meeting SO_x and NO_x emissions regulations in a cost-effective manner. Nowadays, the four different types of LNG engines are in operation where each have different operational characteristics, exhibit different emissions profile and efficiencies. Biofuels can be also utilized as another alternative when blended with LNG or gaseous based fuels. For achieving the 50% reduction in GHG emissions in LNG fueled ship with cost-effectiveness options, all the improved efficiency measures must be implemented.

Thus, the combinations of fuels, technology, and policy together routes to the short-term and long-term approaches of decarbonization process. The economic and technical feasibility with environmental guarantee is considered as the short-term benefits of utilizing the LNG as fuel. Furthermore, the utilization of renewables and hydrogen fuel can be considered as long-term approach of decarbonizing the maritime industry in terms of economic and environment factors [36]. For achieving the zero-shipping carbon emission, the other options are also available i.e., utilizing the electricity or alternative fuels, blue hydrogen, or ammonia. But the major modifications are required for the ships and fuel logistics.

The Onboard Carbon Capture and Storage (OCCS) system is a process of capturing and storing carbon dioxide (CO_2) contained in exhaust gas which are emitted from the internal combustion of the engine in the ship. This process selectively captures CO_2, liquifies it and transport to the port and is stored underground or undergoes methanation. The current OCCS system does not follow the guideline for calculating the attained EEDI as provided by the IMO. As a solution for this problem, a new factor has been taken into consideration for calculating attained EEDI to be implement in the OCCS system. The attained EEDI is an index that represents the design efficiency of individual ships and more precisely, the amount of CO_2 in grams generated from ships to transport 1 ton of cargo per 1 nautical mile. It should be calculated with respect to the EEDI technical guidelines and authorized by recognized organization during the ship building process [47]. The methodology for estimating the attained EEDI formula has been shown in figure 17.

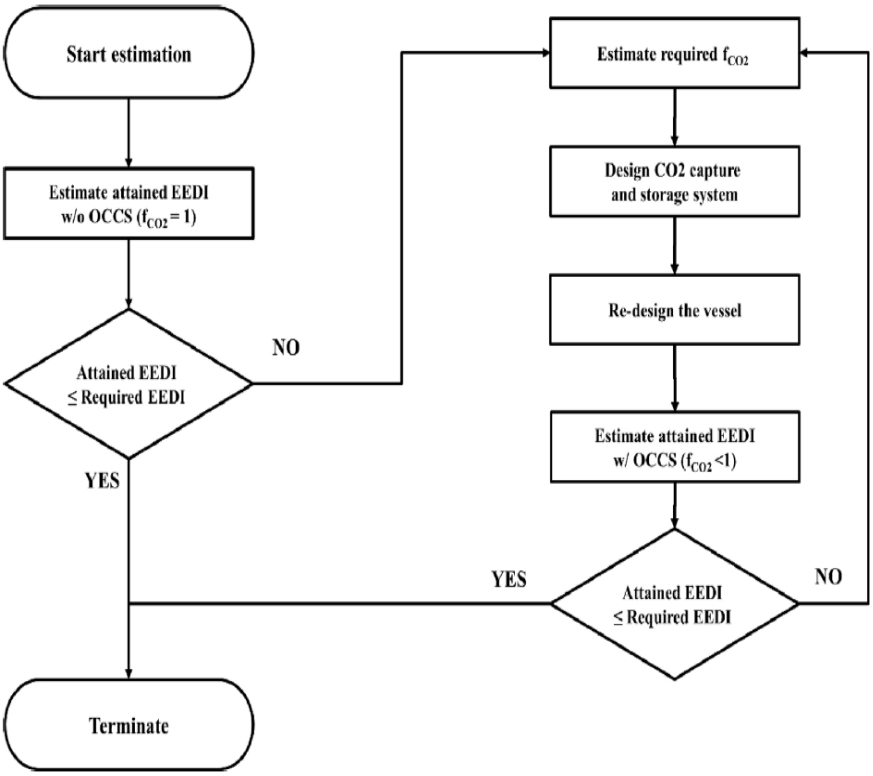

Figure 17: Methodology for estimating the attained EEDI for ships considering OCCS [47]

The simple equation of the attained EEDI formula including the new factor has as provided by the IMO is shown below [48].

$$f_{CO2} = 1 - \frac{M(\text{capture})}{M(Exhaust)}$$

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \times (C_{FME(i)} \times f_{CO2(i)}) \times SFC_{ME(i)}\right) + (P_{AE} \times C_{FAE} \times SFC_{AE}) + PTI + EFF}{f \times Capacity \times V_{ref}}$$

where,

M(capture) = mass flow rate of CO_2 captured in OCCS.

M(Exhaust) = mass flow rate of CO_2 in the exhaust gas.

P = Engine power in KW.

ME = Main engine.

AE = Auxiliary engine

SFC= Specific fuel consumption rate of the installed engine in g/KWh.

C_F= emission factor representing the amount of CO_2 generated per ton of ship.

DWT = gross tonnage of a ships in tons.

V_{ref} =reference speed of a ship in tons.

2.5 Applications of Carbon capture process in onboard

The several applications of the carbon capture methods have been performed in onboard. In [49], solvent-based carbon capture method has been presented for diesel and LNG-fueled vessels utilizing the ship engines of 1280KW and 3000KW using solvent Aspen Plus, with 30 wt%. aqueous monoethanolamine (MEA) and 30 wt.% aqueous piperazine (PZ). When the diesel- fueled ship is utilized with MEA, the cost of capturing rate of 60% CO_2 is 389€/tons and 80% CO_2 is 296€/tons. And, while running with the LNG, there is decrease in the cost to 323€/tons for capturing 60% CO_2 and to 232€/tons for capturing 90% CO_2. When changing the chemical absorption with piperazine to 1280KW diesel-fueled ship, it has shown the capturing rate of 60% CO_2 is 304€/tons and 90% CO_2 is 207€/tons. And the cost reduces to 209€/tons for capturing 60% of CO_2 and 159€/tons for capturing 90% of CO_2 when ship is running on 3000KW engines utilizing LNG fuel. The study concluded that the Ship Based Carbon Capture is more effective on larger LNG-fuel ships utilizing piperazine as obtained cost is lower in the larger ships and concluded that the equipment sizes and weights should be compatible with the designation of ship [49].

Another study proposed the scrubbing method utilizing the aqueous ammonia for the capture of CO_2 and removal of SO_2 from a 10,800 KW Wartsila marine diesel engine. It has been found 70% carbon capture achieving the 85% load through the waste heat recovery process. The study showed carbon capture rate is 75% and is possible to recover heat by utilizing the WHRS (Waste Heat Recovery system). The higher capturing rate would involve more power for burning more fuel. At 85% load, the maximum recovered heat while operation is $4MW_{th}$, and is much enough for capturing 70% of CO_2 and 98% of SO_2. Alongside the capture process of CO_2, some valuable product generated while sailing providing some economic benefits for the shipping company [50].

The feasibility study of the A3C process for the new-built or retrofitted vessels has been done which shows the total fuel consumption increases by 17% and 24% when using LNG-fuel and MGO respectively in process of capturing the 90% of carbon emissions from the main and auxiliary engines and, also the cost of utilizing the A3C process in shipping is relatively low as compared to the vessels utilizing alternative fuels [51].

Norwegian Company TECO 2030, through partnership with AVL, is developing an OCCS technology to reduce the carbon footprint from the marine application. TECO's carbon capture process is designed to work accordance with Sulphur Oxides (SO_X) emission regulations and with future regulations such as Particular Matter (PM), Nitrogen Oxides (NO_x) and Black Carbon. This technology has modular system which has been designed for all ranges of engines and suited for all types of vessels (newly built or retrofitted) [52].

2.6 Transportation of captured carbon

The transportation of the CO_2 means to connect the captured carbon from the emission sources to the storage locations. The transportation of CO_2 is done through the pipelines and shipping ensuring the proper safety. Pipelines can carry large volumes of carbon about 1000 km, both in land and in the sea. The pipeline transportation is considered as the cheapest mode while transporting around 1000 km, either onshore or offshore. It is mainly laid in the heavily populated areas, farmland, and the open range, in the oceans up to 2000m deep. The shipping transportation becomes cheaper when transportation distance became more than 1000 km. The capacity, service speed, number of ships with the schedule, distance, climatic and technical restriction are needed to be considered for transporting the CO_2 through ships. In commercial scale, pipelines and shipping are being used to carry carbon in both gaseous and liquid state. At atmospheric pressure condition, the carbon in gaseous phase occupies a large volume which made it difficult to transport. Normally, the carbon in gaseous state is compressed for lowering the volume so it can easily be transported through pipeline. The volume can be further reduced by applying solidification or liquification process. The solidification process is not preferred due to need of excess energy and cost. But the liquification process of carbon is much preferred from the economical and transportation view. The liquification technology has been the globally accepted and recognized by shipping industry and has been existed with the creation of known carbon transportation network [53].

The odorless and colorless substance which shows the corrosive nature after dissolving into water is real physical property of pure CO_2. It shows four different phases under different pressure and temperature conditions it exist. At 5.2 bar and -56.4^{0}C, the triple point exists where CO_2 can change between solid, liquid, and gaseous phase [54].

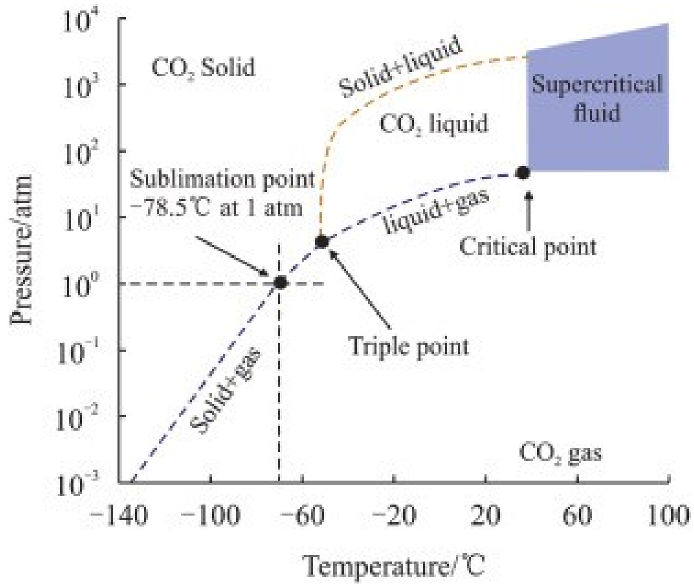

Figure 18: CO_2 phases with different pressure and temperature [54]

Gaseous state: CO_2 is in gaseous state in the standard conditions i.e., 20^0C, 60 bars. It is the phase with the less density of about 172 kg/m^3 and not economical and feasible for transporting in the high volume [54].

Solid state: CO_2 is in solid state with the temperature of -80^0C and 1 bar. It has the density of 1562 kg/m^3 in the solid state. It is the densest phase of CO_2. At the same pressure, when the temperature is lowered upto -78.5°C, the sublimation occurs where the solid CO_2 directly changes into gaseous phase without changing into liquid phase known as dry ice [54].

Liquid state: CO_2 is in liquid state with the temperature of -15^0C and 30 bar. It has the density of 1011 kg/m^3 in the solid state. It is the denser than gaseous and supercritical phase. The liquid phase of CO_2 is most desirable for the transportation through the ships. The liquification is done by lowering the pressure and temperature respectively so that it can be easily utilized in ship transportation [54].

Supercritical phase: CO_2 is in supercritical state with the temperature of 35^0C and 125 bar. It has the density of 757kg/m^3 and is denser than gaseous state. This phase is achieved through compression of CO_2 above 73 bar and above 31.1^0C. This phase of CO_2 is highly preferred for transporting the CO_2 through the pipeline mode [54].

2.7 Long-term Carbon Storage Option

The long-term carbon storage means to store the carbon from the temporary carbon storage to some final storing place for a long period of time to reduce the impact of CO_2 into the atmosphere. The stored CO_2 can be utilized later in chemical and polymer industry, production of plastics and cements, urea production, refrigeration systems, food packaging, carbonated beverages, fire extinguishers, horticulture (greenhouses), calcium carbonate production and other industrial uses.

2.7.1 Geological Storage

Geological storage is the process of injecting the CO_2 into the permeable rock formations. It is only one method of long-term carbon storage which has been commercial support throughout world mostly in the oil and gas company where it is highly applicable with some modifications [55]. This method consists of different approaches of storing CO_2 i.e., in sedimentary basins, in depleted oil and gas fields, saline aquifers, and deep unmineable coal seams. The sites for storing can be either onshore or offshore. Storage safety is a main aspect for geological storage as the stored CO_2 does not leak and harm. Before selecting the site, it should be determined that whether overlying impenetrable cap rock will provide the effective seal or not to withstand for longer period. An impenetrable cap rock is a thick layer of shale and clay rock placed above the storage reservoirs for blocking the upward movement of CO_2. The storage reservoirs mainly consist of sedimentary rock containing a billion of microscopic pores in it which allow CO_2 to be stored in same way as water contained in a sponge. Normally, when CO_2 is injected at depths of 800-1000m below surface, pressure and temperature are kept in the supercritical nature. In this supercritical condition, the CO_2 remained in the ideal state effectively utilizing the space of pores in sedimentary rocks [55].The global CO_2 storage capacity in depleted oil and gas reservoirs is estimated between 675 – 900 Gt CO_2 whereas in saline aquifers, it is estimated between 1000 – 10,000 Gt CO_2. Until 2100, it has been predicted that 1500 Gt CO_2 capacity is required to stabilize the CO_2 at atmospheric levels of 450 ppm [56].

