MES
Maritime Engineering & Solutions

Whitepaper

CO_2 Capture on Board of Ships

Environmental & Technical Feasibility Study

May 2023

1st Edition

Empowering Vessels with Sustainable Solutions

Maritime Engineering & Solutions GmbH (MES) is a leading provider of innovative and sustainable solutions for retrofitting ships. With our headquarters in the vibrant city of Hamburg, Germany, we are committed to supporting the maritime industry in reducing their environmental impact.

Our team of experienced engineers and experts is dedicated to delivering high-quality solutions that prioritize sustainability, efficiency, and safety. We work closely with ship owners and operators to develop tailored retrofitting plans that meet their individual needs and regulatory requirements.

At MES, we specialize in green retrofit engineering for ships, helping our clients to upgrade their vessels with the latest green technologies and solutions. We focus on reducing emissions, improving energy efficiency, and enhancing overall vessel performance.

Our comprehensive services cover a wide range of areas, including feasibility studies, 3D high-resolution scan, full engineering & Class design appraisal, project management, installation, commissioning, and field services. We pride ourselves on our commitment to excellence, and our team works tirelessly to ensure that every project is completed to the highest standard.

Authors

Jürgen B. Gerdes, Dipl. Ing.
Andreas Kisling Harris, PhD
Lena-Katharina Gerdes, MSc

Maritime Engineering & Solutions GmbH
Neuer Wall 84
D-20354 Hamburg
Germany

web www.engship.com
mail contact@engship.com
phone +49 40 524733570

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Disclaimer

It should be stressed that the data collection and analysis for this whitepaper was carried-out from 2021 until mid-2022, when only few companies where claiming to be able to provide CO_2 capturing solutions, many of whom refrained from sharing their relevant data.

Furthermore, the physical units used by different technologies were not uniform resulting in conversions.

Therefore, data published in this white paper might be outdated, whereby projects and technologies listed might not be considered. However, in order to establish an up-to-date database we have created a public dashboard under ccs.engship.com. We strongly encourage owners' of technologies not referred to or of outdated data to contact us at any time for an update.

The technologies and projects presented to be "most suitable" are a result of a specific maritime application weighting, which depending on different vessel types, age, operational profile and fuel usage might result in different results for "most suitable" technologies. Therefore, it is crucial to understand that the white paper reflects a representation of the weighting used in our study, while we enable a tailored selection through the online dashboard.

The data for this study has been collected during 2021 and was funded by the German "Central Innovation Programme for small and medium-sized enterprises (SMEs)"; ID 16KN081890, also known as ZIM – Germanys largest innovation programme for SMEs. It is a funding programme of the Federal Ministry for Economic Affairs and Climate Action that aims to foster the innovative capacity of SMEs.

[1] ZIM- Zentrales Innovationsprogramm Mittelstand

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Introduction

In 2021, it was estimated that international shipping accounted for approximately 2% of global carbon dioxide (CO_2) emissions. Shipping is commonly considered to be only a "modest" contributor to global CO_2 emissions given its energy-efficient mode of transporting goods on an international scale. However, given that sea transport is expected to continue alongside international trade, a comprehensive global strategy to reduce emissions and improve energy efficiency is urgently required.

Given its global nature and operational system, CO_2 emissions from international shipping cannot be attributed to any particular national economy. Recognizing the importance of mitigating climate change and the important role of the maritime sector to the global economic, the International Maritime Organization (IMO) has increasingly focused on limiting and reducing greenhouse gas (GHG) emissions from international shipping.

Based on a variety of realistic long-term economic and energy scenarios, it is projected that emissions in 2050 could reach 90-130% of the emissions recorded in 2008 if current business practices continue. Consequently, the International Maritime Organization (IMO) has been actively involved in a global strategy to advance the energy efficiency of ships, establish measures to decrease greenhouse gas (GHG) emissions from vessels, and offer technical collaboration and capacity-building initiatives.

Accordingly, certain efforts have been made introducing alternative, low-emission power and fuel concepts. In addition to the targeted reduction of sulphur oxides (SO_x), nitrogen oxides (NO_x) and particle matters (PM), further regulations restricting CO_2 emissions from shipping are expected. Even if no binding rules are currently defined, the maritime industry sector must prepare itself for the future considering the lifetime of ships.

Different fuel concepts with existing prime movers as well as alternative fuels with new energy sources such as fuel cells are currently in focus. In addition to the use of liquefied natural gas (LNG), methanol is a promising alternative fuel which can be relatively easily produced synthetically from regenerative sources – the carbon cycle can be closed, CO_2-neutral ship operation becomes feasible. For certain types of ships, the use of methanol is likely to be the only technically and economically feasible alternative. Overall, however, the integration of the maritime world in Power-to-X technologies will be a major step towards climate-neutral shipping.

In order to close the carbon cycle completely, it will be imperative to capture and store intermediately the CO_2 emitted by the ship engines. The required technology should be compatible with conventional internal combustion engines, which are commonly used onboard ships today. The world cannot be changed in a day – the existing world fleet is currently reliant on internal combustion engines burning fossil fuels which cannot be replaced over night with vessels designed to be green. Therefore, retrofitting these ships with CO_2 capture technologies is a crucial part of a) making the world fleet more green and, b) saving the carbon cost of replacing ships before they are ready to retire.

This feasibility study "CO_2 Capture and Storage System on Board of Ship" will:

- Provide an overview of CO_2 capturing and separation technologies – independent of their end use applications
- Establish a technical specification guide for the deployment of CO_2 capturing on board of ships
- Benchmark and evaluate various available technologies for their application in the maritime sector

[2] International Energy Agency (2022)

In addition, we have created an online dashboard with the technical details of the analysed technologies. Based on your input, the dashboard will provide you with the most appropriate technology selection based on the current data. The dashboard can be accessed here (ccs.engship.com).

It is our aim with this study to provide more transparency on CO_2 capturing technologies and thereby motivate the maritime sector to take action today and start reducing CO_2 emissions!

Status Quo: CO_2 Capturing & Separation Technologies

Chapter 1

Status Quo – CO_2 Capturing Technologies

The shipping industry is a significant contributor to global carbon emissions, accounting for approximately 3% of total greenhouse gas emissions in 2020. As the world strives to meet ambitious climate targets and reduce greenhouse gas emissions, there is increasing interest in finding innovative solutions to mitigate carbon dioxide (CO_2) emissions from ships. One such solution is on-board CO_2 capture, which involves capturing and intermediate storing CO_2 emissions generated by ships during their operations.

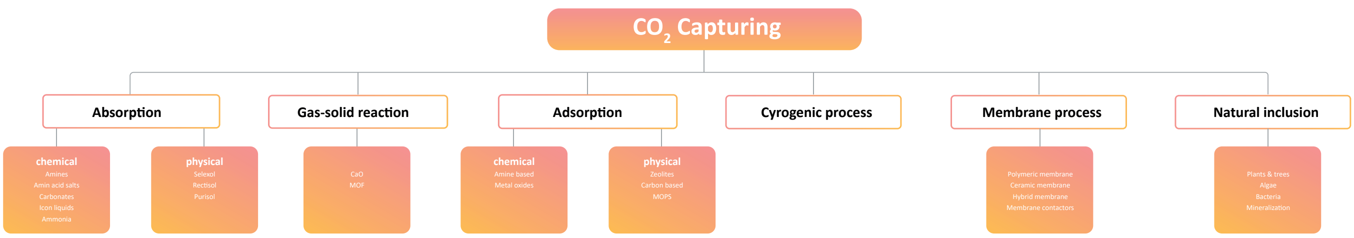
This chapter sets the stage for this research paper by providing an overview of the research scope and the approach taken to evaluate the feasibility of CO_2 capture on board of ships. This chapter provides an overview of the various CO_2 separation technologies in general, followed by a technical specification guide for CO_2 separation on board. It concludes with the benchmarking and evaluation of the explored CO_2 separation technologies for a maritime application.

Overview of available technologies

Firstly, we will explore different separation technologies that can be used for CO_2 capture, including chemical absorption, physical absorption, EMA (Electrochemical Membrane Amine Scrubbing), ESA (Electro-Swing Adsorption), Magnetic Induction Swing Adsorption (MISA), PSA (Pressure Swing Adsorption), TSA (Temperature Swing Adsorption), VPSA (Vacuum Pressure Swing Adsorption), VSA (Vacuum Swing Adsorption), cryogenic, membrane, and gas-solid reaction technologies. This overview reflects currently available technologies for CO_2 separation and capture, independent of whether they are applicable to shipping. When it comes to the separation of CO_2, the technology can either involve an absorption (chemical or physical) or an adsorption process. In summary, absorption processes involve the dissolution of CO_2 into a liquid solvent, either through physical solubility or chemical reaction, while adsorption processes involve the binding of CO_2 onto the surface of a solid material without forming a chemical solution. The adsorption process is a purely physical process in which molecules adhere to the surface of a substance - sorbent. Compared to chemical absorption, this adhesion has a weaker bond and consequently a lower energy requirement for reversal. (Fischedick, Görner, & Thomeczek, 2015, p. 292).

Both absorption and adsorption processes have their advantages and limitations, and the selection of the appropriate process depends on various factors, such as the specific application, operational conditions, and economic considerations.

Figure 1 - Overview of CO_2 capturing methods[3]



[3] Kammerer et al. (2022)

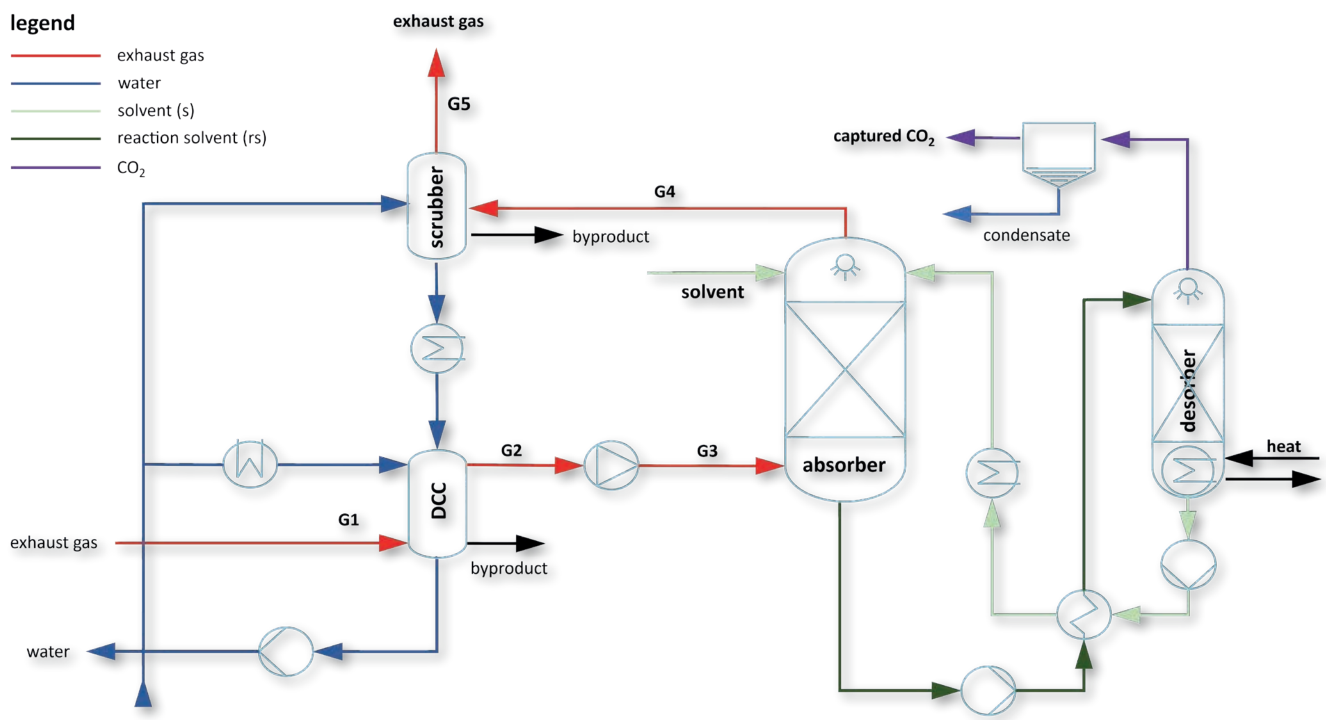
Chemical Absorption

In the chemical absorption process, the flue gas reacts with a solvent. Aqueous solutions from the group of alkanolamines are often used as solvent.

