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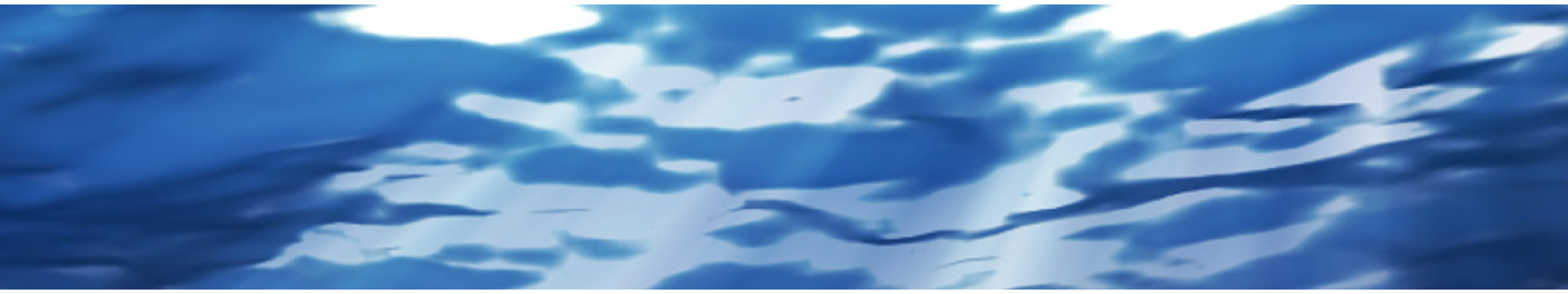

LIGHTHOUSE REPORTS

Carbon capture potential on-board ships

En förstudie utförd inom Trafikverkets branschprogram Hållbar sjöfart som drivs av Lighthouse. Publicerad april 2023

TRAFIKVERKET

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HÅLLBAR
SJÖFART

Carbon capture potential on-board ships

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A pre-study carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

Summary

This study summarizes information related to carbon capture (CC) technologies with potential to be installed on-board ships. Fuels containing carbon is likely to be used on-board ships for many years to come. Carbon capture is, in general, seen as a prerequisite to meet future greenhouse gas GHG emissions targets.

So far, few real installations of CC on-board vessels have been seen. Thus, this measure is still on a pilot scale for shipping.

The estimated costs, found in the literature, for on-board installations of CC have a large spread and range from estimates less than €100 per ton CO_2 up to almost €300 per ton CO_2 captured, liquified and stored on-board. This study finds that it seems technically and economically possible to install CC on-board ships, under the right circumstances, as long as decarbonisation policy measures for shipping continue to develop and technical development of on-board CC continues. Costs for the introduction of CC on-board ships needs to be compared with alternative measures such as switching to e-methanol, renewable hydrogen etc. As example, Brynolf et al., (2022) estimate carbon abatement cost for liquefied hydrogen in shipping of €220–€850 per ton CO_2 and abatement cost for different electrofuels at €150–€1250 per ton CO_2, with combined bio-methanol and electro-methanol in the lower range.

However, the future costs associated with the delivery of the captured CO_2 ashore, transportation and final storage is still difficult to assess and is one of the key questions to explore further.

There is a lot of work ongoing, related to the technical development of carbon capture which will likely lead to decreased capturing costs and improved technical performance.

Three post-combustion CC technologies have been identified as most feasible, and promising, for the application on-board in combination with ICEs: absorption by ammonia (NH_3), cryogenic separation and membrane separation. However, post combustion capturing with the chemical solvent MEA is the most common technical solution being assessed and described in the literature for on-board capturing. And CC with MEA is also widely used as benchmark process for comparisons between CC technologies.

Sammanfattning

Denna studie sammanfattar insamlad och bearbetad information kring koldioxidavskiljningsteknik (CC) med potential att installeras ombord på fartyg. Fossila bränslen kommer sannolikt att användas ombord på fartyg under många år framöver. Och koldioxidavskiljning ses som en förutsättning för att uppfylla framtida mål för utsläpp av växthusgaser generellt men även inom sjöfart.

Hittills har få verkliga installationer av CC-fartyg ombord utförts. Och alla projekt hittills för sjöfart har fortfarande varit i pilotskala.