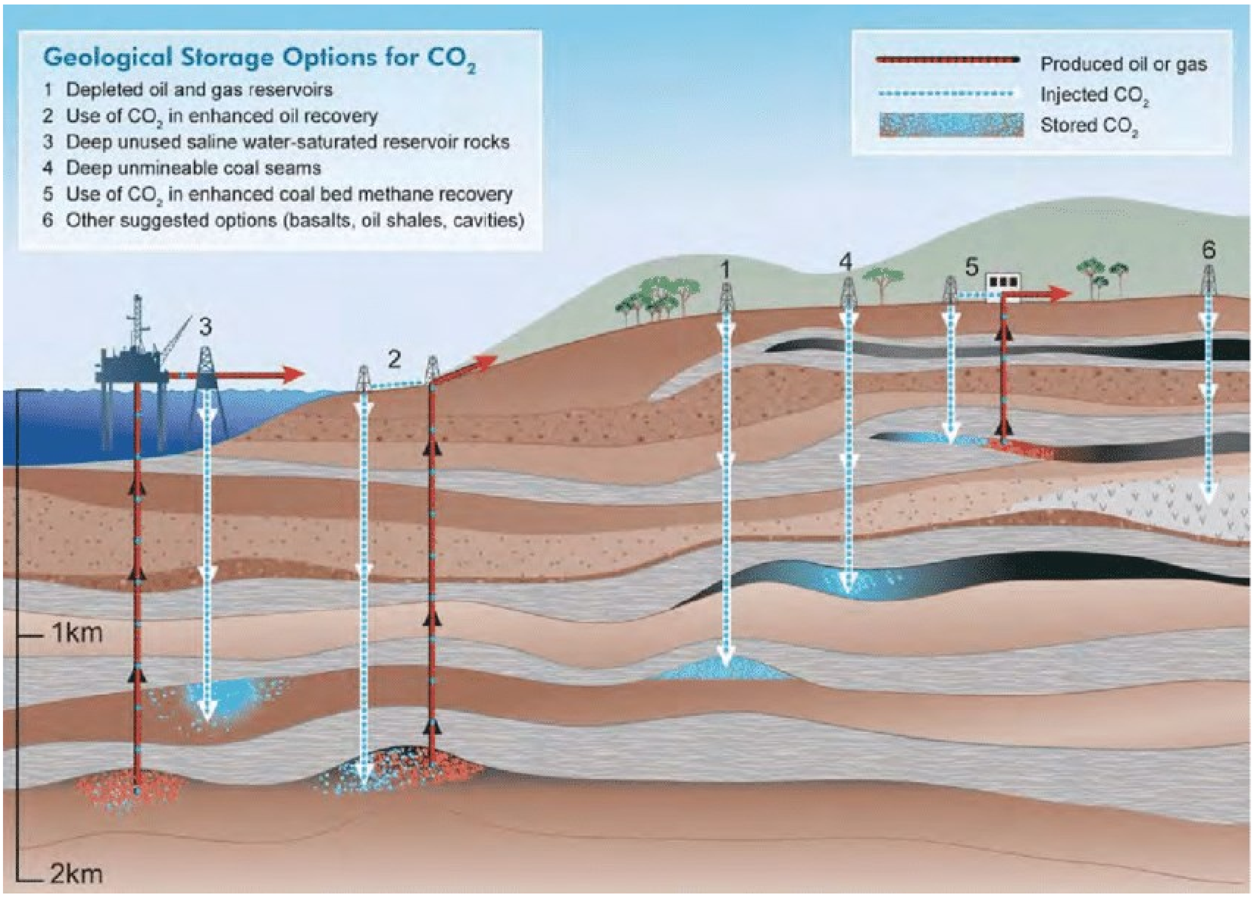

Figure 19 : Geological carbon storage [56]

2.7.2 Ocean Storage

About 70% of earth's surface is covered with ocean with an average depth of about 3,800 meters. There is no limitation on the availability of physical space in ocean for storing the CO_2. The captured CO_2 could be injected into the ocean at great depth, so that it would remain isolated from the atmosphere for long period. It would take over millions of years for injected CO_2 into the oceans at great depth to reach about the same atmospheric equilibrium and to be release into the atmosphere. The amount CO_2 to be stored in ocean for million years' time is dependent on the oceanic equilibrium with the atmosphere [57].

The feasibility of ocean storage is dependent upon possibility of storing CO_2 under huge depth in ocean and retention time of CO_2 from the ocean. Some analysis of oceanic observations and numeric models had suggested that it would take more than hundreds of years for injected CO_2 to release. It further suggests that it takes retention time increase with the increase in the depth of injection of CO_2. The retention time can be prolonged by forming solid CO_2 hydrates, liquid CO_2 lakes on the sea floor and by increasing the solubility of CO_2.Several technologies have been found for the intentional storage of CO_2 in the ocean by utilizing inorganic strategic so that which could be applicable at industrial level. The possible method is to compressed CO_2 and transported through ships and injected directly on the sea floor through pipeline. Another approach would be dispersing CO_2 from a towed pipe or transported to fixed platforms to get mixed on CO_2 lake at the sea floor. But, CO_2 lakes should be placed below 3000 m depth, as liquid CO_2 is mor denser than water below this depth. Another possibility could be injecting CO_2 directly into the ocean, so due to natural process atmospheric and ocean- dissolved CO_2 would try to adjust equilibrium between themselves but this process could be risky, and carbon could not be utilized later [57].

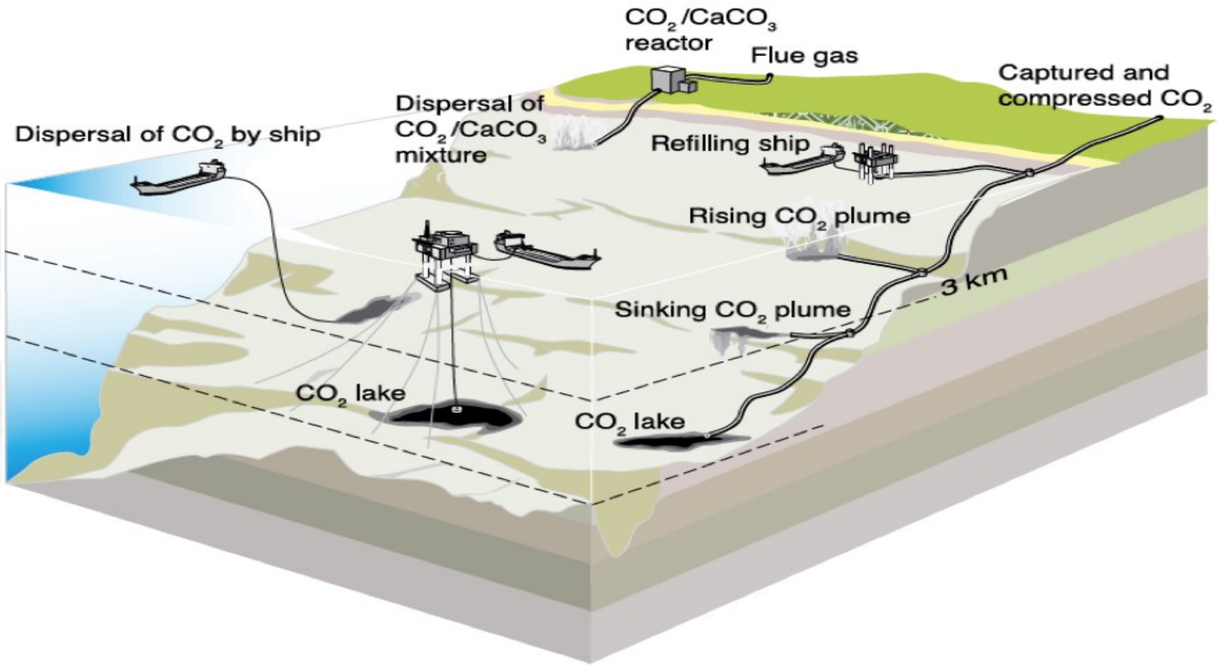

Figure 20: Oceanic Storage process [57]

In the other side of CO_2 oceanic storage, it could also show the harmful effect on the life of marine organism. It is expected that with the increase in the concentration of CO_2 in the ocean, the ecosystem of marine would get disturbed. The study done on individual organism that lives near the ocean surface has shown that the effect of CO_2 increases with the time resulting with the reduced rates of reproduction, circulatory oxygen supply, growth, and mobility as well as increase in the mortality rate. The chronic effects may be observed with the long-term accumulation of CO_2 nearby the injection area. The regular biological and chemical monitoring is essential to evaluate the amount of materials released, the retention of CO_2, and some environmental effects. Also, after certain time in future, the oceans may contain more dissolved inorganic carbon or had a lower pH. In this type of storage, the costs of monitoring, injections nozzles are expected to be small whereas shipping, piping, compression/liquification costs can be considerably high. Though, the ocean storage has both positive and negative side, but has not granted with legal status for the carbon storage till date. The support from the government, public and international offices are also equally essential for the deep ocean storage [58].

2.7.3 Mineral carbonation

One of the options of storing CO_2 is fixing of carbon dioxide in the form of inorganic carbonates. The reaction of captured CO_2 with metal oxide bearing materials forming insoluble carbonates, mainly with calcium and magnesium, resulting the corresponding carbonates of metals and byproducts is known as 'mineral carbonation' or 'mineral sequestration'. The carbonation reaction is the exothermic reaction and as per condition with the application of both low temperature and high temperature and supported by calcination process. The oxides of calcium and magnesium are widely utilized and favorable for mineral carbonation [59]. Silicate rocks, serpentine and olivine minerals are considered as suitable materials to be used for the high scale carbonation process whereas alkaline industrial residues such as slag from steel production or fly ash can be implement for small-scale reaction. For silicate rocks, carbonation process is carried out with some mining and pretreating silicates and processes out in ex-situ in chemical processing plant. The industrial residues can also be carbonated in same processing plant where it has been produced [60].

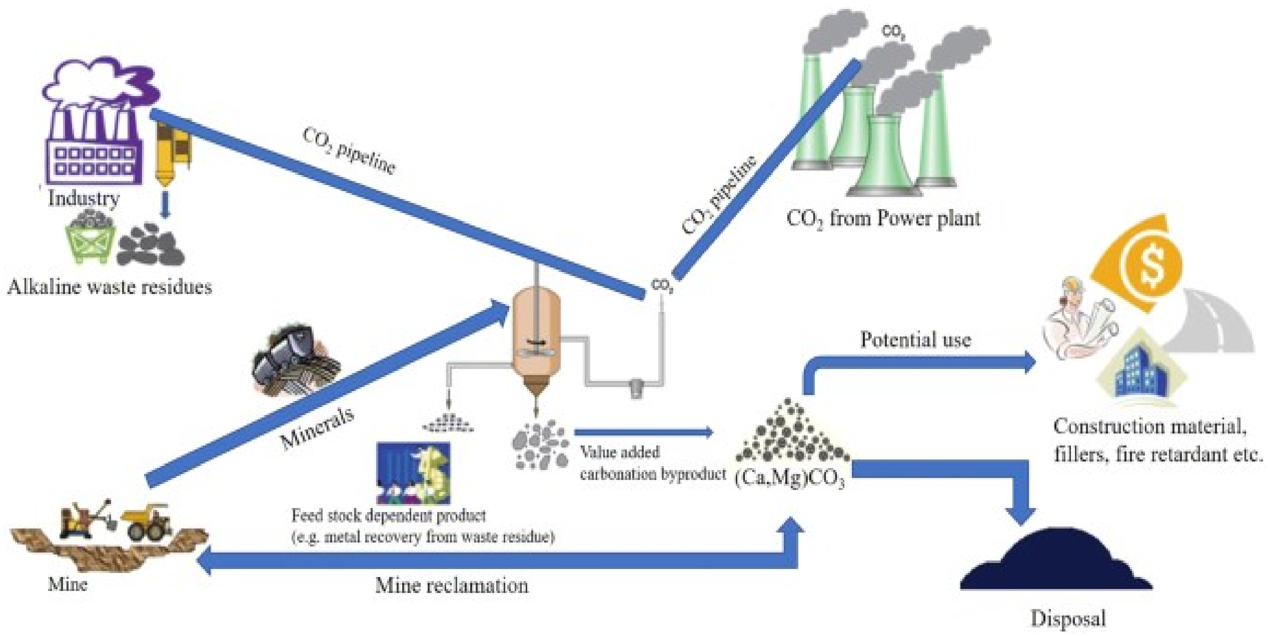

Figure 21 : Mineral carbonation process [60]

Practically, the captured CO_2 can be transported to the mining location through pipeline or by other medium, where the carbonation process occurs resulting with formation of carbonates product i.e., calcium carbonate or magnesium carbonate. The resulted products can be used in various industry for manufacturing building materials, construction materials, ceramic titles, refractory bricks, etc. The product could be either placed in storage sites for future application or could be sold to other disposal purposes. The disposal options are selected according to the mass of the resulting materials. The suitable disposal location could be at mine site as it would not be cost-effective to transport bulk of materials after large-scale mining operation. The cost of mineral carbonation depends upon the transportation of captured CO_2, energy consumption in mining process, waste residual and benefits associated with the final products. The environment issues are key concerns for the mineral carbonation process. It would have large impact on land leading to land clearing, reduces in the air quality, polluting air, water, and soil. The impact made on soil can be controlled by adequate vegetation cover and by covering the soil with protective mulch and conserving the moisture in the soil [61]. The carbon stored through mineral carbonation can be retained even after more than 1000 years with same purity as there is no leakage option associated with this process. This method of storing can be considered as publicly acceptance permanent storage solution of CO_2.

3 Methodology

In this thesis, the feasibility of carbon capture and storage process on marine vessel has been analyzed and investigated from a viewpoint of possible decarbonization in the maritime industry. This project aims to explore how to apply cryogenic carbon capture system (CCS) to capture CO_2 from the exhaust gas emitted from the typical specified vessel through techno-economic assessment and process simulation.

The site visits, several times meeting with companies and some progress presentations were performed while doing this project. The methodology used in this project has been designed in collaboration with the company partner involved in this project.

The work presented in this thesis is based on the following methodology of performing the feasibility study of carbon capture process while implemented in specified vessels.

- Technical analysis.
- Economic analysis.
- Carbon storage option.

3.1 Technical Analysis

The technical analysis is an important method for estimating the feasibility of the new technology or a developed one running at a commercial level. This method is being used more recently in research and development work to identify the critical parameters of technology used. This is done in the early phase of any project, so the methods, assumptions and analysis used are essential factors in determining the feasibility of technology. Technical analysis part is necessary but also challenging one as this analysis should confirm and verify that the product or technology will perform effectively with certain performance level. It determines whether the product or technology can be converted into the working systems. In this thesis, the technical analysis has been performed on implementing the certain CCS system on one specified vessel.

In this thesis, the post- combustion carbon capture technology (Cryogenic carbon-capture process) has been chosen as a carbon capture process system. TECO2030 had designed an exhaust gas cleaning system for ships featuring the cryogenic carbon capture method, developed in cooperation with Chart Industries, Inc. This system has been chosen as CCS system for this thesis as it has the capacity of removing the SOx, NOx, Black Carbon, and Carbon dioxide (CO_2). It is of high quality, optimized design and manufactured with full turnkey solution with a high SOx removal efficiency up to 99.99%. It has an ability to operate easily both in dry and wet condition with low maintenance. This system has so simple design as it could be adjustable with the different types of vessels available in maritime industry [52].

The different types of vessels are found in maritime industry and are categorized into four main types [62]:

- Merchant: Bulkers and tankers, cargo vessels, container vessels, LNG carrier, RO-RO & PCTC vessels.
- Passenger: Cruise, Ferry, Yachts.
- Offshore: Offshore supply vessels, jack up rigs, anchor handling towing supply tugs, drill ships, floating production storage and off landing ships, offshore construction vessels.
- Special Purpose: Fishing vessels, navy vessels, firefighting vessels, submarines, firefighting vessels.

The vessel selected for this thesis is passenger ferry which is known as “MF Lyngen”. This vessel is operated by Torghatten Nord AS and can carry 250 passengers at a time. It uses a LFO as a fuel.