The engines' exhaust gas (G1) is cooled down to the required process temperature of usually 40-60 °C in the DCC (Direct Contact Cooler), which can filter the flue gas if necessary to adapt the flue gas properties to the separation technology. The gas flow (G2) is then conveyed into the absorber by a fan as (G3) to overcome the back pressure of the absorber. In the absorber, the CO_2 reacts with the solvent (s) sprayed from above on the contact surfaces and becomes the reaction solution, which collects at the bottom of the absorber. This solution is then cooled in a heat exchanger and pumped into the desorber. In the desorber, a reaction solution is sprayed in from above and heated up to approx. 125-160 °C, causing the CO_2 to separate from the reaction solution, which can then be stored after water separation. The now regenerated solvent is cooled and reused in the absorber. (Fischedick, Görner, & Thomeczek, 2015). This process is shown in Figure 2.

In order to keep the cycle capacity stable, fresh solvent must be supplied. Parts of the solvent are transported away in the flue gas. In the flue gas aftertreatment, the solvent is filtered out as a by-product through flue gas scrubbing.

Figure 2 - Flow diagram of the chemical absoprtion process

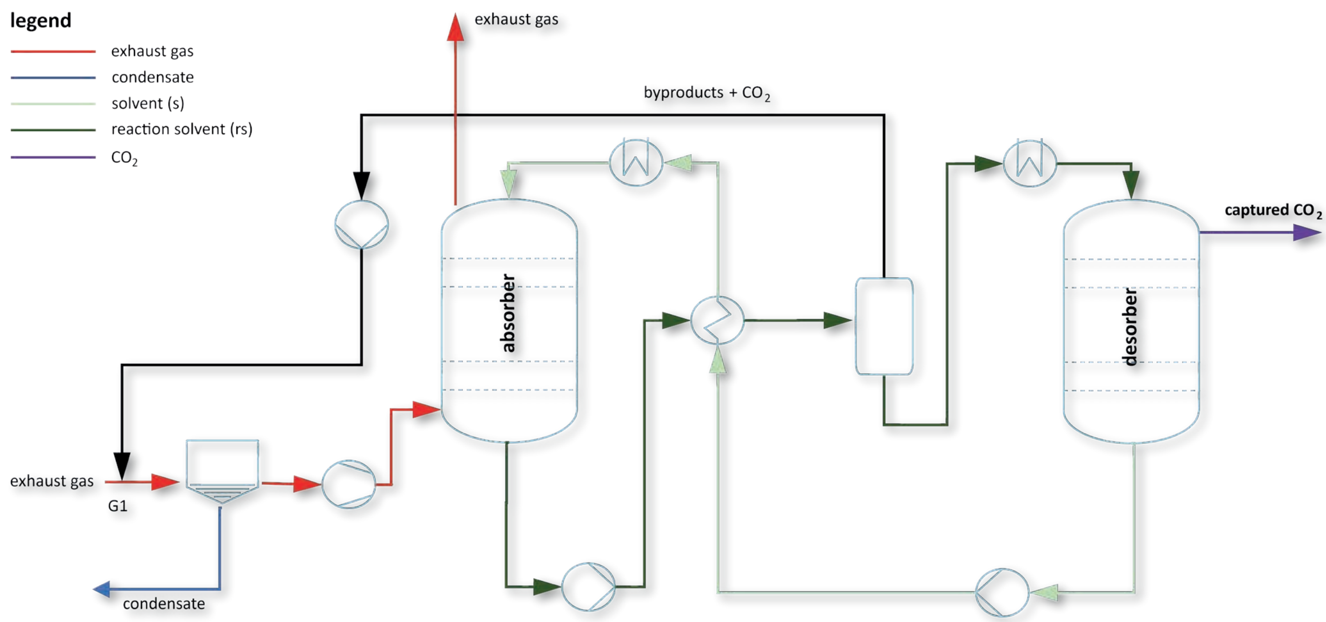


Physical Absorption

Physical absorption is a method used to dissolve a gas in a solvent through physical means. It is commonly understood to follow Henry's law, which suggests that the amount of gas dissolved in a physical solvent is directly proportional to the gas's partial pressure. By utilizing a pressure difference as the driving force, the gas can be separated from the solvent, allowing for the extraction and recovery of the gas with reduced energy requirements[4].

The engines' exhaust gas (G1) is compressed to 10-220 bar after the condensate separator, depending on the process (see table 1), and then brought to the required process temperature before being fed into the sump of the absorption column. This process is shown in Figure 3. column at the necessary process temperature. The temperature is important because it affects the value of Henry's constant and thus determines the absorption capacity. The column is filled with packing to increase the contact area between the solvent and the flue gas. The carbon dioxide is absorbed by the solvent and leaves the absorber at the bottom as loaded solvent. It is then heated by a heat exchanger by cooling the crossing unloaded solvent, which is on its way to the upper part of the absorber. The loaded solvent is injected into the gas separator where the pressure is reduced. Here, unwanted by-products dissolve as well as some carbon dioxide, which is returned to the flue gas source (G1).

Figure 3 - Flow diagram of the physical absoprtion process using an organic solvent[5]



[4] Hansa et al. (2020)

[5] Singhal et al. (2017)

The exact pressure used in the flash column depends on the process. To regenerate the loaded solvent, it is further heated up before entering the desorber. It is injected into the head of the desorber and the pressure is lowered, allowing the CO_2 to dissolve and be fed to storage.

Table 1 - Process values of different physical absorption methods[6]

Parameter	Pressure wash	Purisol	Rectisol	Selexol	Flour Solvent	Sepasolv
Temperature [°C]	20	20 to 43	-51 to -35	-20 to 30	-20 to 30	40 to 95
Pressure [bar]	10 to 30	36 to 75	220	30 to 70	27 to 140	20 to 30

[6] Fischedick et al. (2015)

Electrochemical Membrane Amine Scrubbing (EMA)

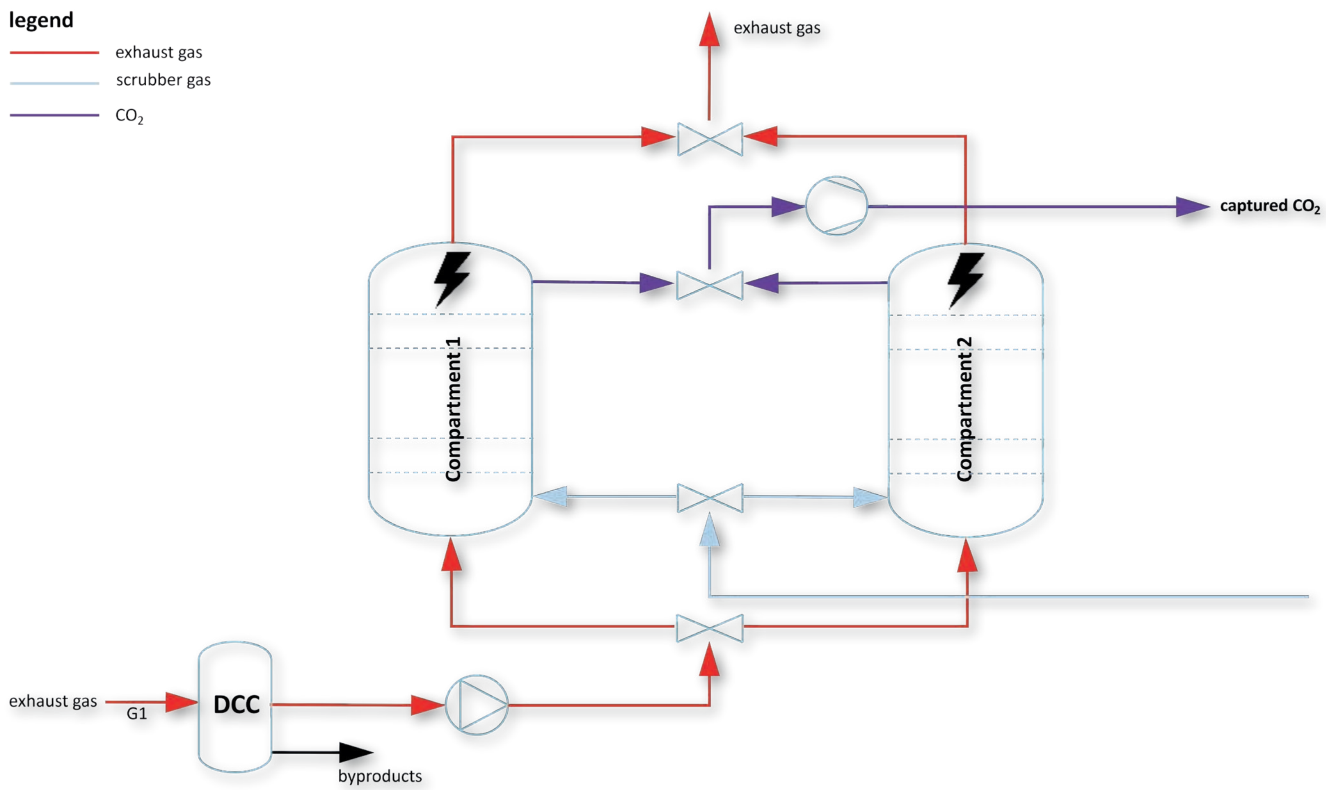
Electrochemical Membrane Amine Scrubbing (EMA) utilizes a combination of electrochemical reactions and membrane separation to capture CO_2 from gas streams. It involves the use of amine-based electrolytes and a membrane to selectively remove CO_2.

Electrochemical CO_2 capturing is an umbrella term and includes: pH Swing, Redox-active Carriers, Molten Carbonate and hybrid systems thereof. In this case, the redox-active carriers represent a solid sorbent and are electrically charged for CO_2 capture. The reversal, i.e. the release of the CO_2 from the sorbent, takes place by removing the applied voltage (Sharifian et al., 2021, p. 797).

In EMA, two tanks are cyclically filled with solid sorbents, which alternately act as adsorbers or regenerators. The flue gas is initially brought to the necessary process temperature by a direct contact cooler (DCC). In this step, the DCC also removes particles from the flue gas. The engines' exhaust gas is then fed into the adsorber, where it comes into contact with the sorbent. Due to the properties of the sorbent, the CO_2 sticks to it. When the sorbent is saturated, i.e. loaded with CO_2, the valve switches over and the flue gas is led into the other container. In the first container, the applied voltage is now removed from the sorbent, which dissolves the CO_2, which can be fed to the storage by supplying a purge gas, ambient air.

It should be noted that due to the adhesion of the CO_2 to the surface of the sorbent, a technically necessary exhaust gas purification is to be expected in the case of combustion with heavy fuel oil, as happens predominantly in maritime application.