De uppskattade kostnaderna, som identifierats i litteraturen, för installationer ombord av CC har en stor spridning och sträcker sig från uppskattningar på mindre än 100 € per ton CO_2 upp till nästan 300 € per ton CO_2 som fångas upp, förvätskas och lagras ombord. Denna studie finner att det är tekniskt och ekonomiskt möjligt att installera CC ombord på fartyg, under rätt omständigheter, så länge som styrmedel mot minskade växthusgaser för sjöfarten fortsätter att utvecklas och att den tekniska utvecklingen av CC ombord fortsätter. Kostnader för introduktion av CC ombord på fartyg behöver jämföras med alternativa åtgärder som att byta till e-metanol, förnybar vätgas etc. Som exempel uppskattar Brynolf et al., (2022) kostnaden för övergång till vätgasdrift (lagrat i flytande form) i sjöfarten till 220–850 € per ton CO_2-reduktion och reduktionskostnad för olika elektrobränslen på 150–1250 € per ton CO_2 reduktion, med biometanol och elektrometanol i det lägre intervallet.

De framtida kostnaderna för att leverera i land den infångade koldioxiden och för vidare transport och slutlagring är dock fortfarande svårbedömda och är en av nyckelfrågorna att utforska ytterligare.

Det pågår mycket arbete relaterat till den tekniska utvecklingen av kolavskiljning, vilket sannolikt kommer att leda till minskade avskiljningskostnader och förbättrad teknisk prestanda.

Tre efterbehandlingsmetoder (post-combustion) CC-teknologier har identifierats som mest genomförbara och lovande för applikationer ombord i kombination med förbränningsmotorer (ICE). Dessa är absorption med ammoniak (NH_3), kryogen separation och membranseparation. Infångning efter förbränningen med det kemiska absorbentmedlet MEA är dock den vanligaste tekniska lösning som bedöms och beskrivs i litteraturen för infångning ombord. Och CC med MEA används också i stor utsträckning som benchmark för jämförelser mellan CC-tekniker.

Contents

Abbreviation list

A3C	Advanced Cryogenic Carbon Capture
ASU	Air Separation Unit
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenses
CC	Carbon Capture
CCC	Cryogenic Carbon Capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CFG	Compressed Flue Gas
DWT	Deadweight Tonnage
ECL	External Cooling Loop
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
e-fuel	Electrofuel
GHG	Greenhouse Gas
GM	Metacentric Height
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IGCC	Integrated coal Gasification Combined Cycle
IMO	International Maritime Organization
LBG	Liquid Bio (methane) Gas
LCOE	Levelized Costs Of Electricity
LNG	Liquid Natural Gas
MC	Membrane Contactor
MGO	Marine Gas Oil
MGS	Membrane Gas Separation
MOF	Metal Organic Framework
OPEX	Operational Expenses
PM	Particulate Matter
PSA	Pressure-Swing-Adsorption

TRL	Technology Readiness Level (1 to 10 where 1 indicates that the basic principle of the technique is observed and 10 that the actual system is proven in operational environment)
TSA	Temperature-Swing-Adsorption
VSA	Vacuum-Swing-Adsorption
WGS	Water Gas Shift reactor

Chemical formulae

$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
CH_4	Methane
CO_2	Carbon Dioxide
H_2	Hydrogen
HCl	Muriatic Acid
Hg	Mercury
K_2CO_3	Potassium Carbonate
MDEA	Monodiethanolamine
MEA	Monoethanolamine
N_2	Nitrogen
N_2O	Nitrous Oxide
$NaOH$	Sodium Hydroxide
NH_3	Ammonia
NO_2	Nitrogen Dioxide
NO_X	Nitrous Oxides
O_2	Oxygen
PZ	Piperazine
SO_2	Sulphur Dioxide
SO_X	Sulphurous Oxides

1 Introduction

The whole energy supply sector, including energy for ships, is under a large restructuring from fossil fuels towards renewable and clean fuels with low or zero global warming contribution. Important to note is however that global shipping still consumes almost 100 percent fossil fuels. It is still too early to tell which are the renewable solutions that will be used in the future. Carbon capture combined with storage to avoid carbon dioxide (CO_2) emissions is more and more often pointed at as one of the needed solutions to include in the toolbox, to be able to meet the global greenhouse gas (GHG) emission targets, and therefore an important solution also to know more about in the shipping sector.

This study is initiated to give a better understanding about if on-board Carbon Capture (CC) can be a promising solution for shipping, despite the added complexity as well as pros and cons with different types of CC solutions.