For conducting the technical feasibility of installing the TECO 2030’s CCS system on the “MF Lyngen”, the following conditions were needed to be investigate:

- ➢ The availability of the sufficient space in vessels for installing the CCS system.
- ➢ Utilities requirement (Electricity supply, cooling water supply) of CCS within onboard during start up time and operation time.
- ➢ Vessel’s capacity to sustain the weight of the CCS.
- ➢ Impact made on vessel after installation of CCS.
- ➢ The capacity of CO_2 storage tank of CCS.

In order to evaluate the performance of the CCS on the specified vessels, the proposed carbon capture system has been developed in Aspen HYSYS software. It is the process simulation software for optimization of conceptual design and process operations used by different leading refineries, industries, and engineering companies [63]. In this thesis, one emission scenario was taken into consideration so flue gas acts an input for the Aspen HYSYS model which gives the output as captured liquified CO_2.

3.2 Economic Analysis

Economic feasibility is an essential parameter concerning the possibility of any technology for practical applications. In this thesis, economic analysis has been performed by determining the cost of captured CO_2. The two essential parameters, i.e., capital expenditure (CAPEX) and operational expenditure (OPEX), is needed to determine the cost of captured CO_2. It is calculated by dividing the total annual cost by annually captured CO_2, as shown in equations [64] (i) and (ii),

$$\text{Cost of captured } CO_2 = \frac{Total\ Annual\ Cost}{annually\ captured\ \mathrm{CO2}} \qquad \text{...........(i)}$$

Total annual cost = Annual CAPEX + OPEX .... (ii)

3.2.1 CAPEX

The value of total CAPEX is calculated from the total equipment cost. The CAPEX is comprised of total direct plant costs (TDPC) and total indirect plant costs (TIDC).

The Total Direct Plant Costs comprises of [65]:

- Main process equipment costs
- Installation And commissioning costs
- Instruments and controls costs
- Electrical equipment costs
- Piping costs
- Civil works costs

The TIDC comprises of:

- ➢ service facilities,
- ➢ engineering and supervision
- ➢ yard improvement

The value of total CAPEX is calculated by adding TDPC and TIDC. The total equipment cost is used as the starting point for calculating the CAPEX value. The procedure utilized in this thesis to calculate the CAPEX is the sum of all components based on the "European Best Practice for Assessment of CO_2 capture Technology" [65] as shown below.

Direct Costs (Y)	In this Thesis	Value ($)
Total Equipment Cost	100%	X
Installation cost	50%	X * 0.5
Instrumentation and Control	9%	X * 0.09
Piping	20%	X * 0.2
Electrical equipment and Materials	12%	X *0.12
Civil works	11%	X * 0.11
Total Direct Plant Costs (TDPC)		**Y = X *2.02**
Indirect Costs (Z)		
Yard Improvements	1.5 %	Y * 0.015
Service Facilities	2%	Y * 0.02
Engineering and supervisions	6.5%	Y * 0.065
Buildings	4%	Y * 0.04
Total Indirect Plant Costs (TIDC)	14%	**Z= Y * 0.14**
Total CAPEX		**= Y + Z**

The main process equipment cost is supposed as 'X' as per the scope of the thesis. The TDPC and TIDC values are assumed as 'Y' and 'Z' respectively.

The annual CAPEX is calculated by multiplying the total CAPEX with capital recovery factor (CRF) as given in equation (iii) & (iv),

ACAPEX = CRF * total CAPEX ………… (iii)

$$CRF = \frac{i*(i+1)^n}{(i+1)^n-1} \qquad \text{………… (iv)}$$

where, n = number of years & i = interest rate

3.2.2 OPEX

Operating cost is further divided into fixed and variable operating cost. The fixed operating cost comprises of:

- operating and maintenance cost (O&M),
- overhead cost,
- service agreement costs.
- insurance and other fixed costs.

  It can be calculated as

FOPEX = 0.03 * CAPEX

The variable operating costs includes the cost of electricity consumptions for blower, dryer, compressor, heat exchanger and other utilities used. This cost is dependent of the extra cost of electricity consumption per hour and changes in the fuel price per kg during operation.

3.2.3 Carbon Transportation Cost

The cost of transportation of the captured CO_2 also has been considered for performing the economic analysis. The carbon transportation cost depends upon the medium, volume for storage and distance of transportation from CO_2 captured point to the final storage destination. The pipeline transportation would be beneficial and cost-effective for short distance carbon transportation, but costs increase slowly as the transporting distance increases. The shipping transport seems to be cheaper than pipeline transport while transporting the large volume of

CO_2 for long distance. But, the costs of transportation vary according to the locations, volume of captured CO_2 and sites for long-term storage [66].

3.3 Carbon Storage Feasibility

The CO_2 storage tank comes with the main carbon capture system. The large CO_2 storage tank will occupy much space in vessels. The capacity of installed CO_2 tank would not be able to accumulate much CO_2 with the increase in the voyage length of vessels. So, in that condition, there would be an option of discharging collected CO_2 either at onshore collection stations or at offshore platforms. The CO_2 could be stored for the long-term with the aim of reducing the impact of CO_2 in the atmosphere. The long-term carbon storage options as presented in chapter 2 are as follows [67]:

- Geological Storage
- Oceanic Storage
- Mineral Carbonation

Among three options, the most viable option appears to be geological storage as it is supported from public and government sector, cost effectiveness, practically easily feasible and provide the scope for more research and development.

The flexible infrastructure is needed for transporting captured CO_2 to a specified location for geological storage. Some companies are working in the developing CO_2 transportation network, pipeline infrastructure, building CO_2 collection hub and selecting the suitable storage sites. Norwegian government has already started a 'Longship Project' with the ambition of developing a full-scale carbon capture and storage value chain in Norway. Northern Lights, as part of Longship project, is working for providing the services on carbon transporting and storage. They are developing essential infrastructure to transport CO_2 utilizing ship networks to terminal for intermediate storage, then transported by pipeline to permanent storage reservoir 2,600 meter beneath the seabed. The first phase will be completed on mid 2024 with a storage capacity upto 1.5 million tons of CO_2 per year. This project is going to be first ever cross-border, open-source CO_2 transport and storage infrastructure networks and offering opportunity to the companies across Europe for storing their CO_2 safely and permanently. The longship projects include the shipping of the liquified CO_2 from carbon capture source location to the onshore terminal of Norwegian's west coast and further transports to a permanent offshore storage site in the North Sea through pipeline [68].

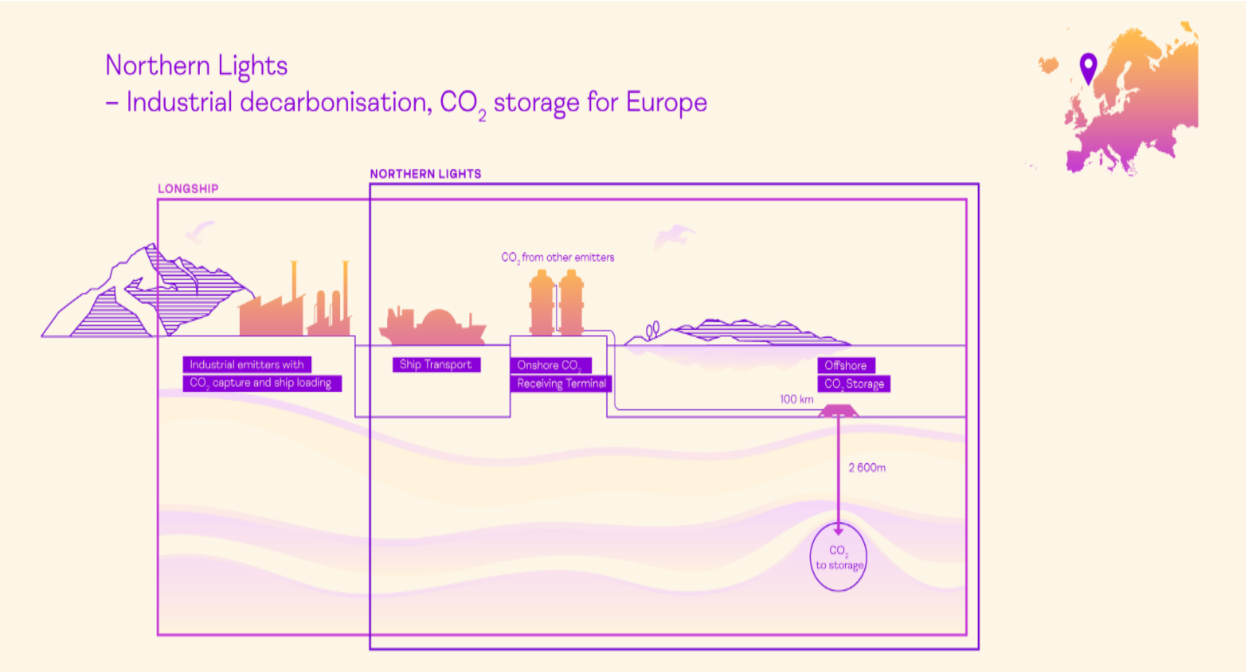

Figure 22: Process of Northern Light's decarbonization project [68]

4 Case Study

In this chapter, the detail study of the vessel, fuel used, engine properties with its emission details has been performed. Also, case study of selected CCS system with its process principle, equipment placement feasibility, economic analysis part, and modelling of the CCS in software has been done.

4.1 Vessel description

The specified vessel used in this thesis for installing the carbon capture system is the open shuttle ferry known as 'MF Lyngen'. The registered name of this ferry was 'MF Jæggevarre'. It was built in 2002 by Fiskerstrand Verft and operated under Norwegian shipping company 'Torghatten Nord'. This ferry can carry 250 passengers and 75 vehicles at a time. It is equipped with a passenger lounge, cafeteria, and crew cabins above the car deck. It is 88.16 m long and 13.20 m wide with the draft length of 5.55m and weight of 2055 tonnage [69]. This vessel connects the two places of Nordland, Norway, Bognes and Skarberget, which is 7.8 km. In one day, it completes total ten trips. This vessel has the gate at both ends so, the vehicles can entry from one gate at boarding station and exit from another gate at destination station.

Figure 23 : MF Lyngen

4.1.1 Fuel Used

Generally, ships operate mainly on three types of fuels. i.e., Heavy fuel oil (HFO), Low sulfur fuel oil (LSFO) and diesel oil. HFO is obtained from the residual part of distillation and cracking process of petroleum and are predominantly used in maritime industry due to higher availability and low costs. MDO, LFO, LSFO are made from petroleum refinery process so also called as 'distillate marine fuel'. The large commercial vessels, i.e., cargo ships, bulk carriers, normally runs on HFO whereas smaller ships, i.e., tugs and fishing vessels, small ferry operates on distillate fuels, such as marine diesel oil or low sulphur diesel fuel [70].

This vessel 'MF Lyngen' operates on the LFO (Light Fuel Oil). Its properties are almost similar to the diesel oil as both have a low viscosity and have high value of distillate. The more description about the LFO used in MF Lyngen is shown in table 2.

Table 2: LFO fuel and its properties

Fuel Type	LFO
Density at 15°C	0.84 kg/l
Net calorific value	42.84 MJ/kg
Carbon content (%m/m)	86.0 %
Hydrogen content (%m/m)	13.5%
Nitrogen content (% m/m)	0.2%
Sulphur content (% m/m)	0.18%

4.1.2 Engine description

This vessel 'MF Lyngen' is powered by two Mitsubishi engines S12R -MPTK of 1040 KW shaft output power. It is a 4 cycle, water-cooled and high-performance turbo-charged engine. This specific engine type can run on diesel oil and LFO. It is powerful and reliable engines because of its high-performance turbocharger, lightweight configuration, easy handling, and maintenance facility. This engine has the power components units which are arranged in such a manner that it occupies less floor space in a generator set arrangement. The internal engine piping system has been made in this engine which eliminates the pipe breaking possibility. It operates with the speed of 1650 rpm. It consumes about 258.7 l/h of fuel when operating under 100% load and full speed. The more detail about the engine is shown in table 3 and drawings of engine is attached in appendix(B).

Table 3: Engine parameter used in MF Lyngen

Engine name	Mitsubishi S12R – MPTK
Charge-air cooling type	Inter cooler
Number of cylinders	12
Cylinder arrangement	V-type
Cylinder head gasket thickness	1.8 mm
Combustion chamber	Open chamber
Bore	170 mm
Stroke	180mm
Displacement	49.30 dm3
Compression ratio	14:1

4.1.3 Propulsion system

The propulsion system used in this vessel is diesel electric pod propulsion aqamaster 1201. It is manufactured by Kongsberg maritime. It is a much efficient propulsion system with an increased operational efficiency and dynamic positioning during the slow speed. This propulsion system has a feature of having smooth and silent operation with reduction in noise and vibration, higher flexibility, redundant configuration and low wear and tear damages. In this system, the power provided from the generator are fed to the frequency-controlled drive through the rectifiers. The drive control system provides the electric power to the motor as per demand. And the shaft of that motor is mounted inside the pod which is responsible for propulsions action, steering and positioning thrust.

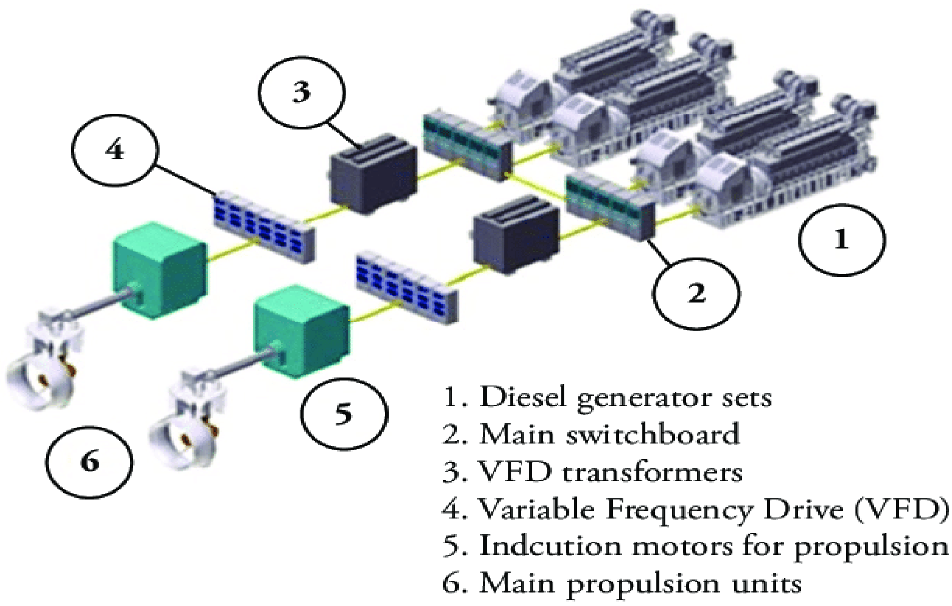

Figure 24: Propulsion system of MF Lyngen [72]

Pod is one type of azimuth propulsion consisting of an integrated electric motor mounted on same shaft enclosed in a watertight fuselage called gondola. The gondola revolves around a vertical axis suitably orienting the propeller for controlling the direction of motion. The driving losses in this process is considered as minimum as the motor coupled directly with the shaft. As the thruster unit can rotate within 360 degrees so that it allows the pleasant mobility of the vessels. Furthermore, the minimal noise and vibrations can be experienced onboard due to external placement of motor and shaft line [71] [72] [73].