Figure 4 - Flow diagram of the Electrochemical Membrane Amine Scrubbing (EMA) process



Electric Swing Adsorption (ESA)

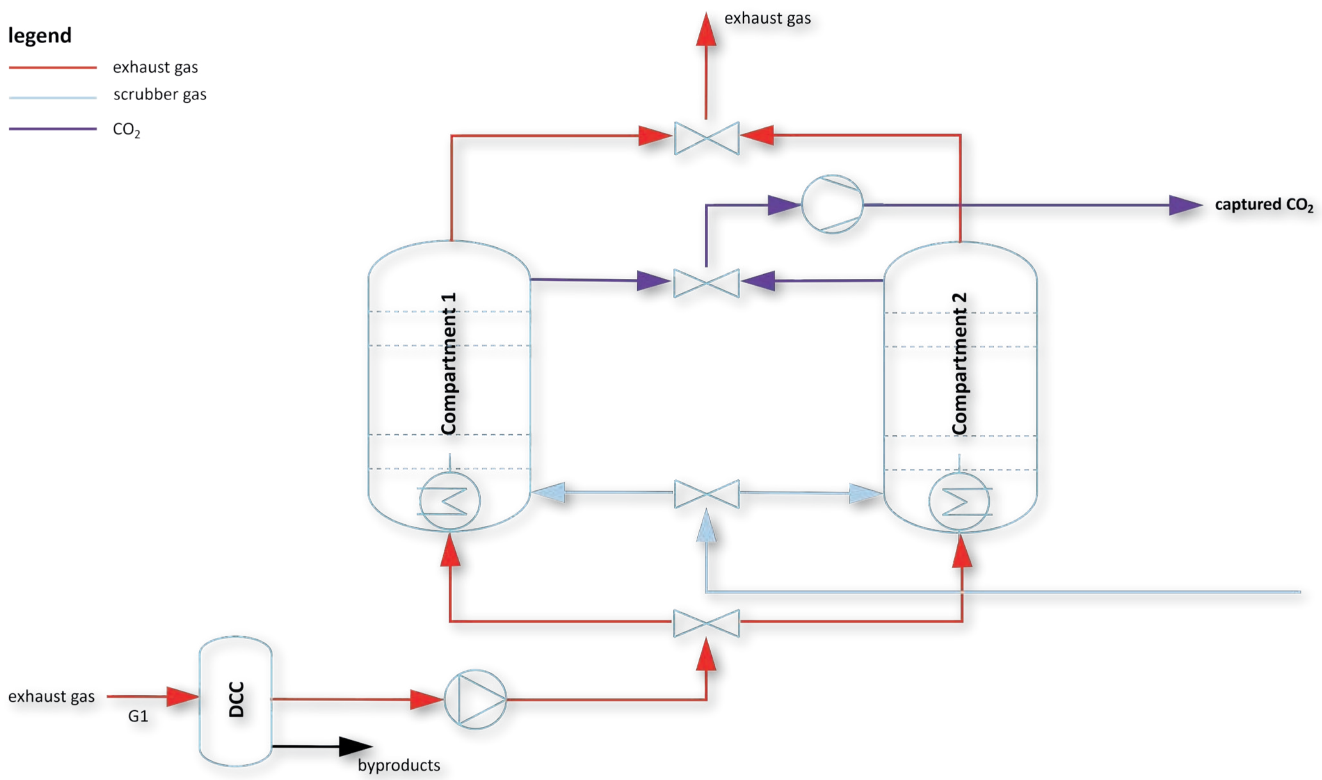
Electric Swing Adsorption (ESA) employs an electric field to enhance the separation of CO_2 from gas mixtures. It involves the adsorption and desorption of CO_2 on solid adsorbents, driven by changes in the electric field, resulting in an efficient and reversible CO_2 capture process.

The reversal, i.e. the dissolution of the CO_2 from the sorbent, takes place in electric swing adsorption by means of a temperature difference between adsorber and desorber, as in temperature swing adsorption. The only difference is that the sorbent is heated electrically.

In Electric Swing Adsorption, two vessels are cyclically filled with metal-organic framework (MOF) pellets (or other solid sorbents), which alternately act as adsorbers or regenerators. The engines' exhaust gas is initially brought to the required process temperature of approx. 20-40 °C by a Direct Contact Cooler (DCC). In this step, the DCC also removes particles from the flue gas. The flue gas is then fed into the adsorber, where it comes into contact with the sorbent. Due to the properties of the sorbent, the CO_2 sticks to it. When the sorbent is saturated, i.e. loaded with CO_2, the valve switches over and the flue gas is led into the other container. In the first container, the CO_2 is now dissolved from the sorbent by means of heat, which can be fed to the storage by supplying a purge gas, ambient air. This process is graphically represented in Figure 5.

It should be noted that due to the adhesion of the CO_2 to the surface of the sorbent, a technically necessary exhaust gas purification is to be expected in the case of combustion with heavy fuel oil, as happens predominantly in shipping.

Figure 5 - Flow diagram of the Electrochemical Swing Adsorption (ESA) process



Magnetic Induction Swing Adsorption (MISA)

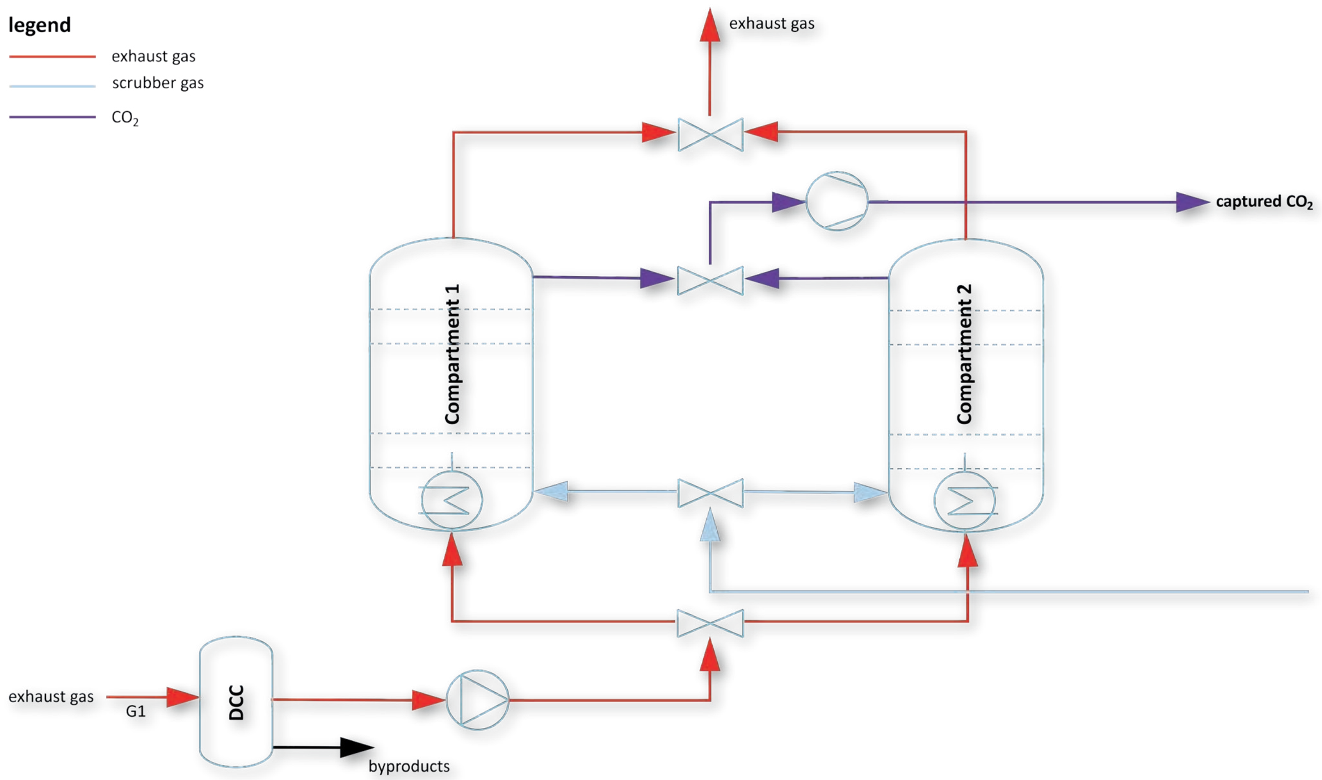
Magnetic Induction Swing Adsorption (MISA) utilizes a magnetic field to enhance the separation of CO_2 from gas mixtures. It involves the adsorption and desorption of CO_2 on solid adsorbents, driven by changes in the magnetic field, resulting in an efficient and reversible CO_2 capture process.

The reversal, i.e. the dissolution of the CO_2 from the sorbent, takes place in magnetic induction swing adsorption by means of a temperature difference between adsorber and desorber, as in temperature swing adsorption. The difference is that the sorbent is heated by magnetic induction.

In MISA, two vessels are cyclically filled with MOF pellets (or other solid sorbents), which alternately act as adsorbers or regenerators. The engines' exhaust gas is initially brought to the required process temperature of approx. 20-40 °C by a Direct Contact Cooler (DCC). In this step, the DCC also removes particles from the flue gas. The flue gas is then fed into the adsorber, where it comes into contact with the sorbent. Due to the properties of the sorbent, the CO_2 sticks to it. When the sorbent is saturated, i.e. loaded with CO_2, the valve switches over and the flue gas is led into the other container. In the first container, the CO_2 is now dissolved from the sorbent by means of heat, which can be fed to the storage by supplying a purge gas, ambient air (see Figure 6).

It should be noted that due to the adhesion of the CO_2 to the surface of the sorbent, a technically necessary exhaust gas purification is to be expected in the case of combustion with heavy fuel oil, as happens predominantly in shipping.

Figure 6 - Flow diagram of the Magnetic Induction Swing Adsorption (MISA) process



Pressure Swing Adsorption (PSA)

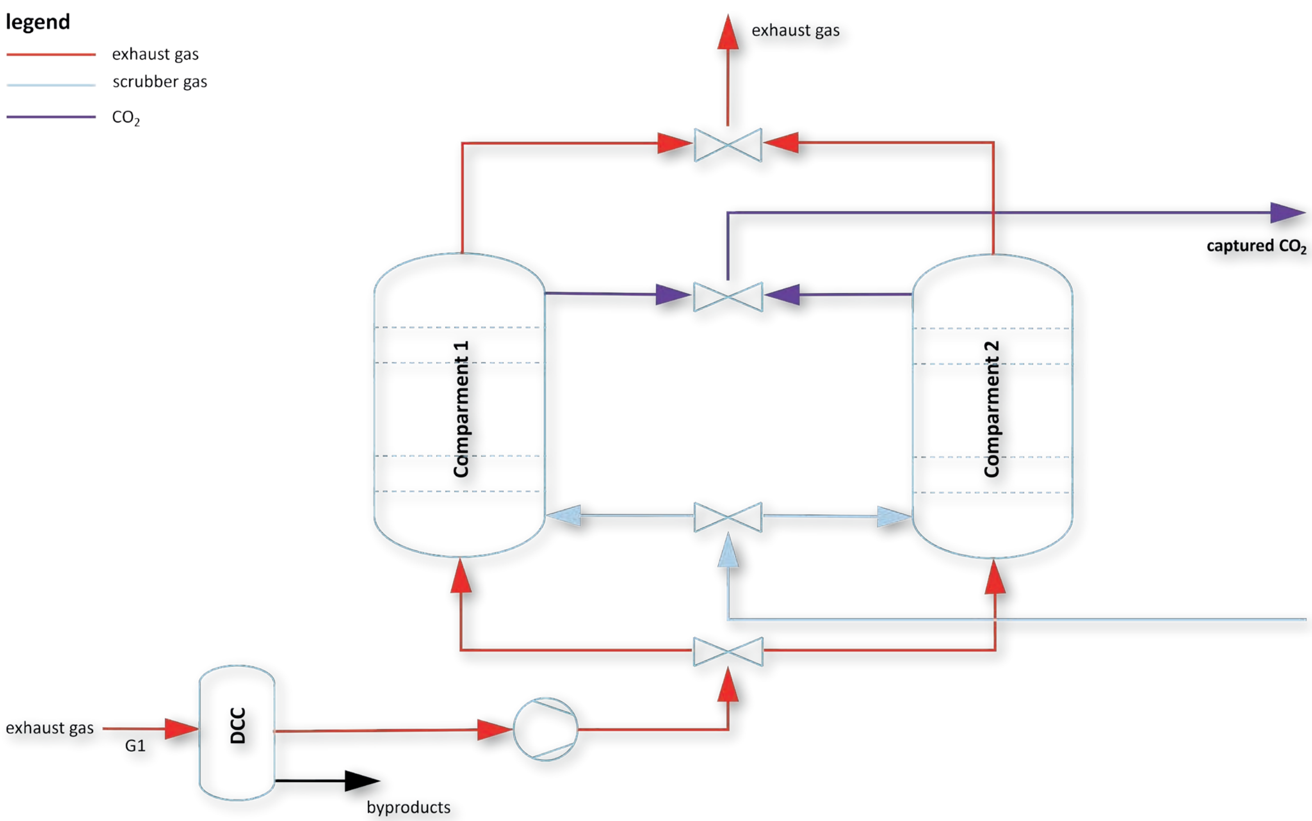
PSA involves the adsorption of CO_2 on a solid adsorbent under high pressure and subsequent desorption of CO_2 by reducing the pressure, allowing for cyclic operation.