1.1 Aim and motivation

The overall aim of this project has been to assess the potential of capturing carbon dioxides from the exhausts on-board ships for further distribution ashore. This with the purpose of either utilizing the CO_2, so called CCU (Carbon Capture and Utilization), for example to produce fossil free fuels *or* for long term storage, for example below surface, Carbon Capture and Storage (CCS). More specifically, this study includes the following parts (i) a mapping of ongoing relevant initiatives for CC on ships, (ii) a literature review on CC related to shipping and (iii) assessment of the most promising CC technologies on-board ships.

This project will contribute with scientifically based decision support for the choice of possible solutions to meet the GHG targets for shipping. Target groups for project results are ship owners, fuel producers, policy makers, regulatory bodies, and other actors. The project contributes with increased knowledge on the possibility to remove GHG from shipping.

This study is focussing on CC technologies related to CO_2 produced on-board ships itself, alternatives for storage and utilisation of CO_2 are not the focus of the assessments.

1.2 Background

To reduce the environmental and climate impact of shipping, the introduction of alternative fuels is required, but very likely there will be fossil fuels available and used also for a long time ahead why these GHG emissions also needs to be addressed accordingly. In addition, some of the available alternative fuels proposed for future use in shipping will need CO_2 as a primary product when produced. For example, if methane is produced in a power to gas process, hydrogen from electrolysis will be combined with CO_2 captured from somewhere. In case CO_2 captured on-board vessels is used for the fuel production, it can be seen as a more or less closed loop (depending on capturing rate etc), potentially enabling low GHG emission ship.

There is also a possibility to fuel ships with biomass-based or other renewable fuels such as LBG (Liquified Bio methane Gas), then capturing and storing the CO_2 and hence potentially creating negative CO_2 emissions. Or with other words, removing CO_2 from the atmosphere.

If CC on-board ships is feasible in practice and at which costs, and which solutions that seem most attractive is the key topic of this study.

1.3 Project layout

The focus of the study has been on possible CC techniques, the technical feasibility on-board ships, and cost estimates.

This project includes:

- A synthesis of knowledge on CO_2 capturing techniques available for use on-board ships and ongoing initiatives (including possible technical pathways, costs, and technical feasibility),
- An analysis of the potential for CC on-board ships and recommendations.

The project has been performed in collaboration between IVL Swedish Environmental Research Institute (IVL) and Chalmers University of Technology (Chalmers).

The first part of the project was conducted in the form of a master thesis made by Jonas Havenstein and Maximilian Weidenhammer at Chalmers (2021) resulting in Havenstein and Weidenhammer (2021). Supervisor for the thesis was Julia Hansson (IVL) and Maria Grahn (Chalmers) and examiner was Selma Brynolf (Chalmers). This report builds to a large extent on the information gathered and assessments made in that master thesis, which has been supplemented. We are very thankful to Jonas and Maximilian for their thorough study, which made an important contribution to and part of this study.

A reference group of interested stakeholders has been engaged and provide input to the project. We would like to take the opportunity to thank the reference group:

- Per Wimby, Stena Teknik
- Christer Bruzelius/ Jonas Moberg, Gotland Tech Development / Gotlandsbolaget
- Clas Gustafsson, Furetank
- Tryggve Möller/ Dick Höglund, Terntank
- Fredrik Larsson, Swedish Shipowners' Association
- Johan Laurell, Energigas Sverige
- Saeed Mohebbi, Swedish Transport Agency
- Bo Ramberg, Biogas Väst/ Energikontor Väst

- Torleif Madsen, Compact Carbon Capture AS / Baker Hughes

The project has gathered information related to available and potentially promising techniques to capture and store carbon dioxide on-board ships. The literature study and information gathering has been carried out with support from the reference group and has also included interviews with relevant persons and organisations.

It shall be noted that the technology and literature studies in Havenstein and Weidenhammer (2021), which was used for the assessment of CC most suitable for on-board CC, were conducted during 2021 while the final study was completed in the beginning of 2023.

Section 1 of the report contains an introduction to the study. Section 2 introduces carbon capture on-board ships. In section 3, several different technologies available for carbon capturing are described and analysed based on the literature identified. In section 4, a short brief of available information on actual real projects with CC installations is given. Section 5 contains methodology for a comparative assessment for on-board CC technologies. Conclusions and discussions are found in section 6. References in section 7. Additional information on the different CC technologies is found in Appendix.

2 Carbon Capture on-board ships

Instead of, or in addition to, the decrease of carbon emissions using low carbon fuels, the exhaust gases can be filtered, and carbon components captured. Such aftertreatment technology is called carbon capture (CC). In principle, CCS and CCU on-board ships will include steps from capturing towards utilisation or final storage of the captured CO_2 and all steps in between, see Figure 1.