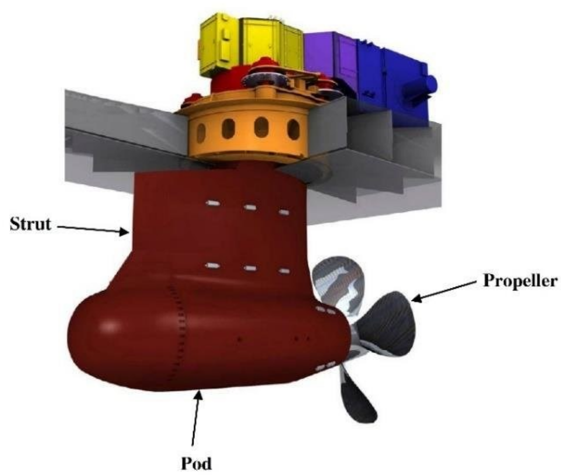

Figure 25:Pod Propulsion System [73]

4.1.4 Emission Profile

The burning of LFO fuel in the Mitsubishi engine S12R -MPTK causes the emission of the flue gas. The flue gas contains various of elements i.e., O_2, CO_2, CO, C_3H_3 and NO_x.

The standard applied methods were used to determine the concentration of various element present in the flue gas. At first, the sample of flue gas is taken in outlet. Then, the flue gas is taken for sample flow at 150°C for filtration process. After filtration, the sample flow is transported through a heated (150°C) teflon tube to a special flue gas cooler. Then, the sample is cooled upto 1°C for removing the moisture present. The concentration of O_2, CO_2, CO, and NO_x present in the filtrated will be processed further for analysis. Whereas for determining the C_xHy, the flue gas is continuously sampled at outlet. The flue gas is processed for filtration at 150°C. Then after filtration, the sample flow is transported through a heated (150 °C) teflon tube to a flame ionization detector where it is monitored and analyzed for determination of C_xHy concentration.

The performance of this vessel engine and its emission parameter had been checked by IMO. Every item of the vessel engine was checked during the inspection time which includes injection nozzle, injection nozzle tips, injection pumps, piston, connecting rods, crank shaft, cylinder heads, cylinder liners, turbo charger, charge air cooler. The emissions and concentrations of flue gas are checked under standard condition (i.e., 0.0% moisture, 0 °C temperature, 1013 mbar pressure, 22.40 m^3/kmol molar volume) resulted with the NO_x specific content of 7.7 g/KWh which showed the NOx emission is within the allowed limit.

The emission of CO_2 and other elements changes with the percentage of load provided operating speed of engine and operating time of engine. The emission test had been performed from the 100% load to 25% load while running the engine at full speed operating each load condition for 30 minutes. The test result shows the CO_2 concentration is 7.0 % and CO_2 mass flow is 529.2 Kg/h while operating at full load condition. The other gaseous emission details are presented in table and overall emission data is attached in appendix(A) with this report.

Table 4: Emission detail of MF Lyngen

Data	1	2	3	4
Load Condition	100 %	75%	50%	25%
Fuel flow(m^3/h)	0.202	0.149	0.103	0.060
Exhaust temperature(°C)	437	402	359	282
Fuel oil temperature(°C)	36.3	37.8	38.5	39.4
CO_2 concentration (%)	7.0	6.3	5.5	4.2
O_2 concentration (%)	11.4	12.3	13.4	15.3
CO concentration(ppm)	67.3	47.6	47.5	74.9
HC concentration(ppmC)	61	50	49	52
CO_2 concentration(kg/h)	529.2	39.06	269.4	156.9
CO concentration(kg/h)	0.3261	0.1878	0.1472	0.1803
O_2 concentration(kg/h)	632.5	555.2	473.1	419.9
HC concentration(kg/h)	0.1678	0.1130	0.0860	0.0714

4.2 TECO 2030 and Chart Industries Carbon capture technology

The increase in CO_2 emission is continuously causing global warming whose effect can be directly observed in the climate and environment. So, TECO 2030 along with Chart industries, came up with the aim of reducing the CO_2 from the shipping industry supporting the goal of IMO to reduce the emission from the shipping industry by 70% by 2050. They have come with solution of introducing the carbon capture technologies for capturing the CO_2 from the exhaust gas emitted from the ships. The presently available carbon capture technologies are more focused on manufacturing industries mainly in a stable environment with a fixed position with much available space for installation. This carbon capture technology works under post- fuel combustion strategy utilizing the cryogenic carbon capture method resulting the captured carbon in form of liquid. The cryogenic carbon capture process separates CO_2 from the flue gases mainly utilizing low temperature and desublimation properties. This CCS process cools the flue gas upto desublimation point of CO_2(-100 °C to -135 °C), followed by the separation and pressurization of the solid. Then, the warming of all streams will separate a CO_2-depleted stream and pure liquid CO_2 stream at ambient temperature. This process has an ability of capturing all gas impurities which are less volatile than CO_2. It utilizes the minimum energy for changing the CO_2 phase from a mixed vapor phase to a pressurized fluid and removes the refrigeration energy required. This technology offers 30%-60% lower energy and cost as compared with other technology.

TECO 2030 cryogenic carbon capture process system has a modular and flexible design which can easily retrofitted in the existing vessel without requiring much modifications on the vessels. This system has an advantage of being highly efficient (90-95% efficiency), cost effective and simple modular design. It is available in different sizes and scales which can be applicable from cargo bulk carrier to small fishing ferry. The variation in the equipment specification (sizes, weight, and power consumption) depends upon the ship sizes, its carbon capture requirement, area for installation, specific situation, and other factors. This technology contains several equipment units i.e., pre-cooling unit, dryer, blower, refrigerant compressor, cold box, CO_2 separation unit, distillation column and CO_2 storage where each of the component have their own specification and applications.

4.2.1 Process flow Description

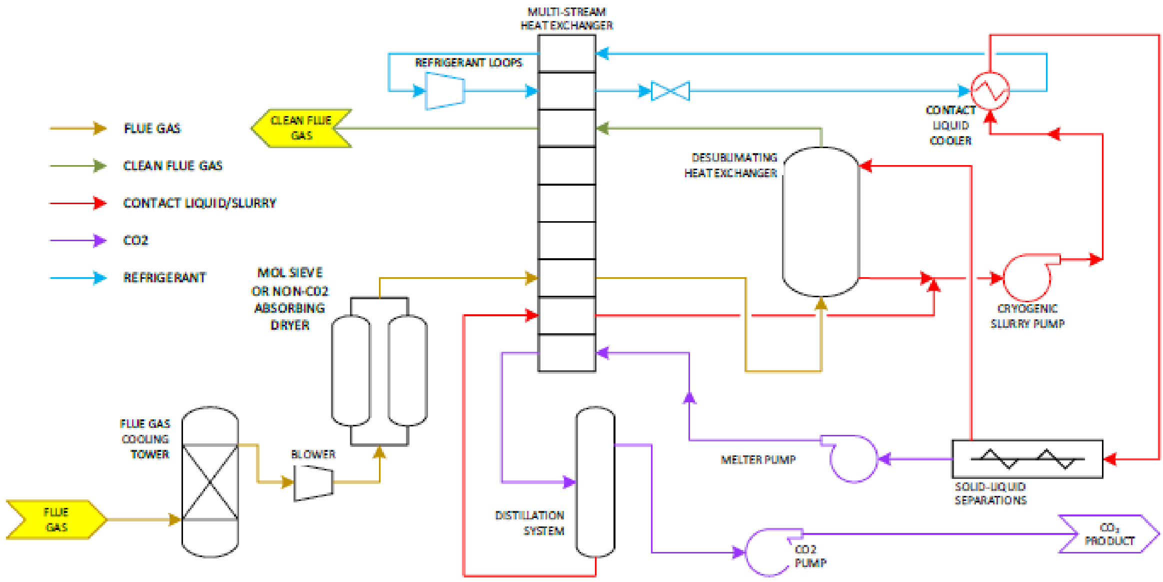

Figure 26: Process flow diagram of TECO's and Chart industries carbon capture technology

The exhaust gas from the vessel enters at the cooling tower for cooling purposes. The blower blows the cooled flue gas up to the dryer where the flue gas is dried with minimal pressure drop for removing the gas impurities present. Then, the flue gas enters from the bottom of the desublimating heat exchanger. This desublimating heat exchanger is a counter-flow spray tower about the temperature of -100°C, where the super cooled contact liquid droplets flow from the top against the flow of flue gas from the bottom. As a result, the cold droplets get warm while flowing down as it cools the flue gas and accumulated as a desublimating CO_2. Whereas the flue gas moving towards top of DHX will gets super cooled at the top of tower and helps to determine the amount of remaining CO_2 in the flue gas. Then, the flue gas exits the tower and gets warm by attaining the same initial temperature outside.

The captured CO_2 in the form of slurry starts getting warm at bottom of the heat exchanger. Then, the slurry is pumped through the slurry pump to the contact liquid cooler. In this stage, it is cooled by closed loop refrigeration systems combine with multi-stream heat exchanger. After cooling, it moves towards a solid-liquid barrier filter separation. In this separator, the liquid stream is recirculated towards the desublimating heat exchanger whereas the solid form of CO_2 is pumped further to melter. The melter melts the solid CO_2 and heat it back to ambient temperature. Then, it is further passes through the distillation column for the purification purposes and almost 99% purified CO_2 in a liquid phase can be obtained as a final product.

4.3 Installation of CCS in vessel

4.3.1 Selecting the location for the capture equipment

The most important of placing the equipment is selection of location within the vessel. The various parameters are needed to be analyzed while finalizing the area for onboard installation i.e., equipment sizes (length, breadth, height, weight), power sources and water supply accessible for components and sufficient space for placement of the CO_2 storage tank.

After performing the closely inspection on the 'MF Lyngen' vessel, the two locations seem to be the most suitable place for installation. The one location was outside on the vessel near about the exhaust pipeline. In this preferred location, the placement of the equipment could be done on two outside balconies/platforms floor as shown as in figure 27. But, the lowered floor was located just outside of the passenger lounge and cafeteria where the passengers could stand and enjoy with the scenery whereas the upper floor was for the crew members and navigator needs the clear view for pointing and driving the vessel in the right direction. Also, there was only 2.8 m of clearance height available between the floor to the navigator mirror. Most of the components of this capture process was needed to be placed vertically with some spaces between them. The spacing between components is considered important for inspection, maintenance and repairment purposes. So, this onboard location has not been selected for the installation purpose because of the unavailability of enough spaces for each component, not enough required height for component, creating the problem for passenger for movement in outdoor spaces, and ruins the beauty of this vessel.

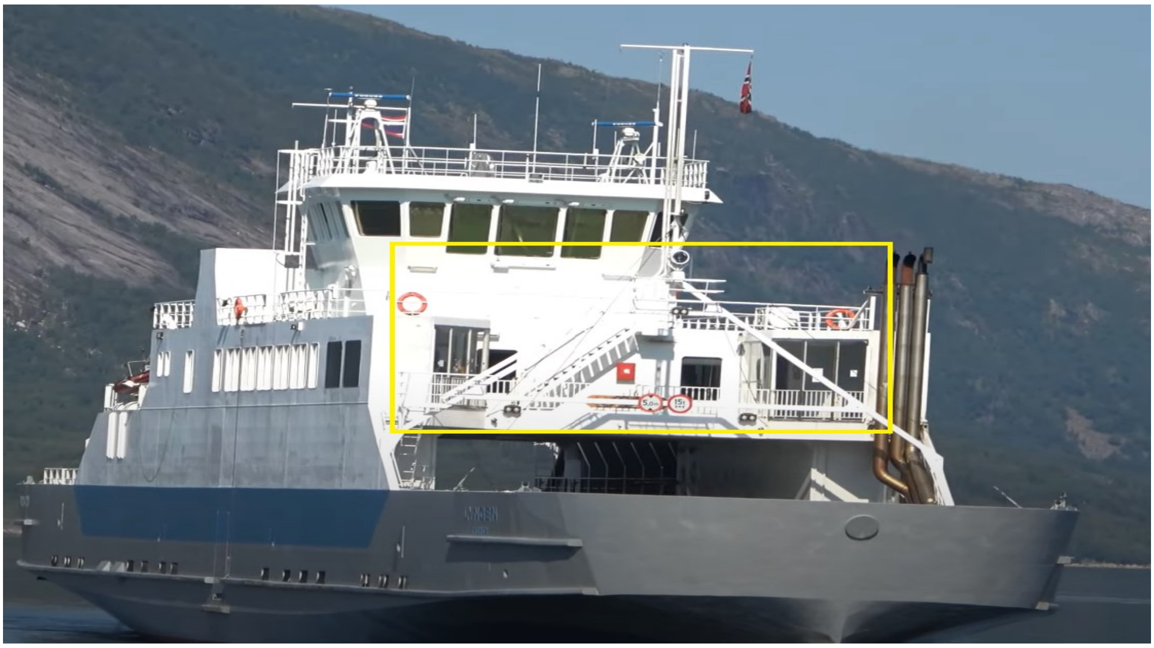

Figure 27: Possible location/area outside the MF Lyngen to install the carbon capture equipment

Another preferably location would be the place below the main deck of the vessels as shown in figure 28. There are two engine rooms and one thruster room located under the main deck. All three rooms were interconnected to each other. The first engine room consists of diesel generator, main board, transformer, and frequency converter whereas second engine room had two sets of diesel generator, main board, transformer, and frequency converter. The thruster room consist of the AC short circuit motor for propulsion and counter rotating compass thruster. From the inspection, it has been found that the first engine has enough spaces of area (3* 6 * 3.1) m for installing the component on the either side of the main engine with the clearance height of 3.1m. The components could be arranged accordingly with the sizes and weight in the preferred area. The access towards the main engine is provided through stairs from the main deck.

Figure 28: Area showing the main deck of the MF Lyngen.

Figure 29: Connection of all the exhaust pipe of MF Lyngen at one node and routed towards capture system.

This vessel consists of three exhaust pipes in the front and one exhaust pipe at the back. All the exhaust pipes could be connected at one point and routed towards the carbon capture system. Some piping works are needed to be performed at the outside of the vessel as shown in figure 29. The MF Lyngen is a small shuttle ferry which operate in short distance. So, the smallest unit of carbon capture equipment (i.e., 1 ton capacity) has been selected for this purpose.

The list of each component of TECO carbon capture process which is required to be mounted on the MF Lyngen is shown in table no. 5.