In pressure swing adsorption, two vessels are cyclically filled with MOF pellets (or other solid sorbents), which alternately act as adsorbers or regenerators. The engines' exhaust gas is initially brought to the necessary process temperature of approx. 40-60 °C by a Direct Contact Cooler (DCC). In this step, the DCC also removes particles from the flue gas. In its function as an adsorber, the flue gas is pressurized, causing the CO_2 to combine with the sorbent. When the sorbent is saturated, i.e. loaded with CO_2, the valve switches and the flue gas is fed into the other container. The first container is depressurized by air supply and the CO_2 separates from the sorbent, which can then be fed to storage (see Figure 7).

At a pressure of 5 bar in the adsorber, a CO_2 purity of 15% is achieved, which is 55-75% at 10 bar (Dupuy Pol, 2019, p. 49).

It should be noted that due to the adhesion of the CO_2 to the surface of the sorbent, a technically necessary exhaust gas purification is to be expected in the case of combustion with heavy fuel oil, as predominantly happens in shipping.

Figure 7 - Flow diagram of the Pressure Swing Adsorption (PSA) process



Temperature Swing Adsorption (TSA)

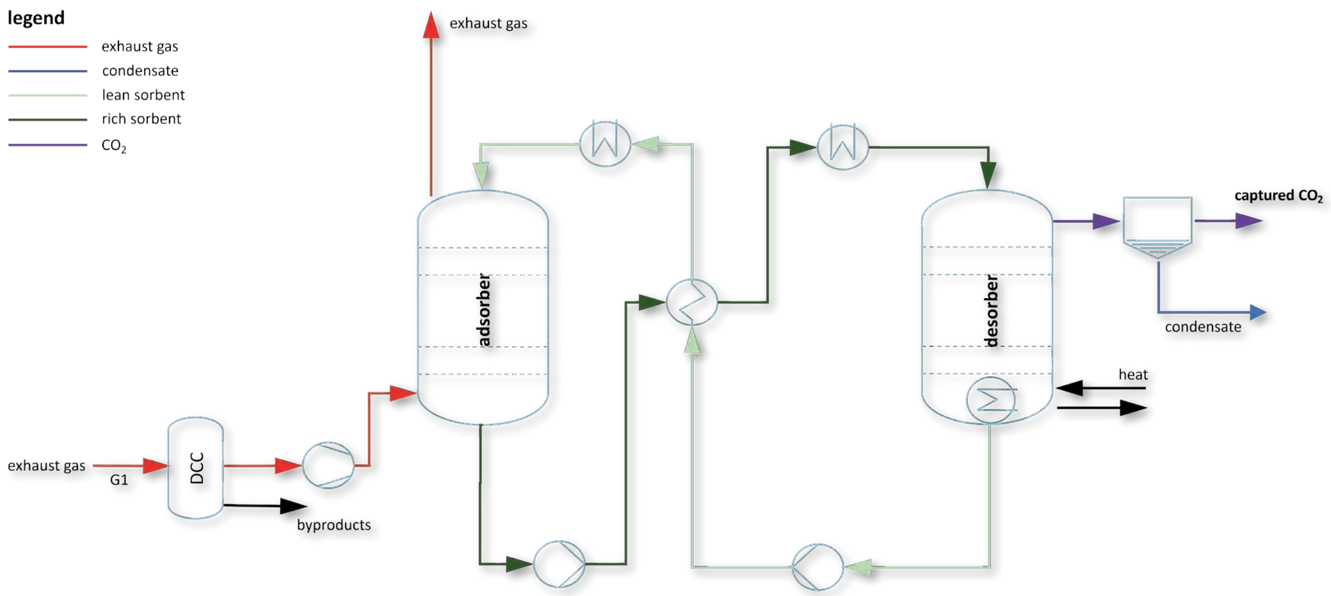
TSA involves the adsorption of CO_2 on an adsorbent at low temperatures and desorption by increasing the temperature, followed by cyclic operation. The reversal, i.e. the dissolution of the component, can take place in different ways. In this case, adsorption is described by temperature change, which is divided into three phases.

1. adsorption- sorbent absorbs CO_2
2. desorption- sorbent is heated and releases CO_2
3. regeneration- sorbent is cooled to reach the adsorption temperature.

Thus, in the process diagram shown below, the engines' exhaust gas is initially cooled in the Direct Contact Cooler (DCC) to the process temperature of approx. 25-50 °C. At the same time, particles are removed by the DCC. At the same time, particles are removed from the flue gas by the DCC. The flue gas is then passed through the adsorber, where it comes into contact with the sorbent coming from above. The CO_2 adheres to the sorbent and is collected at the bottom before it is conveyed to the desorber. Along the way, the CO_2 is preheated by heat exchangers before it is heated to a temperature of 110-180 °C in the desorber. The CO_2 thus separated is then separated from liquid in the condenser. The now dried CO_2 is ready for storage. The sorbent collects at the bottom of the desorber and is regenerated or cooled on its way to the adsorber.

It should be noted that CO_2 adsorption and desorption in Rapid Temperature Swing Adsorption (RTSA) is done by a rotating drum in the exhaust gas stream (Dhoke et al., 2021, p. 5) Another point, due to the adhesion of the CO_2 to the surface of the sorbent, a technically necessary exhaust gas cleaning is to be expected in case of combustion with heavy fuel oil, as it happens predominantly in shipping.

Figure 8 - Flow diagram of the Temperature Swing Adsorption (TSA) process[7]



[7] Netušil & Ditl (2012), p. 7

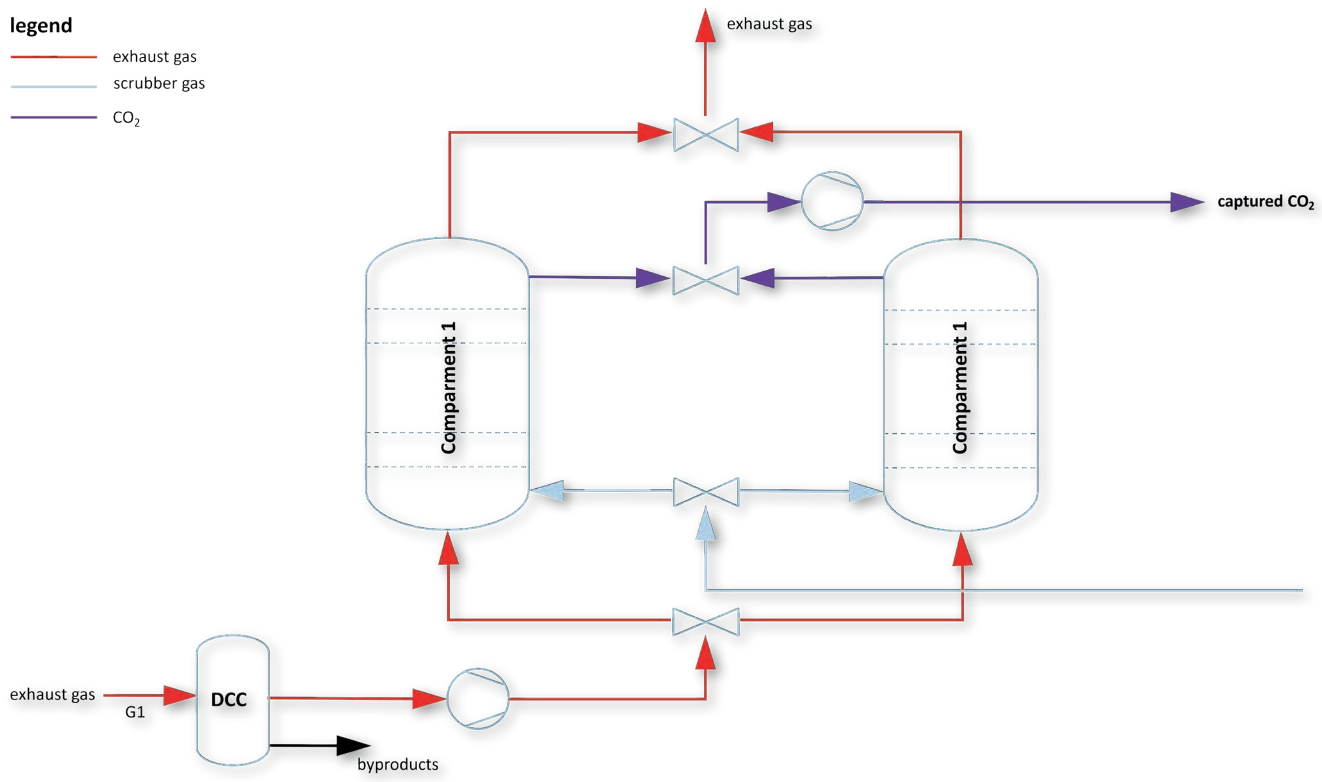
Vacuum Pressure Swing Adsorption (VPSA)

VPSA combines the principles of PSA and VSA, where CO_2 is adsorbed under vacuum and desorbed under pressure. The reversal, i.e. the dissolution of the CO_2 from the sorbent, takes place in vacuum pressure swing adsorption by means of a pressure difference between adsorber and desorber.

In vacuum pressure swing adsorption, two vessels are cyclically filled with MOF pellets (or other solid sorbents), which alternately act as adsorbers or regenerators. The engines' exhaust gas is initially brought to the necessary process temperature of approx. 20-60 °C by a Direct Contact Cooler (DCC). In this step, the DCC also removes particles from the flue gas. The flue gas is then compressed and fed into the adsorber, where it comes into contact with the sorbent. Due to the properties of the sorbent, the CO_2 sticks to it. When the sorbent is saturated, i.e. loaded with CO_2, the valve switches over and the flue gas is led into the other container. In the first container, the CO_2 is now released from the sorbent by means of a vacuum, which can be fed to the storage by supplying a purge gas, ambient air.

It should be noted that due to the adhesion of the CO_2 to the surface of the sorbent, a technically necessary exhaust gas purification is to be expected in the case of combustion with heavy fuel oil, as happens predominantly in shipping.

Figure 9 - Flow diagram of the Vacuum Pressure Swing Adsorption (VPSA) process



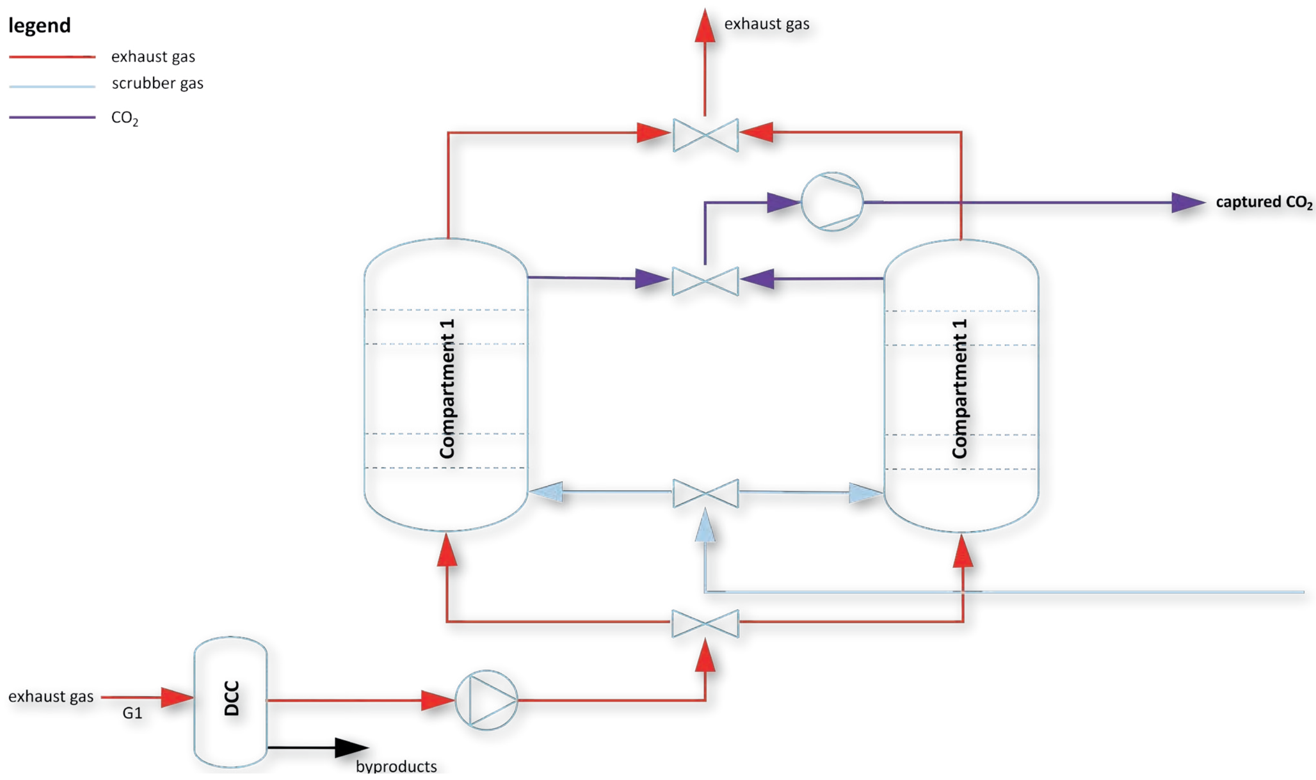
Vacuum Swing Adsorption (VSA)

VSA involves the adsorption of CO_2 under vacuum and desorption by reducing the vacuum, allowing for cyclic operation. The reversal, i.e. the dissolution of the CO_2 from the sorbent, takes place in vacuum swing adsorption by means of negative pressure in the desorber.

In vacuum swing adsorption, two vessels are cyclically filled with MOF pellets (or other solid sorbents), which alternately act as adsorbers or regenerators. The engines' exhaust gas is initially brought to the necessary process temperature of approx. 55-75 °C by a Direct Contact Cooler (DCC). In this step, the DCC also removes particles from the flue gas. In its function as an adsorber, the flue gas is fed under atmospheric pressure, whereby the CO_2 combines with the sorbent. When the sorbent is saturated, i.e. loaded with CO_2, the valve switches over and the flue gas is fed into the other container. In the first container, the CO_2 is now released from the sorbent by means of a vacuum, which can then be fed into the storage system.

It should be noted that due to the adhesion of the CO_2 to the surface of the sorbent, a technically necessary exhaust gas cleaning is to be expected in the case of combustion with heavy fuel oil, as happens predominantly in shipping.

Figure 10 - Flow diagram of the Vacuum Swing Adsorption (VSA) process



Gas-Solid Reaction

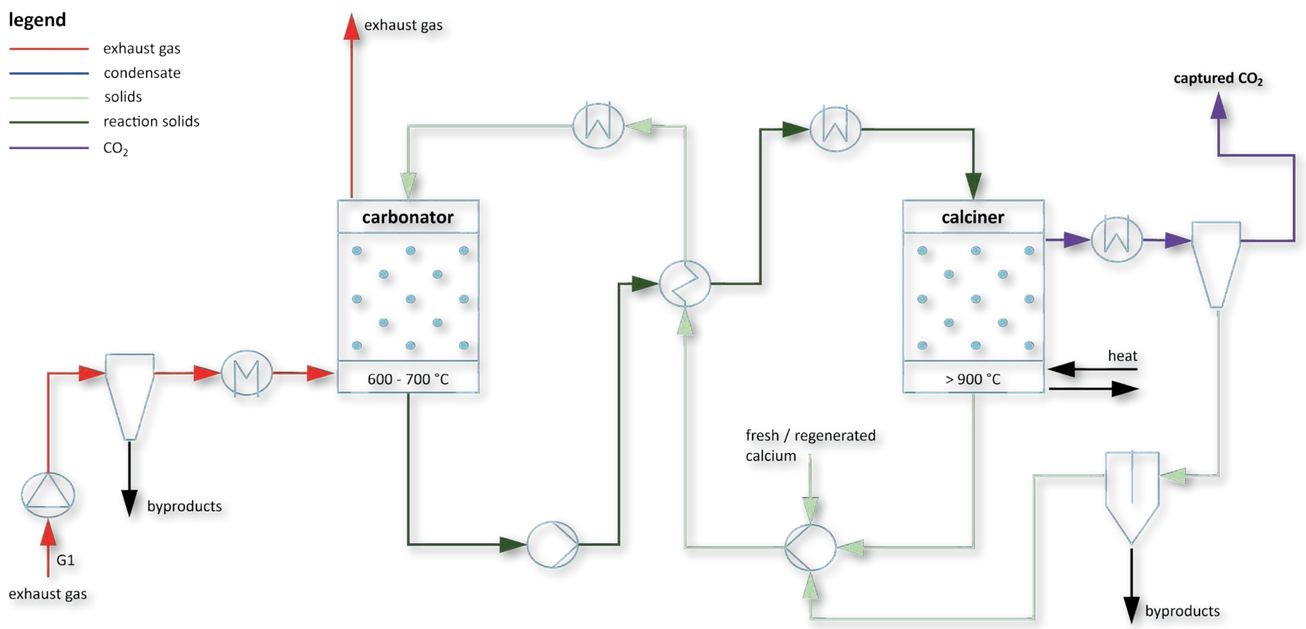
Gas-solid reaction involves the reaction of CO_2 with a solid adsorbent, leading to the formation of a stable compound, such as metal carbonate, and subsequent regeneration of the adsorbent by changing the conditions, such as temperature or pressure. The gas-solid reaction is a dry sorption in which mostly solid alkaline earth oxides such as calcium (Ca) react chemically with CO_2 to form carbonates (calcium carbonate- $CaCO_3$).

The engines' exhaust gas is separated from particles in a cyclone and then preheated in a heat exchanger. Particles > ~100 µm should be separated, otherwise they would clog the pores of the calcium in the carbonator and prevent the CO_2 from entering the pores (Valverde, 2018, p. 15). Once the solid reaction has formed in the carbonator, at a process temperature of ~ 600-700 °C, it is heated using a heat exchanger before entering the calciner.

In the calciner, the process temperature is heated to over 900 °C, which reverses the chemical reaction and dissolves the CO_2. The concentrated CO_2 is cooled in a heat exchanger and separated from solids in a cyclone. The CO_2 is then sent for storage. The solids are separated from sulphur compounds on their way to the carbonator, mixed with fresh material (make-up) and cooled by heat exchangers. The reaction cycles are negatively affected by the deactivation of the solid material through irreversible combination with sulphur (SO_2), which typically occurs in flue gases. Make-up is necessary to keep these reaction cycles constant (Valverde, 2018, p. 14). This process is demonstrated in Figure 11.

In marine application, if fuels with higher sulphur content are used, could result in the need for additional desulphurization / scrubber.

Figure 11 - Flow diagram of the Gas-Solid Reaction process



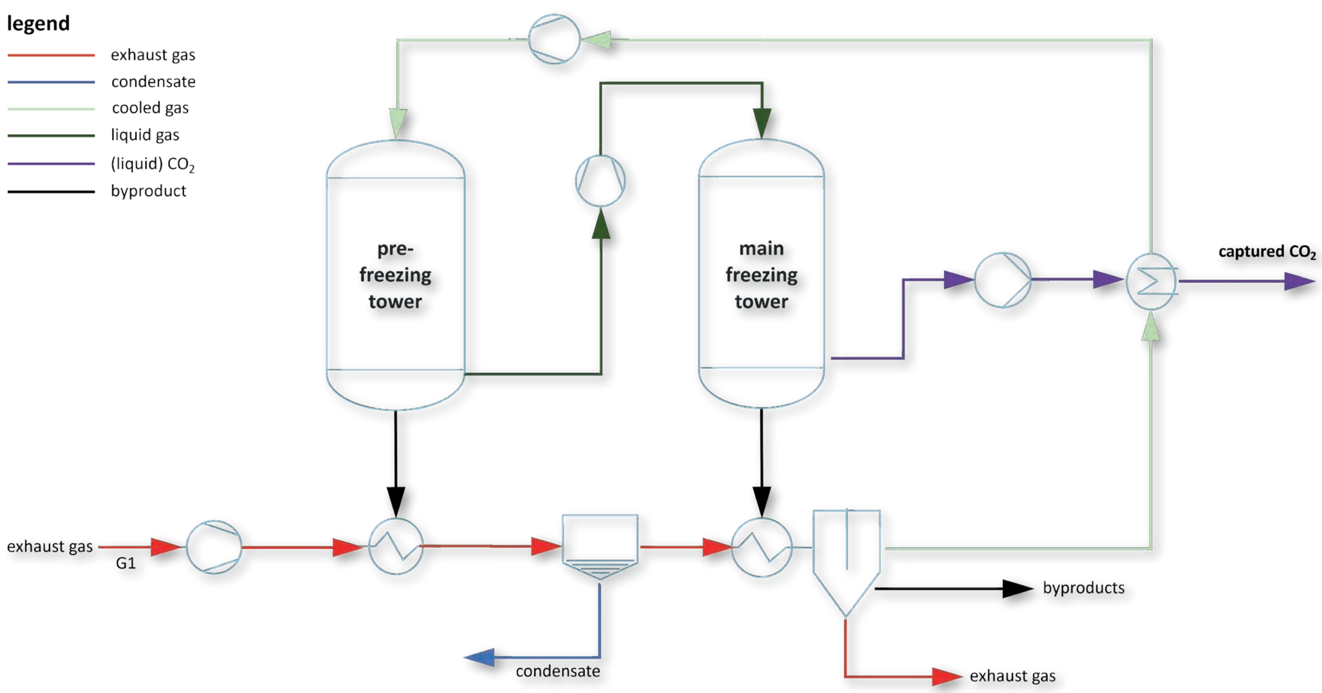
Cryogenic CO_2 Capture (CCC)

In the cryogenic process, the CO_2 is separated from the engines' exhaust gas by its physical properties. This is done by condensation, sublimation or distillation. It should be noted that the condensation and sublimation temperature of CO_2 must be higher than that of the other components in the exhaust gas. (Fischedick et al., 2015, p. 292).