Table 5 : Table showing component unit of TECO carbon capture process

No.	Component Unit
1.	Blower
2.	Dryer
3.	De-sublimating HX
4.	Multistage heat exchanger
5.	Refrigerant Compressor
6.	Flash drums
7.	Screw press
8.	Melter
9.	Pumps
10.	Distillation Column
11.	CO_2 storage tank

The suggested area and location for the placement of components in the engine room is shown in figure 30. and 31. The overall fourteen components are needed to build carbon capture system including two storage tank and three pumps. The large yellow rectangular in the picture indicates the main engine room and circle and rectangular mark is made according to the physical appearance of each component.

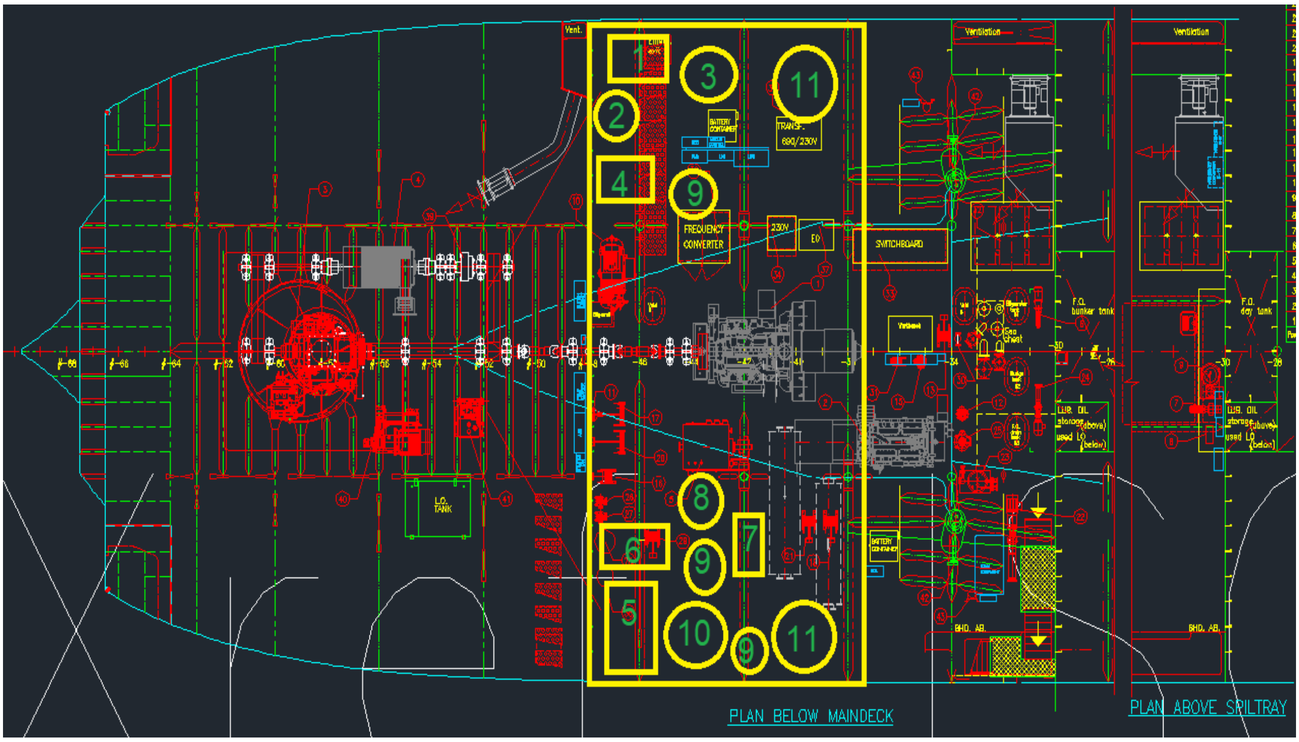

Figure 30: Top view of the MF Lyngen showing the engine room where the placement of equipment is suggested as shown (1) blower,(2) Dryer,(3) De-sublimating HX,(4) Multistage heat exchanger, (5) Refrigerant compressor, (6) flash drums, (7)Screw press, (8) Melter, (9) Pumps, (10) Distillation column, (11) CO_2 storage tanks

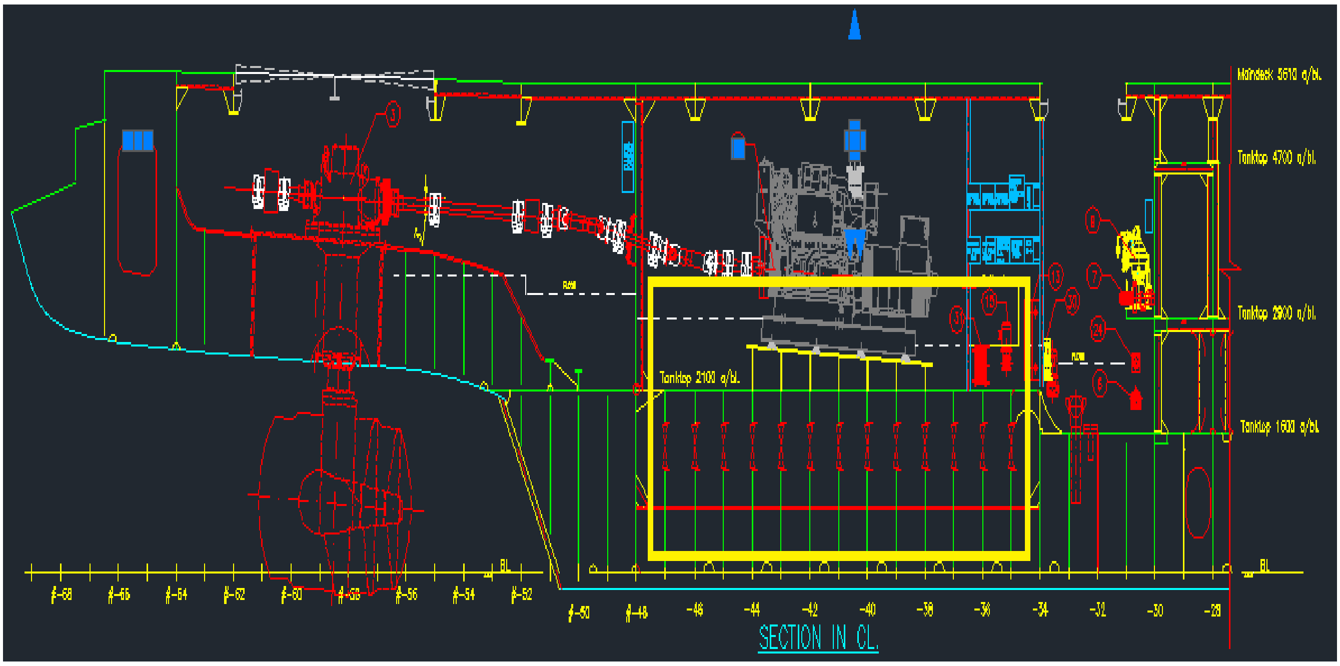

Figure 31: Sectional view of MF Lyngen showing the recommended area for placing the capture equipment.

4.3.2 Utilies supply

The electrical power supply of 230V, 50Hz is the essential requirement for operating almost all the components connected. The major consumer of electrical power is blower, two heat exchanger, compressor, distillation column. It has been calculated that electric power requirement by the system will be around 110 KW. In each engine room, the main supply of 230 V, 50Hz is available, provided through the three 690/230 V transformer. The two main boards are present in engine room through which cable connections could be made whereas for operating the blower and pumps the connections could be taken from the motor control center (230 V,160 A). If more supply needed, the connection could be added from another engine room. The seawater can be utilized for cooling the exhaust gases.

4.3.3 CO_2 Storage tank

The placement of the CO_2 storage tank can be determined based on the vessel operation profile and space availability within the engine room. Generally, this vessel operates for short route of 7.8 km for almost half an hour, so the small unit of storage tank of 1 ton would be enough for this purpose. So, two tanks each of half ton could be placed at both sides of the main engine. Assuming the optimum condition of vessel running with 100% load at full speed, with the carbon capture efficiency of 90%, then 476.2 kg of liquified carbon will be captured at -15°C temperature and 20 bar pressure. So, the one tank will be filled up on one-way whereas another tank in return way. Also, the large CO_2 storage tank capacity of almost 1000 tons is needed to be built up onshore nearby station for releasing the CO_2 from the onboard storage tank. So, after each trip the onboard CO_2 storage tank could transfer the liquified CO_2 to the large tank through pipeline and will be ready to make another trip.

4.3.4 Stability

The stability of the vessel is dependent on the weight added by the capture equipment in the vessel. The newly added weight would be almost 6-7 ton and uniformly distribution of the component within the engine room is an important task. The CO_2 storage tank are needed to be placed at either side of main engine for maintaining the weight balance within the vessel. Normally, in small ferry when adding the more weight, the vessel's center of gravity tends to increase which would have a bad effect in the buoyancy of the vessel. So, the equipment should be placed below the vessels' center of gravity so the metacentric height (GM) will be same as previous unloaded condition.

4.3.5 Power Required

When the capture system is added on MF Lyngen, the power requirement for propulsion would increase slightly. It is also assumed that maximum power required for propulsion is about 80% of rated power. So, it can fulfill the remaining power needed for propulsion. Also, the fuel consumption would increase by 4-5 % than before loading the carbon capture equipment.

4.4 Economic Evaluation

The economic evaluation is performed to determine the total capital expenditure, operating expenditure, total cost of captured carbon and cost of carbon transportation. The process of calculating cost per ton has already shown in chapter 3. The total equipment costs of TECO's carbon capture process for installing in MF Lyngen amounts to around $ 2,500,000. This is an estimated cost and taken reference from the similar available carbon capture system [74]. The total CAPEX cost is determined through the total equipment cost. Also, the same value of total CAPEX is utilized for calculating the operational expenditure (OPEX).

After determining the value of CAPEX, the annual capital expenditure can be estimated by multiplying the value of CAPEX with Capital Recovery Factor (CRF). For calculating the value of CRF, it is assumed that the lifetime value of capture system is 25 years, and the interest rate value is assumed to be 8%.

This vessel, MF Lyngen, normally completes 10 trips in a day. The number of vessel operation is counted as 330 days. Here, only 11 months has been considered as the normal operation days whereas other days is assumed as off days for maintenance purpose, etc. Assuming the capture efficiency of 90% with 100% load and full speed scenario, then the 952 kg of liquified carbon will be captured for completing one round trip.

Monthly carbon captured = 952 kg * 10 trips * 30 days = 285600 kg/ month = 285.6 ton/month
Yearly carbon captured = 285.6 ton/month * 11 months = 3141.6 tons/year

Table 6 : Table shows the financial description for calculating CAPEX

Direct Costs (Y)	Value ($)
Total Equipment Cost	**2,500,000**
Installation cost	1,250,000
Instrumentation and Control	225,000
Piping	500,000
Electrical equipment and Materials	300,000
Civil works	275,000
Total Direct Plant Costs (TDPC)	**5,050,000**
Indirect Costs (Z)	
Yard Improvements	75,750
Service Facilities	101,000
Engineering and supervisions	328,250
Buildings	202,000
Total Indirect Plant Costs (TIDC)	**707,000**
Total CAPEX	**= $ 5,757,000**

Annualized CAPEX = 0.095* 5,757,000 = **$ 546,915**.

The FOPEX is calculated from the CAPEX.

FOPEX = 0.03 * 5,757,000

= $ 172,710.

The VOPEX value can be considered as $500 for the extra consumption of fuel and variable fuel prices.

The annual OPEX = $ 172,710 + $ 500 = **$ 172,670**

The total annual cost of capturing carbon = $ 546,915+ $ 172,670

= **$ 720,125**

So, the cost of captured carbon would be

$$= \frac{720{,}125\ \$/year}{3141.6\ \text{tons/year}} = \mathbf{229\ \$\ /\ ton\ CO_2.}$$

It has been investigated that the Norwegian company Northern lights takes the responsibility for the transportation and long-term storage of the liquified carbon. This company routes the ship to carry the liquified CO_2 from the various part of the country and transported it to the Øygarden (western coast) where the site has been made for permanent store of CO_2.The costs of transporting the captured liquified CO_2 from the Nordland to Øygarden (western coast) will be at the rate of around $ 18/ton [75]. Annually four trips are needed to collect the CO_2 from the large storage tank as it gets filled up within 3 months. The ship will transport the CO_2 to destination where it is stored 3000 meters below the seabed in the North Sea.

4.5 Modelling of the TECO's carbon capture process

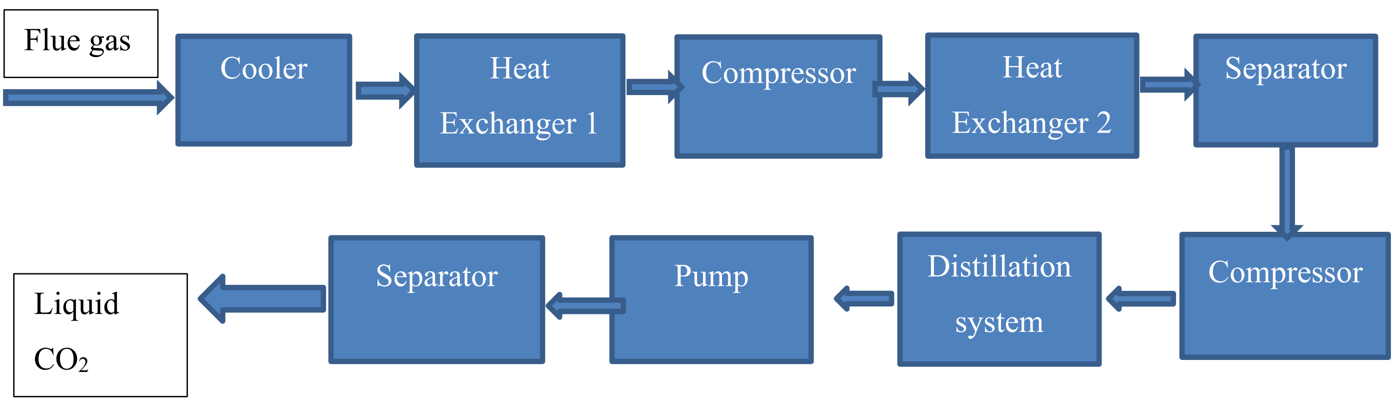

Figure 32: Simplified Process flow diagram modelled in Aspen HYSYS

The cryogenic carbon capture process designed by TECO 2030 as utilized in this thesis was modelled in Aspen HYSYS. The real capture system is quite complicated, so the simplified flow process has been considered for developing the model as shown in figure 32. Some of the parameters initialized for this modelling purposes were exact value from the real system whereas few parameters were provided as a predicted value. Some modifications has been done in this model according to the functional suitability of the software.

The flue gas comprised of methane, nitrogen, carbon dioxide and water has been initialized as an input for this model. The concentration level of CO_2 is set as 90% in the vapor phase in the flue gas. The modelling has been done to investigate an accuracy and performance of a real system. The result acquired from the simulation shows the final carbon output product is in liquid phase with the temperature of -28°C and pressure of 17.60 bar. The simulation result shows the good agreement with real capture process system. The TECO 2030's carbon capture process also produces output CO_2 in the liquid phase between 12 bar to 25 bar pressure and -35°C to -15°C temperature. The modeling flow diagram as performed in Aspen HYSYS, properties, and composition of output product is attached to the appendix(D) of this report.

Stream Name	Liquid carbon	Vapour Phase	Aqueous Phase
Vapour / Phase Fraction	0,0000	0,0000	1,0000
Temperature [C]	-28,00	-28,00	-28,00
Pressure [bar]	17,60	17,60	17,60
Molar Flow [kgmole/h]	0,1019	0,0000	0,1019
Mass Flow [kg/h]	2,034	0,0000	2,034
Std Ideal Liq Vol Flow [m3/h]	2,108e-003	0,0000	2,108e-003
Molar Enthalpy [kcal/kgmole]	-7,121e+004	-9,449e+004	-7,121e+004
Molar Entropy [kJ/kgmole-C]	-910,3	179,9	-910,3
Heat Flow [kcal/h]	-7255	0,0000	-7255
Liq Vol Flow @Std Cond [m3/h]	1,951e-003	0,0000	1,951e-003
Fluid Package	Basis-1		
Utility Type			

Figure 33 : Result obtained from Aspen HYSYS

5 Discussion

The study had been conducted on the various onboard carbon capture system to installed in vessels. The different carbon capture technologies are present in recent scenario with the aim of mitigating the carbon emission from the vessels. Different maritime industries are working to achieve goals of International Maritime Organization (IMO) of reducing the total annual emission from the maritime industry to 70% by 2050. The several post-combustion carbon capture technologies have shown to be matured and promising one. The absorption and adsorption technology are considered energy effective but also has the limitations like solvent degradation and corrosion. The cryogenic carbon capture technology is considered as the most energy efficient and technologically matured one. The energy consumption is less, and carbon captured efficiency is much higher as compared with other available process. The different cryogenic process is available characterized according to the fuel usage, energy consumption, cold energy sources and CO_2 recovery state. The CO_2 can exist in four different states whereas the liquid state is most desirable one for the transportation through the shipping. The captured carbon can be stored for a long period through different options to reduce the impact of CO_2 into the atmosphere and later can be utilized for different purposes in the industry. Among options available, the geological storage was found to be most mature and feasible one for long-term storage.

The detail study had been done on investigating the feasibility of installing cryogenic carbon capture technology designed by TECO 2030 on the shuttle ferry vessel 'MF Lyngen'. This vessel uses a LFO as a fuel and normally makes ten trips in a day travelling 7.8 km connecting the two places Bognes and Skarberget. It is operated by the two Mitsubishi engines of 1040 KW shaft power and utilized the diesel electric pod propulsion as the propulsion system. It shows the CO_2 emission of 529.2 kg/h when operating under 100% load condition and full speed. This cryogenic carbon capture technologies utilizes the low temperature and desublimation properties and delivered the final product of CO_2 in liquid state at -15^{o}C temperature and 20 bar pressure. This CCS system is available in different sizes and scales depending upon the vessels type, installation area, distance covered, specific situation, etc. The smallest scale (i.e.,1 ton per day) of this system has been selected in this thesis.

The main goal of performing the study was to investigate the feasibility of installing the TECO's carbon capture technology on MF Lyngen. The feasibility study had been divided into three parts, i.e., technical analysis, economic analysis, and storage feasibility. The technical analysis shows that the equipment of the CCS could be install below the main deck in the main engine room at either side of main engine in the area of (3*6*3.1) m. All the exhaust pipes of this vessels needed to be connected at one node and routed inside the vessel. The equipment needed to be placed below the vessel's center of gravity to maintain buoyancy within the vessel. The electrical supply of 230V,50 Hz is available through the two main boards present in two engine room which are required for operating the capture equipment. The two-storage tank of 500 kg is selected which means each tank would be filled up while travelling in both ways. The large tank of almost capacity of 1000 ton is needed to build up at onshore near station for unloading the CO_2 from the onboard tank. It was assumed that the propulsion power and fuel consumption would increase slightly with the placement of capture equipment. The modelling done in HYSYS also validate the performance and working of the real carbon capture system.

The result from the economic analysis showed that total capital expenditure of $ 5,757,000 and total operating expenditure of $ 172,670. The cost of carbon capture would be around $ 229 / tonnage. The cost of captured carbon could reduce further if the vessel operating company runs MF Lyngen for long period of time could receive a tax subsidy for the avoided carbon dioxide from the government. The options of selling of CO_2 might also help to reduce the captured CO_2 cost. It is however difficult for providing the exact estimation of the cost analysis as the various factor is still dependent on installing the carbon capture equipment which had not been analyzed in this thesis. Furthermore, the responsibility of transportation and storage of carbon would be taken by Norwegian company 'Northern Lights' which will transport annually the liquified CO_2 at the rate of around $18 / ton through the ships.

6 Conclusion

This study has been performed in this thesis to implement the cryogenic carbon capture system in the specified vessel to reduce the CO_2 emission from the maritime industry by performing the technical and economic analysis. The answer for the four question below would better conclude the thesis work.

- Is it technically feasible to install the CCS system onboard??

➢ The design, size and weight of the capture equipment must be predefined so the location for installation could be analyzed accordingly. The power supply and cooling requirement of the capture equipment should be arranged within the allocated location for smooth operation. In this thesis, a shuttle ferry was able to sustain the CCS system which shows it is technically possible to install the onboard CCS system. But the same system could not be applied to big vessels so vary according with the vessel size.

- What effect could be seen after installing the CCS system onboard??

➢ The arrangement of the capture equipment is an important factor to minimize the effect on vessel. The placement of capture equipment must be done in such a way (below the center of gravity of vessel) so that it doesn't affect the movement of vessel. The installation of CCS system will slightly increase the propulsion power and fuel consumption of vessel.

- How much carbon could be captured annually by implementing CCS system on onboard??

➢ The CCS system implemented in this thesis works with the 90% efficiency. It could capture 3141.6 tons annually. The equipment size could be larger for the cargo vessels, bulk carriers, etc. and amount of captured product would vary with the voyage distance, load, and speed.

- Is it economically feasible to install the CCS system onboard??

From this thesis, the calculated CAPEX and OPEX is \$5,757,000 and \$ 172,670, respectively. The cost of carbon captured is calculated as \$ 229 / ton which is not in the expensive range as compared with the cost from other existing carbon captured technology (i.e., chemical absorption, adsorption, membrane, etc.). It shows CCS system onboard is economically feasible, but the cost would vary with the vessels type and its operating characteristics.

The installation of carbon capture and storage system onboard vessel is technically and economically feasible which could drastically minimize the CO_2 emission from the maritime industry. It is an optimistic solution to be applied in the shipping industry for the reduction of carbon emission in the atmosphere and protect the environment from the effect of global warming.

6.1 Future works and recommendations

From this thesis, it is concluded that it is feasible to implement CCS system in vessel but there remains some works to be analyzed and explored thoroughly in future. They are described below:

- In this thesis, the technical feasibility only deals with the placement of equipment, utilities supply, and requirement of propulsion power. But it does not address the effects and performance of the CCS system due to continuous movement of vessel during high tides and worst climatic condition. It should be found about the capture rate when the vessel is rolling, pitching, heaving in the middle of the ocean. Also, the damage stability has not been investigated in this thesis. This task can be carried out as future works.

- In economic analysis, the overall calculation was performed based on the main process equipment cost. But, there are many factors to be considered during cost estimation. Practically, in-depth analysis of the building process, risk analysis, uncertainty in the price level, logistics, contract or agreement between ship owner and CCS seller, etc. are essential parameter needed for the cost estimation. So, in future more in-depth financial analysis could be done.

- The investigation on small shuttle ferry using filtrate oil has been done in this thesis. As the future work, the feasibility study could be performed on the large vessel like cargo vessel, bulk carrier utilizing the HFO fuel as these vessels are the major emitters of the maritime industry.

- Practically, the challenges could be seen while offloading the liquified CO_2 from the onboard tank to offshore large tank and further to the transport ships so the potential solutions for offloading could be analyzed as future works.

- It would be technically challenge but the possibility could be found out in the future to implement same tank for storing the fuel and CO_2 applying some separation techniques. If it happens, then the volume within the vessel will reduce and ultimately reduces the cost of captured carbon.

- Also, it is necessary to keep the storage tank under certain pressure and temperature for maintaining the carbon in the liquid phase so the continuous monitoring should be given to the storage tank (onboard and offshore).

- The modification towards the technology and performance could be done in CCS system in the future accordingly with the requirement to make maritime industry more sustainable.

7 Bibliography

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APPENDIX

A. Emission report of MF Lyngen

1. Ambient and Gaseous emission data

MITSUBISHI
DIESEL ENGINES
TURBOCHARGERS

Emission test report no.EZ/09/2656-29 **Ambient and gaseous emission data**

Mode		1	2	3	4	5
Power/Torque	%	100/100	75/75	50/50	25/25	10/10
Speed	%	100	100	100	100	100
Time at beginning of mode		10:35	11:11	11:44	12:15	12:49
Ambient data						
Atmospheric pressure	kPa	102.1	102.0	102.0	102.0	102.0
Intake air temperature	°C	31	31	30	33	29
Intake air humidity	g/kg	8.65	8.52	8.81	8.58	9.40
Relative humidity (RH) of intake air*	%	31	30	31	33	38
Air temperature at RH sensor*	°C	31	32	32	30	29
Dry bulb temperature of intake air*	°C					
Wet bulb temperature of intake air*	°C					
Test condition parameter	f_a	1.02	1.02	1.01	1.03	1.01
Gaseous Emissions Data:						
NOx concentration dry	ppm	764.7	704.6	632.7	451.1	276.3
CO concentration	ppm	67.3	47.6	47.5	74.9	109.0
CO2 concentration	%	7.0	6.3	5.5	4.2	2.8
O2 concentration dry	%	11.4	12.3	13.4	15.3	17.1
HC concentration	ppmC	61	50	49	52	61
NOx humidity correction factor, k_{hd}		0.992	0.990	0.991	0.996	0.995
Dry/wet correction factor, k_{wr}		0.935	0.941	0.947	0.958	0.968
NOx mass flow	kg/h	6.086	4.567	3.220	1.784	0.944
CO mass flow	kg/h	0.3261	0.1878	0.1472	0.1803	0.2268
CO2 mass flow	kg/h	529.2	390.6	269.4	156.9	91.6
O2 mass flow	kg/h	632.5	555.2	473.1	419.9	406.6
HC mass flow	kg/h	0.1678	0.1130	0.0860	0.0714	0.0721
NOx specific	g/kWh	7.29	7.29	7.71	8.58	11.33

2. Engine test data

MITSUBISHI
DIESEL ENGINES
TURBOCHARGERS

Emission test report no.EZ/09/2656-29 **Engine test data**

Mode		1	2	3	4	5
Power (kW)/Torque(Nm)	%	100%	75%	50%	25%	10%
Speed	%	1800	1800	1800	1800	1800
Time at beginning of mode		10:35	11:11	11:44	12:15	12:49
Engine Data						
Speed	rpm	1800	1800	1800	1800	1800
Auxiliary power	kW					
Dynamometer setting	kW	828	621	414	207	83
Power	kW	828	621	414	207	83
Mean effective pressure	kPa	1630	1222.5	815	407.5	163
Fuel rack left pump	mm	Specified by position of sealed fuel rack stopper plate at 100% load				
Fuel rack right pump	mm					
Uncorrected spec. fuel consumption g/kWh		203.4	200.3	207.2	241.4	352.9
Fuel flow	-kg/h or m³ /h*	0.202	0.149	0.103	0.060	0.035
Air flow	kg/h					
Exhaust flow (q_{mew})	kg/h	5133	4171	3266	2526	2173
Exhaust temperature	°C	437	402	359	282	206
Exhaust back pressure	kPa	4.41	2.7	1.5	0.7	0.4
Charge air coolant temperature in °C		45	40	35	35	35
Charge air coolant temperature out °C		52	44	36	34	32
Charge air temperature	°C	62	52	42	36	34
Charge air reference temperature °C						
Charge air pressure	kPa	167	113	67	31	18
Fuel oil temperature	°C	36.3	37.8	38.5	39.4	39.8

3. Parent engine test data

MITSUBISHI
DIESEL ENGINES
TURBOCHARGERS

Parent engine test data						
FAMILY 51EF						
Parent engine						
Model/type	S12A2-MPTAW					
Nominated rated power	kW		828			
Nominated rated speed	rpm		1800			
Parent engine test fuel oil						
Reference fuel designation						
ISO 8217:2005 grade (DM or RM)						
Carbon	% m/m		86.6			
Hydrogen	% m/m		13.2			
	% m/m					
Nitrogen	% m/m		0.1			
Oxygen	% m/m		0.1			
Water	% V/V		<			
Measured data (parent engine)						
Power/torque	%	100	75	50	25	10
Speed	%	100	100	100	100	100
Mode point		1	2	3	4	5
Engine performance						
Power	kW	828	621	414	207	83
Speed	rpm	1800	1800	1800	1800	1800
Fuel flow	~~kg/h~~ or m^3/h*	0.202	0.149	0.103	0.060	0.035
Intake air flow (wet/dry)	kg/h					
Exhaust gas flow	kg/h					
Intake air temperature	°C	30	31	32	31	31
Charge air temperature	°C	62	52	42	36	34
Charge air reference temperature	°C					
Charge air pressure	kPa	167	113	67	31	18
Additional parameter(s) used for emission corrections (specify)						

MITSUBISHI
DIESEL ENGINES
TURBOCHARGERS

Ambient conditions						
Atmospheric pressure	kPa	102.1	102.0	102.0	102.0	102.0
Relative humidity (RH) of intake air	%	30.8	30	31	32.5	37.7
Air temperature at RH sensor*	°C	31.3	31.5	31.5	30.2	29.2
Dry bulb temperature of intake air*	°C					
Wet bulb temperature of intake air*	°C					
Absolute humidity of intake air*	g/kg	8.65	8.52	8.81	8.58	9.40
Emission concentrations						
NOx dry	ppm	765	705	633	451	276
CO_2	%	7.0	6.3	5.5	4.2	2.8
O_2 dry	%	11.4	12.3	13.4	15.3	17.1
CO	ppm	67	48	48	75	109
HC	ppmC	61	50	49	52	61
Calculated data (parent engine)						
Intake air humidity	g/kg	8.65	8.52	8.81	8.58	9.40
Charge air humidity	g/kg	52	42	32	29	29
Test condition parameter, f_a		1.02	1.02	1.01	1.03	1.01
Dry/wet correction factor, k_{wr}		0.935	0.941	0.947	0.958	0.968
NOx humidity correction factor, k_{hd}		0.002	0.000	0.001	0.006	0.006
Exhaust gas flow rate	kg/h	5133	4171	3266	2526	2173
NOx emission flow rate	kg/h	6.086	4.567	3.220	1.784	0.944
Additional emission correction factor(s) (specify)	g/kWh	0.05	0.25	0.30	0.30	0.10
NOx emission	g/kWh	7.3	7.3	7.7	8.6	11.3
Test cycle		**D2**				
Emission value	g/kWh	**7.7**				