The CCC technology, shown in Figure 12, separates CO_2 and other pollutants from flue gases by cooling the flue gas to about -130°C, at which temperature CO_2 forms a solid (dessublimates). For this purpose, the flue gas (G1) is compressed (~2 bar) (Song et al., 2017), pre-cooled by a heat exchanger, and then fed into the condensate separator. The flue gas is then further cooled in the second heat exchanger, which is fed by the main freezing tower. This enables subsequent gas separation, in which the flue gas and other by-products are separated. The gas with increased CO_2 content is cooled again by a third heat exchanger, which is fed by the liquid CO_2, before it enters the pre-freezing tower in compressed form. In this tower, the CO_2 purity (dry gas) is increased and he by-products are used to supply the first heat exchanger with cold. The dry gas is then compressed and finally separated in the main freezing tower by means of sublimation. While the by-products feed the second heat exchanger with cold, the liquid CO_2 is pumped for storage. On this path, the cold of approx. -130°C is used to further cool the crossing gas.

In summary, Cryogenic CO_2 capture is a process that involves the separation of CO_2 from a gas mixture using low-temperature conditions. CO_2 gas is cooled to very low temperatures, typically below its critical temperature, causing it to condense into a liquid or solid form, while other gases remain in the gaseous state. The condensed CO_2 can then be separated from the gas mixture and collected for storage. Cryogenic CO_2 capture is energy-intensive due to the low temperatures required, but it has high efficiency in capturing CO_2 and can achieve high purity levels. The resulting low-temperature condensed CO_2 is at an optimum temperature level for storage onboard and does not require any additional cooling compared to other capture technologies.

Figure 12 - Flow diagram of the cryogenic CO_2 capture (CCC) process



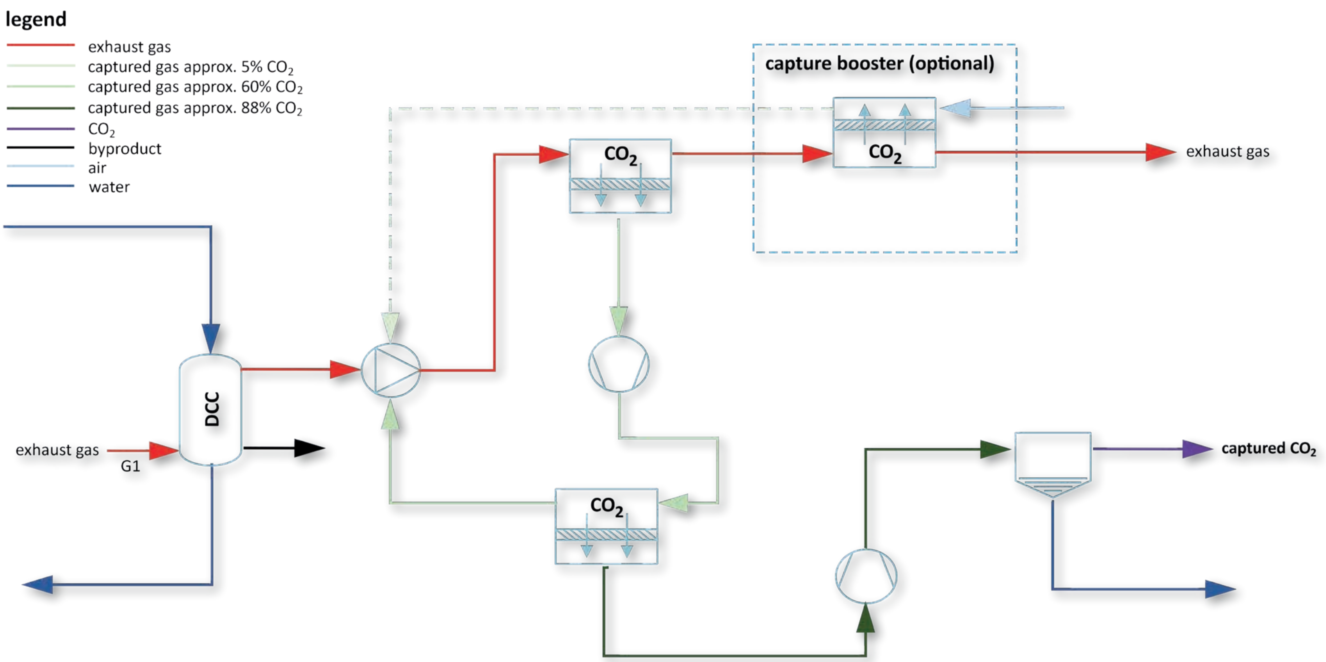
Membrane CO_2 Capture

Membrane CO_2 capture is a process that utilizes selectively permeable membranes to separate CO_2 from a gas mixture. These membranes have selective properties that allow CO_2 to pass through while blocking other gases. The driving force for separation is typically the difference in partial pressure or concentration of CO_2 on either side of the membrane. Membrane CO_2 capture is a relatively simple and energy-efficient process, with potential for scalability and flexibility. However, the selectivity and permeability of membranes can be influenced by various factors, such as temperature, pressure, and gas composition, which may affect the overall performance of the process.

The engines' exhaust gas (G1) is cooled to the required process temperature of usually 25-50 °C in the DCC (Direct Contact Cooler), which can filter the flue gas if necessary to adapt the flue gas properties to the separation technology. This includes especially larger particles that would otherwise block the membrane surface. Depending on the emission source and the application, an additional flue gas cleaning system may be necessary. The gas flow is then passed through the membrane, in which a negative pressure prevails on the permeable side. Due to this negative pressure and the membrane property, the CO_2 is directed to the permeable side. The now CO_2-reduced flue gas can be released into the environment. Depending on the desired separation rate, an optional membrane circuit can be added to increase this rate. At the same time, this circuit increases the CO_2 concentration in the flue gas and has a positive influence on the subsequent membrane CO_2 separations.

Following the first membrane, the gas is fed at approximately 15% into the second membrane, where the CO_2 is again further separated by means of negative pressure. The gas components that are not separated are returned to the flue gas after the DCC, which improves the CO_2 inlet concentration. On the permeable side of the membrane, the CO_2 now has a purity of approx. 88 % and is still dried before storage (see Figure 13).

Figure 13 - Flow diagram of the membrane CO_2 capture process



Technical Specification Guide for CO_2 Capture on Board of Ships

Chapter 2

Technical Specification Guide for CO_2 Capture on Board of Ships

Having established an extensive overview of available CO_2 separation and capturing technologies, we now move towards the specifications required for the use of CO_2 capturing on board of ships.

In order to identify which technologies can be utilized in the maritime industry, this chapter focuses on defining a technical specification guide. This guide defines the conditions under which the carbon capture technology must function when installed / retrofitted in a ship, taking into consideration the exhaust gas values of the ship.

In a first step, we consider a list of general factors that are deemed relevant to the possible deployment of CO_2 technologies on board of ships. These are follows:

- Technological Readiness Level
- Data availability
- Plant inlet pressure
- Exhaust gas temperature after turbocharger
- Exhaust gas temperature after boiler
- CO_2 purity
- CO_2 capture rate
- CO_2 temperature before storage
- Energy demand
- Reactent solvent consumption
- Waste gas pre-treatment
- Space requirements

We apply these factors to our overview of technologies available for carbon separation and capture, independent of whether they were developed for maritime application or their level of commercialisation.

The data collected on these technologies was derived from an extensive literature review, and where available, extended by individual project case studies.

Table 2 provides an overview of the scores allocated to the various technologies, when considering an end-use application on board of a ship.

Out of the 25 technologies evaluated, the KS-1 / KS-21 solvent absorption technology scored the highest with a total of 183 points. From the relevant criteria, it scored full points on technological readiness level (TRL = 9), data availability, entry pressure, CO_2 purity, CO_2 capture rate and no requirements for exhaust pre-treatment. Areas of challenges for this technology exist in respect to the exhaust temperature after the turbocharger and boiler as well as with the CO_2 temperature before storage and general energy consumption. The solvent absorption technology was followed in ranking by the cryogenic technology demonstrated in the Cryogenic Carbon Capture project with 163 points and the cryogenic technology used in the A3C project with 155 points. Even though both cryogenic technologies exhibit significantly lower technological readiness level (TRL 5 and 3 respectively), they scored full points on entry pressure, CO_2 purity, CO_2 capture rate, and solvent consumption.

The technology that scored the lowest was the Polyactive Membrane technology with 58 points and the supported ionic liquid membrane technology with 68 points. Even though, both technologies scored high on the entry pressure, they scored specifically low on the CO_2 purity and capture rate criteria.

Table 2 - Technical evaluation of available CO_2 separation and capturing technologies

Technology	Subtechnology	Project	Technology Readiness Level	Data Availability	Plant Inlet Pressure	Exhaust Gas Temperature after TC	Exhaust Gas Temperature After Boiler	CO_2 Purity	CO_2 Capture Rate	CO_2 Temperature Before Storage	Energy Demand	Solvent Consumption	Exhaust Gas Pre-Treatment	Space Requirement	**Overall Qualification Score**
Absorption	Amine Absorption	APBS-CDRMax	◕	●	●	◔	◔	◑	●	◔	○	n/a	◑	○	◑ 123
Absorption	Amine Absorption	Ecoamina FG Plus	●	●	●	◔	◑	◑	●	n/a	○	n/a	○	○	◑ 109
Absorption	KS-1/KS-21 Solvent Absorption	KM CDR Process	●	●	●	◔	◑	●	●	◑	◑	n/a	●	○	● 183
Absorption	Monoethanolamine Solvent Absorption		◕	●	●	◔	◔	n/a	●	n/a	○	n/a	◔	○	◔ 103
Absorption	Amine Absorption	Shell Cansolv	●	●	●	n/a	n/a	●	●	n/a	◔	◕	◔	○	◑ 129
Absorption	Amine Absorption	Simulation for IMO Req.	◔	●	●	○	◔	●	◑	◑	○	n/a	◔	○	◔ 94
Adsorption	TSA Amine Bound Resin	ADAsorb	◑	◑	●	◔	◔	○	●	◔	n/a	●	○	n/a	◔ 92
Adsorption	PSA Zeolite 13X	CO2-PSA	◕	◕	◑	○	○	◑	◕	◑	n/a	●	○	n/a	◔ 88
Adsorption	TSA Potassium Carbonate Sorbent	Hadong Plant - Korea	◑	◑	●	◔	◑	◑	◕	◔	○	●	●	○	◕ 136
Adsorption	VPSA Activated Carbon		◔	◑	◕	○	●	◕	◑	n/a	●	●	○	n/a	◑ 109
Adsorption	VPSA Zeolite		◑	◑	◕	◔	◔	○	●	◔	◑	●	○	n/a	◑ 108
Adsorption	VSA Amine Grafted Porous Silica		◔	◑	●	◔	◑	◕	●	◔	◕	●	○	n/a	◑ 131
Adsorption	Sodium Carbonate Absorption		◔	◔	●	○	◔	◑	●	n/a	◕	n/a	●	○	◕ 136
Calcium Looping		CaL Process	◑	◕	●	◔	○	●	◕	○	n/a	n/a	●	◑	◕ 136
Calcium Looping		Calix Recast	◔	◑	●	◔	○	●	◑	n/a	●	n/a	●	◔	◕ 151
Calcium Looping		TU Darmstadt	◑	◕	●	◔	○	●	◕	○	n/a	n/a	●	○	◑ 122
Cryogene		A3C	◔	◕	●	○	◔	●	●	◑	◕	●	○	◕	◕ 155
Cryogene		AntiSublimation	◑	◕	●	◔	◕	●	◕	◑	◕	●	○	n/a	◕ 147
Cryogene		Cryogenic Carbon Capture	◑	◕	●	◔	◑	●	●	◑	n/a	●	◕	◑	● 163
Cryogene		Cryogenic Stirling Coolers	◑	◕	●	◔	◔	●	●	●	◕	●	○	n/a	◕ 152
Membran	PolyActive Membrane		◕	◕	◕	○	◔	○	○	◑	n/a	n/a	○	n/a	○ 58
Membran	Four Step Hollow Fibre Membrane System		◑	◕	●	○	◔	◕	●	◑	n/a	n/a	○	n/a	◔ 94
Membran	Supported Ionic Liquid Membrane (SLIM)		◔	◕	●	○	◔	○	○	◔	n/a	n/a	◑	n/a	○ 68
Membran	Spiral Wound Amine Facilitated Transport		◔	◕	●	◔	◑	◕	○	◔	n/a	n/a	◔	n/a	○ 77
Membran	Three Step Amine Facilitated Membrane		◑	◕	●	○	◔	◕	●	◑	◑	●	◔	◔	◕ 143