4. Emission test Result

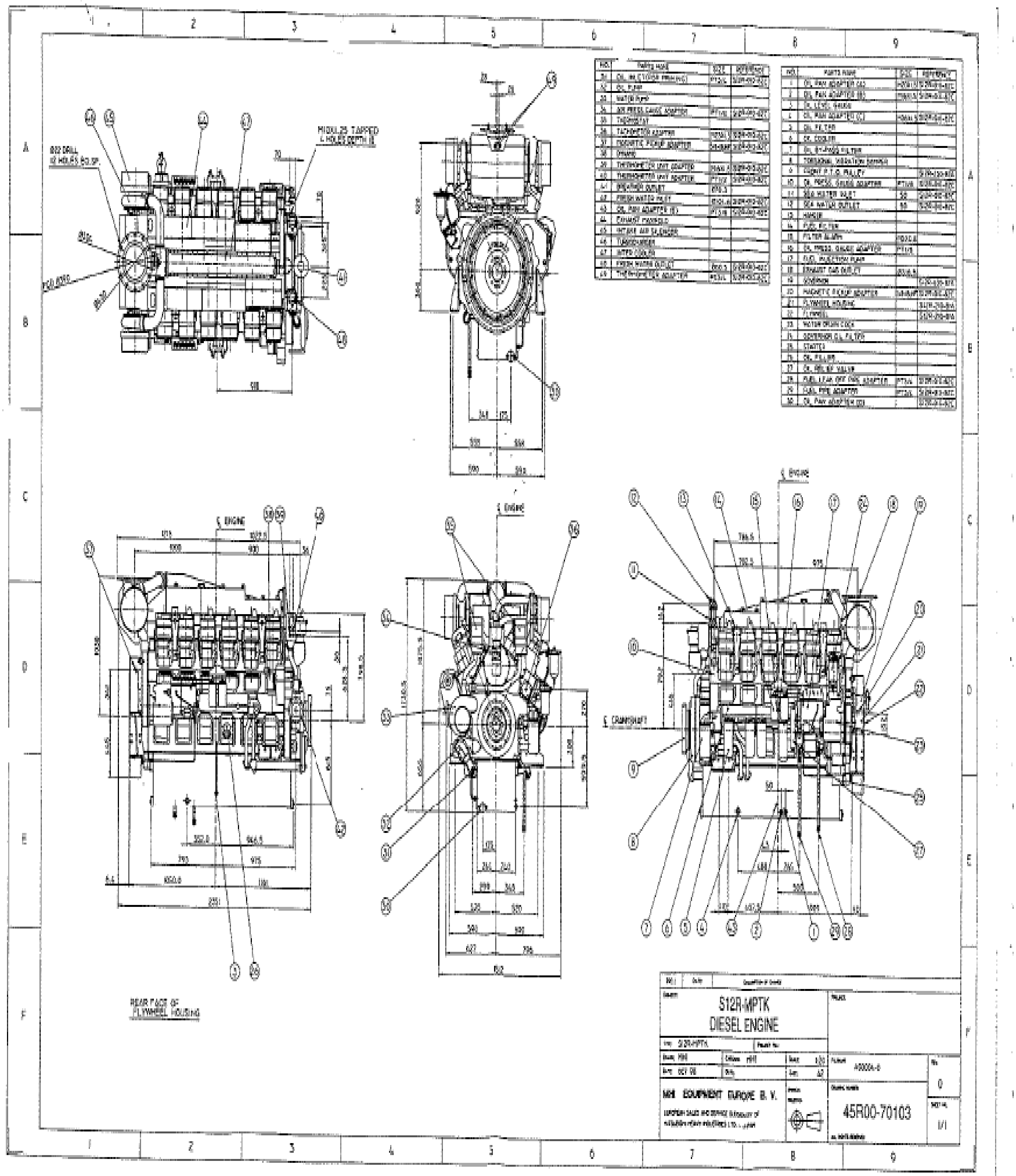
MITSUBISHI
DIESEL ENGINES
TURBOCHARGERS

Emission test report no. EZ/09/2656-29

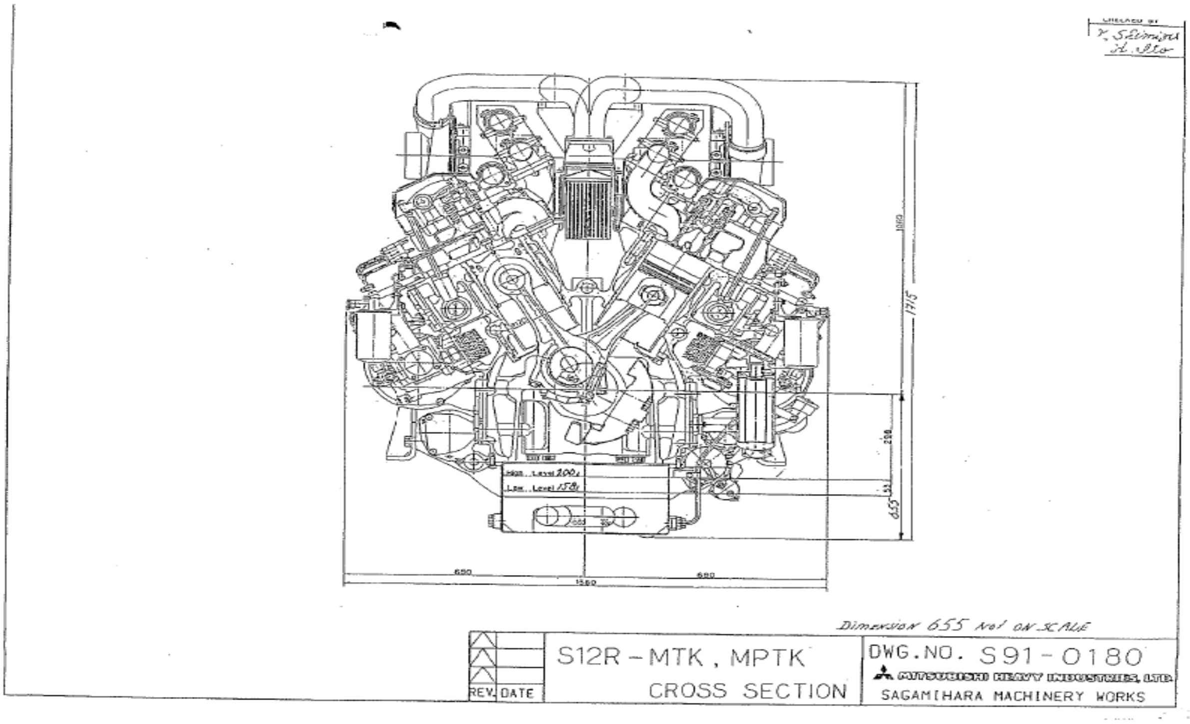
Engine				
Manufacturer	Mitsubishi Heavy Industries, Ltd.			
Engine type	S12A2-MPTAW			
Engine family or engine group identification	51EF			
Serial number	26630			
Rated speed	1800 rpm			
Rated power	828 kW			
Intermediate speed	rpm			
Maximum torque at intermediate speed	Nm			
Static injection timing	30 deg CA BTDC			
Electronic injection control	no:	~~yes:~~		
Variable injection timing	N/A			
Variable turbocharger geometry	N/A			
Bore	150 mm			
Stroke	160 mm			
Nominal compression ratio	15.3:1			
Mean effective pressure, at rated power	1630 kPa			
Maximum cylinder pressure, at rated power	14 000 kPa			
Cylinder number and configuration	Number: 12	V: 60 degrees	~~In-line:~~	
Auxiliaries				
Specified ambient conditions				
Maximum seawater temperature	25°C			
Maximum charge air temperature, if applicable	60°C			
Cooling system spec. intermediate cooler	~~No:~~	Yes:		
Cooling system spec. charge air stages	single stage			
Low/high temperature cooling system set points	/	°C		
Maximum inlet depression	3.92 kPa			
Maximum exhaust back pressure	4.41 kPa			
Fuel oil specification	DMX ISO 8217			
Fuel oil temperature	38 °C			
Emissions test results:				
Cycle			**E2**	
NOx			**7.4**	g/kWh
Test identification	20100629-01			
Date/time	29.06.2010 / 10:35			
Test site/bench	Almere / testbench B			
Test number				
Surveyor	Rob Vonk			
Date and Place of report				
Signature				