Table 3 - Legend of technical evaluation of available CO_2 separation and capturing technologies

	Technology Readiness Level	Data Availability [data points]	Plant Inlet Pressure [mbar]	Exhaust Gas Temperature after TC [°C]	Exhaust Gas Temperature After Boiler [°C]	CO_2 Purity [%]	CO_2 Capture Rate [%]	CO_2 Temperature Before Storage [°C]	Energy Demand [kWh/t CO_2]	Solvent Consumption [kg/t CO_2]	Exhaust Gas Pre-Treatment [WPSN] *	Space Requirement [TEU]
Weighting Factor	5	6	4	5	5	3	7	4	10	3	10	7
Requirement	>8	>400	1013	350	145	>98	>90	< -78.5	<300	0	n/r	n/r
Evaluation Unit			+/-%	+/-%	+/-%							
●	8-9	>400	<10	<10	<10	>98	>90	<-78.5	<300	0	0	0**
◕	6-7	>199	<31	<31	<31	>94	>80	<-56.5	>299	<0.30	1	<10
◑	4-5	>99	<61	<61	<61	>89	>70	<32.0	>499	<0.51	2	<29
◔	2-3	>49	<91	<91	<91	>84	>60	<151	>799	<0.81	3	<41
○	1	<50	>90	>90	>90	<85	<61	>150	>900	>0.80	4	>40
Notes	* W: water / P: particle / S: SOx / N: NOx // e.g. ‚2‘ means two out of 4 ** ‚0‘: the treatment plant can be integrated within existing vessel structure											

When evaluating available carbon capture technologies for on-board CO_2 capturing – either for new builds or for retrofitting on existing ships, we have to be aware of the existing ship design, vessel operating and trading pattern, fuel usage, electrical load balance and finally space availability for captured CO_2.

We have established these ship-operation specific criteria:

- Technological Readiness Level (TRL)
- Fuel used (e.g. HFO)
- Treated exhaust gas amount
- Concentration of CO_2 in the exhaust gas
- CO_2 capture rate
- CO_2 temperature after capturing
- Electrical energy demand
- Thermal energy demand
- Process solvent consumption
- Possibly-required pre-treatment of the exhaust gas
- Space requirement

The full technical specification guide can be found in Chapter 3.

Benchmarking & Evaluation of CO_2 Capturing Technologies for Ships

Chapter 3

Benchmarking & Evaluation of CO_2 Capturing Technologies for Ships

In the previous chapter we concluded with defining a technical specification guide for the utilization of CO_2 capturing technologies on board of ships. This chapter now focuses on evaluating the previously identified technologies for their fit in maritime applications.

The vessel-specific criterial have been applied using a weighting function specific to a ship operation point-of-view. For example, the purity of captured CO_2 is significantly less important than the electrical energy demand required for capturing or the space required to retrofit a capture plant on board of a ship. However, it should be noted that weights applied are not an objective criterion and might change depending on e.g. vessel type or trading pattern. We therefore highly recommend using the dashboard available at ccs.engship.com – it allows users to distribute different weightings resulting in a tailored analysis for their specific context.

Overview of existing and ongoing CO_2 capturing projects

In a second step, a survey was conducted to identify companies providing CO_2 capturing technologies and currently ongoing carbon capture projects using different technologies. These projects come from various industries and are not necessarily specific to the maritime industry. Based on the previously defined technical specifications and weights, the various capture technologies will be benchmarked in order to provide more transparency on their utilization potential for shipping.

Based on our own technical specification guide, we attributed various weights to the technical criteria in order to evaluate existing projects. The weighting is reflective of the importance we attributed towards the criterion for the use of the technology on a ship and captures a scale of 1-10. Again, this weighting, and thereby the results, can vary depending on ship-specific factors. The weighting applied in this study is as follows:

Table 4 - specified weightings applied to evaluate ongoing CO_2 caputring projects

	Technology Readiness Level	Data Availability [data points]	Plant Inlet Pressure [mbar]	Exhaust Gas Temperature after TC [°C]	Exhaust Gas Temperature After Boiler [°C]	CO_2 Purity [%]	CO_2 Capture Rate [%]	CO_2 Temperature Before Storage [°C]	Energy Demand [kWh/t CO₂]	Solvent Consumption [kg/t CO₂]	Exhaust Gas Pre-Treatment [WPSN] *	Space Requirement [TEU] **
Weighting Factor	5	6	4	5	5	3	7	4	10	3	10	7
Requirement	>8	>400	1013	350	145	>98	>90	< -78.5	<300	0	n/r	n/r
Evaluation Unit			+/-%	+/-%	+/-%							

* W: water / P: particle / S: SOx / N: NOx // ‚n/r': not required / e.g. ‚2' means two out of 4
** ‚n/r': not required - the treatment plant can be integrated within existing vessel structure

The following Table 5 provides an overview of ongoing CO_2 capturing projects and their evaluation based on our weighted criteria selection.

For a full description of the criteria and associated weighting, please see Table 6.

Table 5 - Summary of ongoing CO_2 capturing projects and their ranking

Project	Technology Readiness Level	Fuel Tested	Treated Exhaust Gas Amount	CO_2 Concentration in Exhaust Gas	CO_2 Capture Plant Inlet Pressure	CO_2 Capture Plant Inlet Temperature	CO_2 Purity	CO_2 Capture Rate	CO_2 Temperature Before Storage	Energy Demand - Electrical	Energy Demand - Thermal	Solvent Consumption	Exhaust Gas Pre-Treatment	Space Requirement	Technology Applied *	**Overall Qualification Score**
Carbon Capture Cyclone	◕	n/a	n/a	●	n/a	◔	●	◕	◔	n/a	○	◕	◔	n/a	AB	◔ 2.8
CC-Ocean	n/a	●	○	n/a	n/a	◔	●	◔	◔	n/a	n/a	n/a	n/a	●	AB	◔ 2.5
CC2asts / Cruise Ship	◑	◑	n/a	n/a	n/a	◔	◕	◔	◔	●	○	n/a	◔	●	AB	◑ 3.8
CC2asts / Dredger	◑	◑	n/a	n/a	n/a	◔	◕	○	◔	●	○	n/a	◔	●	AB	◑ 3.6
CC2asts / Sea-River Vessel	◑	◑	n/a	n/a	n/a	◔	◕	◑	◔	◕	○	○	◔	●	AB	◑ 4.0
DerisCO2	◑	◑	◕	●	●	◔	◕	◔	◔	●	○	◕	◔	○	AB	◕ 4.7
EverLoNG	◕	◑	○	●	●	◔	◕	n/a	◔	●	○	◔	◔	n/a	AB	◑ 3.8
Filttree	●	●	◕	n/a	●	◔	n/a	○	n/a	n/a	n/a	n/a	n/a	●	AB	◑ 3.6
IMO 2030 Case	◑	◕	◔	n/a	●	◔	◕	◕	◔	●	○	◑	◔	n/a	AB	◑ 4.4
OASE® blue	●	n/a	n/a	n/a	◕	◔	●	◕	n/a	n/a	○	◑	◕	n/a	AB	◑ 3.3
Offshore Just-Catch	n/a	n/a	n/a	n/a	n/a	n/a	●	◕	n/a	n/a	n/a	n/a	n/a	◔	AB	○ 1.3
Pentair	●	●	◔	n/a	●	◑	◕	●	◔	●	○	○	◕	n/a	AB	◕ 5.8
Alfa Laval PureSOx	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	AB	○ 0.0
Saipem	●	○	n/a	◕	●	○	●	◕	◔	●	○	●	○	n/a	AB	◑ 4.1
Wärtsilä	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	AB	○ 0.0
Yara	◔	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	AB	○ 0.0
Polaris	◕	○	◕	n/a	○	◔	●	◕	◑	◕	n/a	●	◔	●	ME	◕ 5.0
PSA Process	n/a	○	○	◑	○	○	◔	◕	◑	n/a	○	n/a	◑	n/a	AD	◔ 1.8
MemKor	◕	○	○	n/a	●	◔	◕	◔	◔	●	n/a	●	◑	n/a	ME	◑ 3.9
Calix RECAST	◔	●	n/a	●	●	◔	●	◔	◑	●	●	n/a	●	○	CL	◕ 6.0
A3C	◔	●	n/a	●	●	○	●	◕	◑	◕	n/a	●	○	○	CR	◑ 4.3
Future Funnel	◑	n/a	n/a	n/a	●	n/a	●	◕	n/a	n/a	n/a	●	●	n/a	CR	◑ 3.5

* AB: Absorption / AD: Adsorption / CL: Calcium Looping / CR: Cyrogene / ME: Membrane

Table 6 - Criteria legend applied for evaluation of ongoing CO_2 capturing projects

	Technology Readiness Level	Fuel Tested *	Treated Exhaust Gas Amount [m³/h]	CO_2 Concentration in Exhaust Gas [Vol %]	CO_2 Capture Plant Inlet Pressure [mbar]	CO_2 Capture Plant Inlet Temperature [°C]	CO_2 Purity [%]	CO_2 Capture Rate [%]	CO_2 Temperature Before Storage [°C]	Energy Demand - Electrical [kWh/t CO_2]	Energy Demand - Thermal [kWh/t CO_2]	Solvent Consumption [kg/t CO_2]	Exhaust Gas Pre-Treatment [WPSN] **	Space Requirement ***
Weighting Factor	5	6	7	3	4	5	3	7	4	9	7	3	10	7
Requirement	>8	HFO	125k	>5.8	1013	350	>98	>90	-78.5	<350	<50	0	n/r	n/r
Evaluation Unit				%	%	%								*** TEU
●	8-9	HFO	>125k	<5.8	<=5	<=10	>98	>90	<= -78.5	<350	<50	0	0	0
◕	6-7	MDO	<=125k	>=5.8	>5	>10	<=98	<=90	<= -56.6	<=500	<=100	<=0.3	1	<=10
◑	4-5	LNG	<=70k	>=10	>=30	>=30	<=94	<=80	<=31	<=650	<=150	<=0.5	2	<=28
◔	2-3	Meth.	<=30k	>=15	>=60	>=60	<=90	<=70	<=150	<=800	<=200	<=0.8	3	1T28
○	1	+	<1k	>20	>90	>90	<85	<61	>150	>800	>200	>0.8	4	2T28

Notes

* +: no commerical marine fuel / Meth.: Methanol

** W: water / P: particle / S: SOx / N: NOx // e.g. ‚2' means two out of 4; ‚0': the treatment plant can be integrated within existing vessel structure

*** 2T28: 2 towers of each >30m height plus max 28 TEU space; 1T28: 1 twoer of max 30m height, plus max 28 TEU space

Overall, our survey identified 22 companies or projects deploying CO_2 capturing technologies. From these, the project "Calix RECAST" scored the highest with 6.0 points. It achieved highest scores as heavy fuel oil (HFO) was used as fuel, a low CO_2 flue gas concentration of <5.8%, plant inlet pressure in the range of 1012 mbar (+/- 5%) and achieving a captured CO_2 purity of nearly 100 %. Furthermore, the "Calix RECAST" scored highest in terms of energy demand (both thermal and electrical) and do not require any exhaust gas pre-treatment.

The "Pentair" project also scored high by TRL, fuel used, inlet process pressure and CO_2 capture rate and electrical energy requirement. Several companies or projects scored in the lower range; however, as visible in the table, this is often due to missing or undisclosed data. At this point we would like to emphasise the importance of transparency and encourage carbon capture companies and project managers to contribute to this technology overview and make their data available.

Existing CO_2 capturing projects for shipping

In a final evaluation step, we applied our technical specifications as well as weighted criteria to CO_2 capture projects focusing on applicability on a 1'000 TEU container feeder (Table 7).

Unfortunately, the analysis is greatly limited due to the incompleteness of data. Several technology providers could not provide us with their capture plant data in a format usable for this comparison; public by enforcing NDA requirements or providing incomplete feedback.

As a result, the performance of a listed technology solution or provider might skewed to in both directions, or a solution or provider might not be listed at all as it was not existent / replying at the time of data collection.

Table 7 -Scoring of CO_2 capturing projects with an application focus on shipping

Project	Technology Readiness Level	Fuel Tested	Treated Exhaust Gas Amount	CO_2 Concentration in Exhaust Gas	CO_2 Capture Plant Inlet Pressure	CO_2 Capture Plant Inlet Temperature	CO_2 Purity	CO_2 Capture Rate	CO_2 Temperature Before Storage	Energy Demand - Electrical	Energy Demand - Thermal	Solvent Consumption	Exhaust Gas Pre-Treatment	Space Requirement	Technology Applied *	**Overall Qualification Score**
DerisCO2	◑	●	n/a	●	●	◔	◕	◔	◔	●	○	◑	n/a	◕	AB	◑ 4.7
Filtree	n/a	◕	●	●	●	◔	n/a	n/a	n/a	n/a	n/a	n/a	◔	◕	AB	◑ 3.4
IMO – 2030	n/a	●	●	●	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	AB	◔ 2.0
OASE – BASF (1)	●	●	●	●	◕	◔	●	●	n/a	n/a	○	◑	◔	◕	AB	◕ 5.6
OASE – BASF (2)	●	●	◑	●	◕	◔	●	◕	n/a	n/a	○	◑	◔	◕	AB	◑ 4.9
Pentair	●	●	●	●	●	◔	●	◕	◑	●	○	○	○	n/a	AB	◕ 5.7
Saipem	n/a	●	●	●	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	AB	◔ 2.0
Calix RECAST	◔	●	n/a	●	●	◔	●	◔	◑	●	●	n/a	●	n/a	CL	◕ 6.0
A3C	◔	●	n/a	●	●	○	●	●	◑	◕	n/a	●	○	n/a	CR	◑ 4.5
Teco2030 Carbon Capture	n/a	●	●	●	●	◑	●	n/a	◑	●	n/a	●	●	◕	CR	◕ 6.8
Memkor – Hereon (1)	◕	●	●	●	●	◑	○	◔	◑	◕	○	●	◑	◕	ME	◕ 6.3
Memkor – Hereon (2)	◕	●	●	●	●	◑	○	◔	◑	●	○	●	◑	◕	ME	◕ 6.5
Memkor – Hereon (3)	◕	●	●	●	●	◑	◔	◔	◑	◕	○	●	◑	◕	ME	◕ 6.3
Polaris	n/a	●	●	●	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	ME	◔ 2.0

* AB: Absorption / CL: Calcium Looping / CR: Cyrogene / ME: Membrane

In this current data context, we came to the conclusion that that the projects “Teco2030 Carbon Capture” using a cryogenic capturing technology and “Memkor – Hereon” using a membrane capture technology, present the most potential with an overall score of 6.8 and 6.5 respectively (out of 10 points achievable). Both projects scored specifically high through their possibility to use HFO as fuel, achieving high quantities of treated flue gas, a low CO_2 flue gas concentration of <5.8%, capturing plant inlet pressure suitable for diesel engines, and not consuming any process means. Despite the highest score, it is evident that we did not receive data on the TRL, CO_2 capturing rate or thermal energy demand for the “Texo2030 Carbon Capture”, which could skew the scoring.

Moving Forward

References

Moving forward

As noted throughout the study, a core limitation to this evaluation is data availability and disclosure. Unfortunately, we did not receive data for key data fields which can significantly impact the scoring of the projects.

Furthermore, it should be noted that the criteria were chosen in order to evaluate the potential of CO_2 capturing solutions for a variety of ships. Nonetheless, they are user specific and evaluation results could vary according to specific ship or a ship owner's needs.

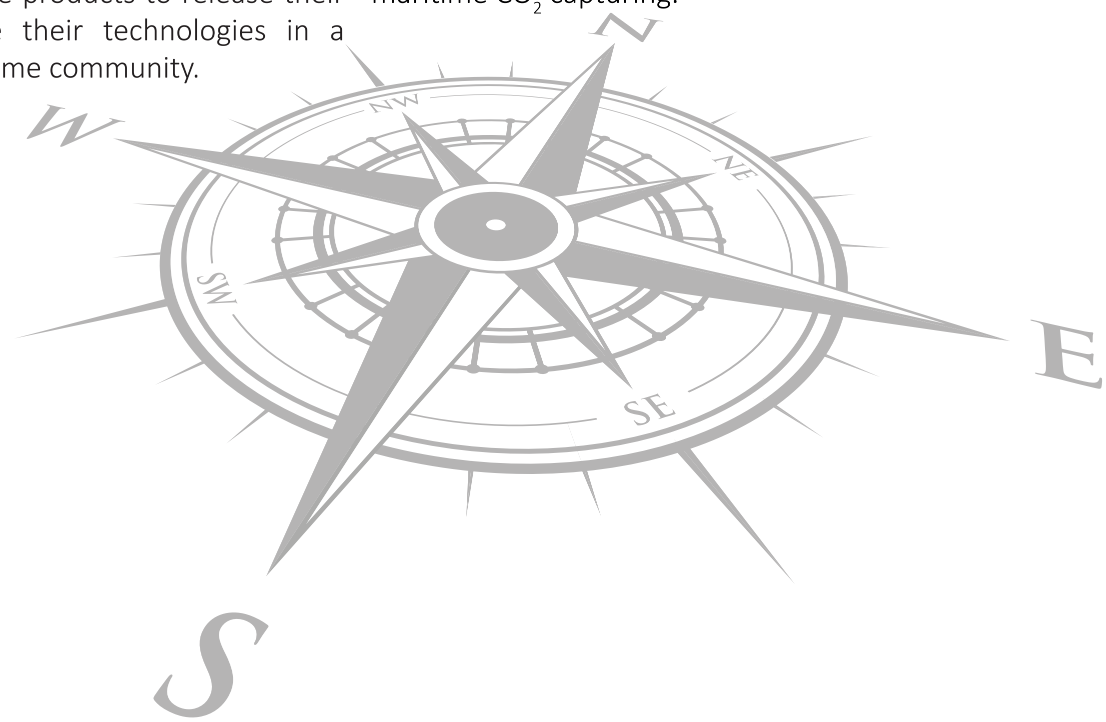
To provide both transparency and a tool for potential end-users, we have created a virtual dashboard, allowing you to enter your own weighting for the criteria and see the resulting evaluation. You can access the dashboard via this link (ccs.engship.com).

It is crucial for the maritime market to have access to transparent data in order to assess the best technology fit for their vessels and accelerate the deployment of CO_2 technologies on board of ships. It is thereby absolutely necessary for owners of technologies and capture products to release their data and communicate their technologies in a transparent to the maritime community.

Despite the data limitations, our study has set the ground for a direct comparison of CO_2 capturing on board of ships and developed the means to score technologies for their fit to be deployed in the maritime sector.

We will continue to survey providers and will receive technology updates throughout, enabling us to continuously update the CCS online dashboard resulting in a fair demonstration of maritime carbon capture capabilities.

Going forward, it is our aim to provide a transparent and reflective overview of CO_2 capturing technologies appropriate for maritime applications. We aim to extend the analysis beyond the technological fit, by identifying the market potential and new business model opportunities resulting from the capturing of CO_2 – such as deploying the captured CO_2 in Power-to-X processes. Further research will therefore focus on determining the scientific and technical resources, as well as cooperation partners and thereby determine the market potential for maritime CO_2 capturing.



References

This whitepaper is based on a number of academic and market literature, as well as individual surveys and interviews conducted with companies. Due to NDAs we cannot openly share the full list of companies we have surveyed.

To inquire if company specific details can be shared, please mail us at contact@enghsip.com

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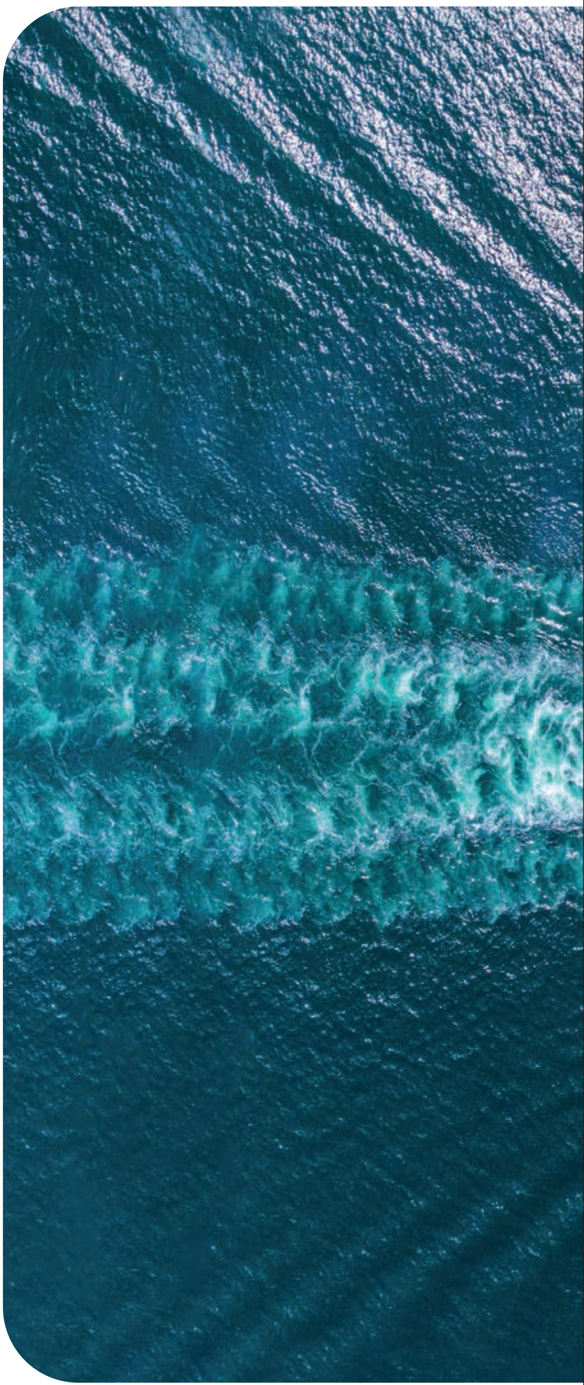


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