B. Drawings of Diesel Engine: Mitsubishi engines S12R -MPTK

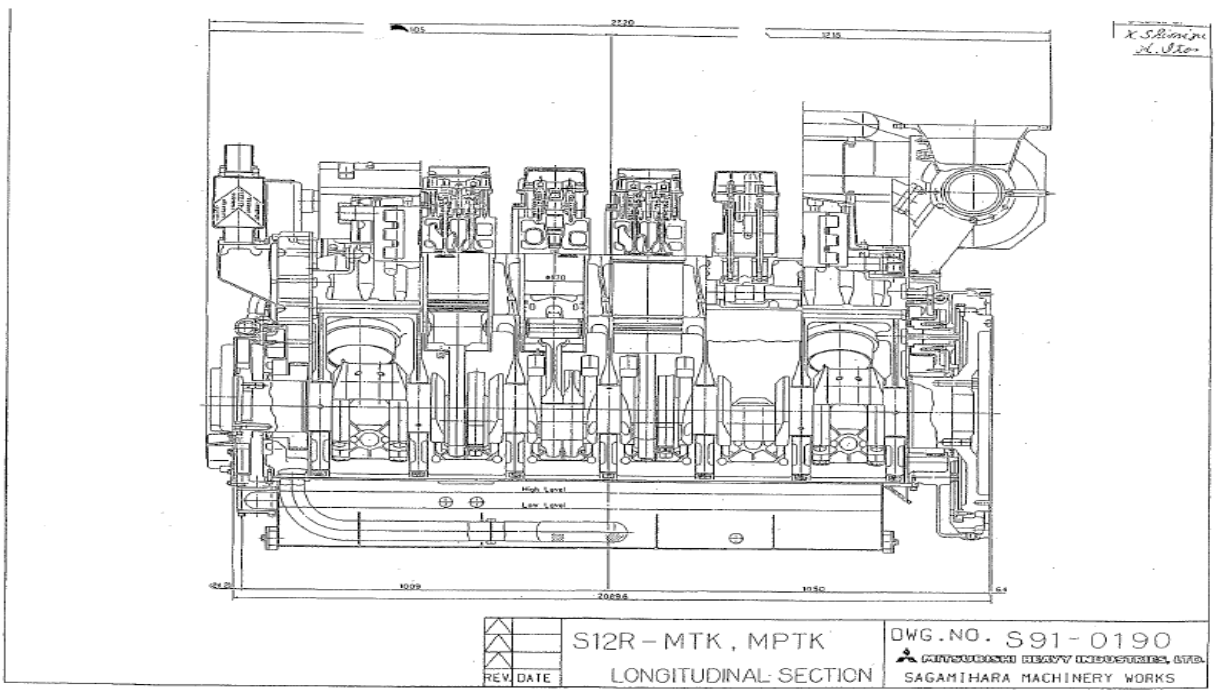
1. Main drawing



2. Cross- Sectional drawing

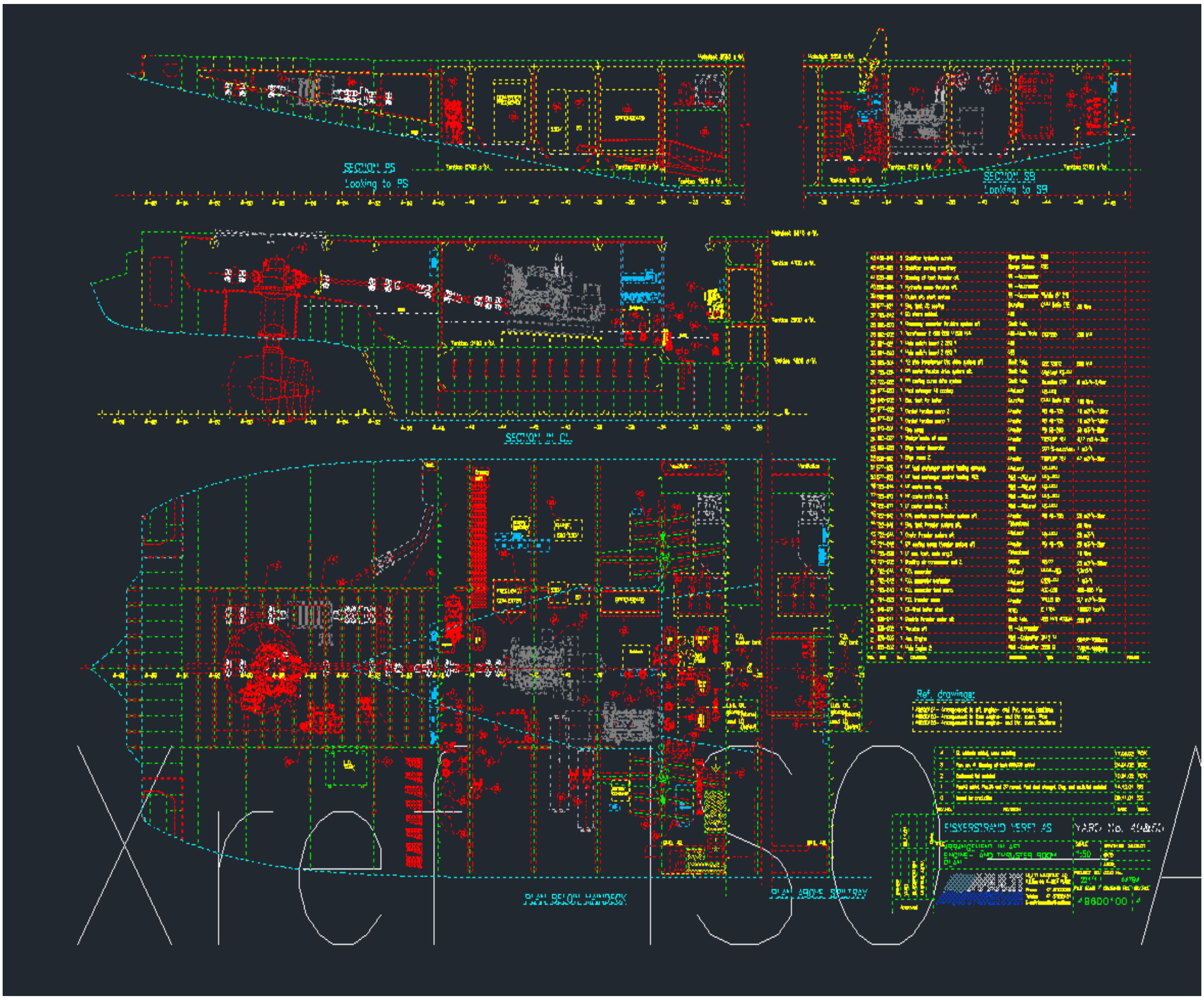


3. Longitudinal Sectional drawing

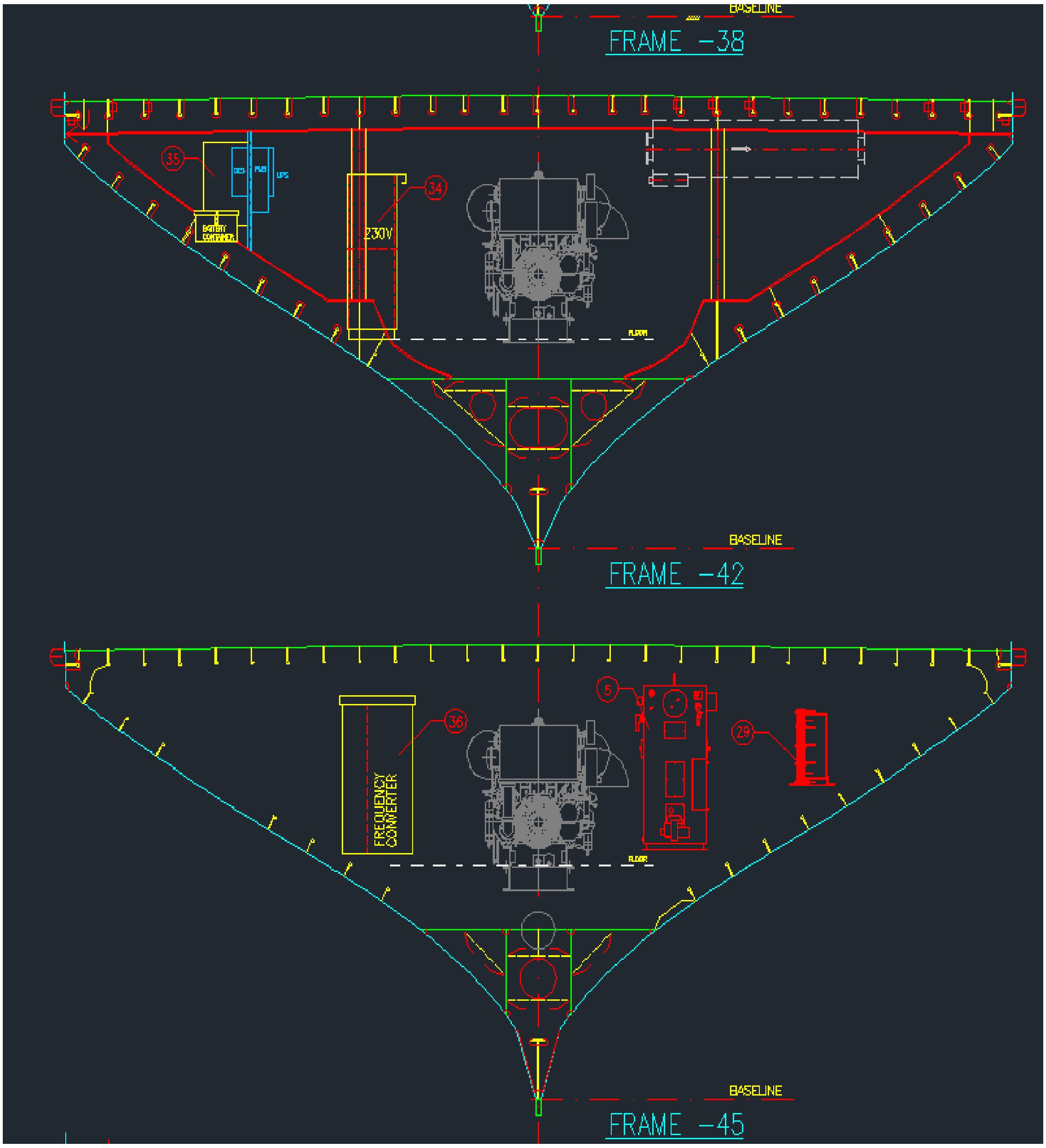


C. Technical drawing of MF Lyngen

1. Top view and sectional view drawing of MF Lyngen.



2. Drawing showing the power supply(230V/50Hz) source available at the engine room of MF Lyngen.



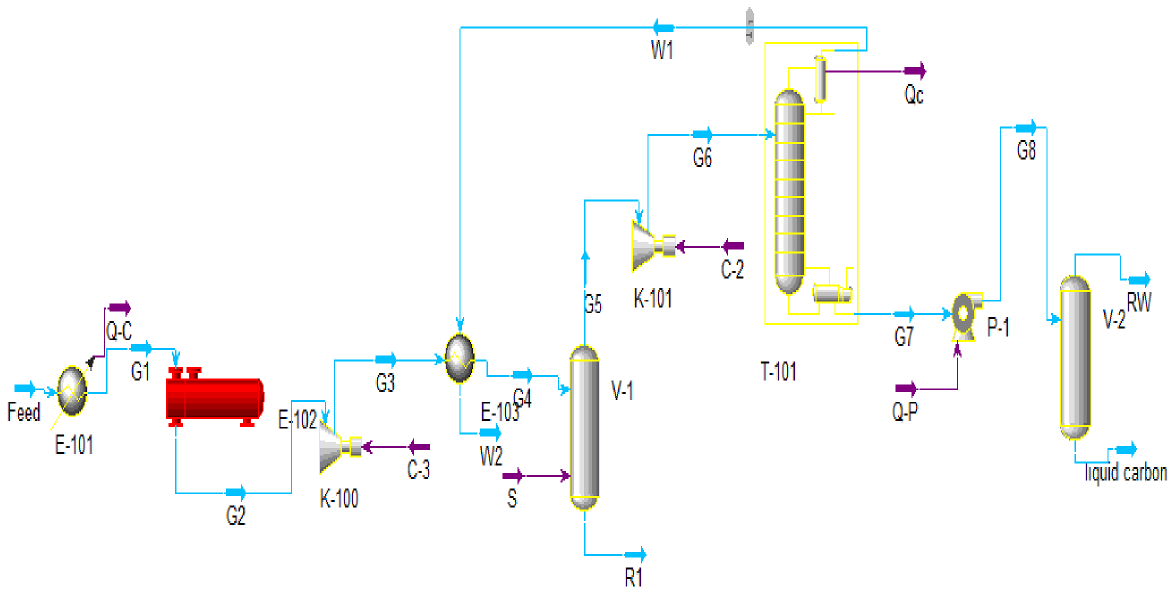
D. Aspen HYSYS modelling

1. Picture of modelling of TECO capture process done in ASPEN HYSYS

Component Selected: Methane, Nitrogen oxide, CO_2 and H_2O

Fluid package selected: NRTL

Picture of modelling of simplified version of carbon capture process.



2. Result obtained from Aspen HYSYS

aspentech

UNIVERSITY OF TROMSO
Bedford, MA
USA

Case Name:	NoName_2.hsc
Unit Set:	EuroSI
Date/Time:	Sat May 14 02:37:40 2022

Material Stream: Liquid carbon

Fluid Package:	Basis-1
Property Package:	NRTL - Ideal

CONDITIONS

		Overall	Vapour Phase	Aqueous Phase
Vapour / Phase Fraction		0.0000	0.0000	1.0000
Temperature:	(C)	-28.00	-28.00	-28.00
Pressure:	(bar)	17.60	17.60	17.60
Molar Flow	(kgmole/h)	0.1019	0.0000	0.1019
Mass Flow	(kg/h)	2.034	0.0000	2.034
Std Ideal Liq Vol Flow	(m3/h)	2.108e-003	0.0000	2.108e-003
Molar Enthalpy	(kcal/kgmole)	-7.121e+004	-9.449e+004	-7.121e+004
Molar Entropy	(kJ/kgmole-C)	-910.3	179.9	-910.3
Heat Flow	(kcal/h)	-7255	0.0000	-7255
Liq Vol Flow @Std Cond	(m3/h)	1.951e-003 *	0.0000	1.951e-003

PROPERTIES

		Overall	Vapour Phase	Aqueous Phase
Molecular Weight		19.96	43.97	19.96
Molar Density	(kgmole/m3)	54.07	0.8635	54.07
Mass Density	(kg/m3)	1079	37.97	1079
Act. Volume Flow	(m3/h)	1.884e-003	0.0000	1.884e-003
Mass Enthalpy	(kcal/kg)	-3568	-2149	-3568
Mass Entropy	(kJ/kg-C)	-45.61	4.092	-45.61
Heat Capacity	(kJ/kgmole-C)	76.81	36.53	76.81
Mass Heat Capacity	(kJ/kg-C)	3.848	0.8307	3.848
LHV Molar Basis (Std)	(kcal/kgmole)	0.4735	233.6	0.4735
HHV Molar Basis (Std)	(kcal/kgmole)	9068	257.8	9068
HHV Mass Basis (Std)	(kcal/kg)	454.3	5.863	454.3
CO2 Loading		---	---	---
CO2 App ML Con	(kgmole/m3)	4.048	---	4.048
CO2 App WT Con	(kgmol/kg)	3.751e-003	---	3.751e-003
LHV Mass Basis (Std)	(kcal/kg)	2.372e-002	5.313	2.372e-002
Phase Fraction [Vol. Basis]		---	---	1.000
Phase Fraction [Mass Basis]		0.0000	0.0000	1.000
Phase Fraction [Act. Vol. Basis]		0.0000	0.0000	1.000
Mass Exergy	(kcal/kg)	3270	---	---
Partial Pressure of CO2	(bar)	0.0000	---	---
Cost Based on Flow	(Cost/s)	0.0000	0.0000	0.0000
Act. Gas Flow	(ACT_m3/h)	---	---	---
Avg. Liq. Density	(kgmole/m3)	48.33	18.75	48.33
Specific Heat	(kJ/kgmole-C)	76.81	36.53	76.81
Std. Gas Flow	(STD_m3/h)	2.409	0.0000	2.409
Std. Ideal Liq. Mass Density	(kg/m3)	964.7	824.7	964.7
Act. Liq. Flow	(m3/s)	5.234e-007	---	5.234e-007
Z Factor		---	1.000	1.597e-002
Watson K		8.524	8.529	8.524
User Property		---	---	---
Partial Pressure of H2S	(bar)	0.0000	---	---
Cp/(Cp - R)		1.121	1.295	1.121
Cp/Cv		1.130	1.295	1.130
Heat of Vap.	(kcal/kgmole)	1.203e+004	---	---
Kinematic Viscosity	(cSt)	2.293	0.3281	2.293
Liq. Mass Density (Std. Cond)	(kg/m3)	1042	824.6	1042
Liq. Vol. Flow (Std. Cond)	(m3/h)	1.951e-003	0.0000	1.951e-003
Liquid Fraction		1.000	0.0000	1.000
Molar Volume	(m3/kgmole)	1.849e-002	1.158	1.849e-002
Mass Heat of Vap.	(kcal/kg)	602.5	---	---
Phase Fraction [Molar Basis]		0.0000	0.0000	1.0000
Surface Tension	(dyne/cm)	76.24	---	76.24
Thermal Conductivity	(W/m-K)	0.4746	1.446e-002	0.4746
Viscosity	(cP)	2.475	1.246e-002	2.475

Aspen Technology Inc. Aspen HYSYS Version 9 Page 1 of 3

* Specified by user.

aspentech	UNIVERSITY OF TROMSO Bedford, MA USA	Case Name:	NoName_2.hsc
		Unit Set:	EuroSI
		Date/Time:	Sat May 14 02:37:40 2022

Material Stream: Liquid carbon (continued)

Fluid Package: Basis-1

Property Package: NRTL - Ideal

PROPERTIES

	Overall	Vapour Phase	Aqueous Phase		
Cv (Semi-Ideal) (kJ/kgmole-C)	68.49	28.21	68.49		
Mass Cv (Semi-Ideal) (kJ/kg-C)	3.431	0.6416	3.431		
Cv (kJ/kgmole-C)	68.00	28.21	68.00		
Mass Cv (kJ/kg-C)	3.407	0.6416	3.407		
Cv (Ent. Method) (kJ/kgmole-C)	---	---	---		
Mass Cv (Ent. Method) (kJ/kg-C)	---	---	---		
Cp/Cv (Ent. Method)	---	---	---		
Reid VP at 37.8 C (bar)	84.92	85.50	84.92		
True VP at 37.8 C (bar)	171.3	2356	171.3		
Liq. Vol. Flow - Sum(Std. Cond) (m3/h)	1.951e-003	0.0000	1.951e-003		
Viscosity Index	12.74	---	---		

COMPOSITION

Overall Phase

Vapour Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0076	0.0749	0.3357	0.1651	0.0004	0.1929
H2O	0.0943	0.9251	1.6980	0.8349	0.0017	0.8071
Total	0.1019	1.0000	2.0337	1.0000	0.0021	1.0000

Vapour Phase

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Methane	0.0000	0.0012	0.0000	0.0004	0.0000	0.0012
Nitrogen	0.0000	0.0001	0.0000	0.0001	0.0000	0.0001
CO2	0.0000	0.9986	0.0000	0.9995	0.0000	0.9987
H2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Aqueous Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0076	0.0749	0.3357	0.1651	0.0004	0.1929
H2O	0.0943	0.9251	1.6980	0.8349	0.0017	0.8071
Total	0.1019	1.0000	2.0337	1.0000	0.0021	1.0000

K VALUE

COMPONENTS	MIXED	LIGHT	HEAVY
Methane	493.4	---	493.4
Nitrogen	1238	---	1238
CO2	13.34	---	13.34
H2O	3.592e-005	---	3.592e-005

UNIT OPERATIONS

FEED TO	PRODUCT FROM	LOGICAL CONNECTION
	Separator: V-100	

UTILITIES

(No utilities reference this stream)

PROCESS UTILITY

* Specified by user.

aspentech — UNIVERSITY OF TROMSO Bedford, MA USA	Case Name: NoName_2.hsc Unit Set: EuroSI Date/Time: Sat May 14 02:37:40 2022

Material Stream: Liquid carbon (continued)

Fluid Package: Basis-1
Property Package: NRTL - Ideal

DYNAMICS

Pressure Specification	(Inactive)	17.60 bar					
Flow Specification	(Inactive)	Molar:	0.1019 kgmole/h	Mass:	2.034 kg/h	Std Ideal Liq Volume	2.108e-003 m3/h

User Variables

NOTES

Description