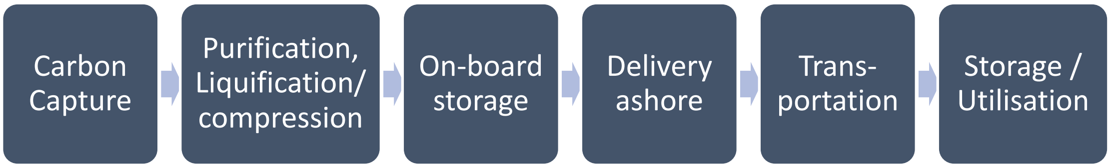

Figure 1. Main on-board CCS/CCU steps.

CC technologies are already applied in production processes for cleaning of gases such as oxygen and bio-methane fuels. Within these processes, CO_2 is absorbed and afterwards released to the atmosphere or stored for further use. The potential of carbon capture to filter exhaust gases from industrial applications has been explored in trials in Sweden, such as the Preem refinery pilot capturing in Lysekil, Sweden (Biermann et al, 2022) and at a global basis where there are already several industrial CC plants up and running[1] however many of them capturing CO_2 for other purposes than storage. At present, many Swedish as well as international energy companies with bio- or waste-heat power plants, have projects ongoing or in planning and in some cases close to starting up CC at their production sites.

An alternative to CCS is CCU. The captured CO_2 can be utilised as a commodity within industrial processes, e.g., to produce synthetic fuels but also for other purposes. By combining H_2 with CO_2, so-called electrofuels (e-fuels) can be synthesised, for example e-methanol.

Whereas the application of CC technology in industrial processes ashore is already in trial, the feasibility of such technology for on-board applications is still mostly discussed in theory. For example, the shipping company K-Line has together with Mitsubishi Shipbuilding performed a small-scale demonstration test for CO_2 capture on-board the coal carrier Corona Utility. This was claimed as the "the world's first" on-board CO_2 capture plant (Offshore Energy, 2021, K-line, 2021).

Carbon capture is by DNV assessed to have a potential to contribute to over 30 percent of total GHG reductions within the shipping sector according to their *Maritime forecast to 2050* report (DNV, 2022). However, DNV also concludes that "no full-scale CCS system has yet been implemented on board, nor any large-scale demonstration projects" (DNV, 2022).

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[1] As example, the Shute Creek Gas Processing Plant, in the United States is claimed to be the largest operational carbon capture and storage facility in the world. With a CO_2 capturing capacity per year of seven-million-ton, to be used for enhanced oil recovery projects.
Source: www.statista.com/markets/408/topic/948/environmental-technology-greentech

While space and weight are less important in shoreside applications, these factors are of high interest on-board. The ships value is mainly defined by its ability to transport a certain amount of cargo. Especially the space needed for storage of the captured CO_2 on-board might reduce the ships transport capabilities, and thereby lowers the opportunity for earnings. At a capturing rate of for example 90 percent of the produced carbon dioxide, approximately three tons of CO_2 needs to be stored for each ton of fuel oil being consumed on-board[2]. Due to the non-existence of CC technology on-board vessels, there is in general yet no infrastructure in ports being able to receive captured CO_2 from vessels.

Research until today has mainly focused on the application of CC in shoreside applications. However, the interest in economically and technically feasible solutions for reducing the CO_2 emissions from shipping, is drawing the interest of research towards the application of CC technology on-board.

Johnsson et al (2020) have estimated the costs of CCS for the 28 largest land-based CO_2 sources in Sweden (biogenic and fossil CO_2), corresponding to 23 Mt/year and arrived at a cost for separation, transport, and storage of approx. €80-135/ton CO_2, assuming a standard MEA based CO_2 absorption process is adopted for all industrial processes. Such cost levels are similar to what today is being paid for carbon emission allowances within the European Emission Trading System (EU ETS). Compared to land-based CCS, introduction of CCS on-board ships will come with added costs and complexity due to smaller scale of installations, more demanding environment, the logistics to store the CO_2 on-board ships and bring it ashore etc.

It might be easier and or less costly to integrate certain CC technologies into existing on-board installations in comparison to alternative decarbonising technologies, i.e., CC may be a feasible solution to retrofit for the reduction of carbon intensity of existing vessels. This for example due to possible lack of supply of low carbon fuels in enough quantities and/or high costs for alternative low carbon fuels. Although worth to note that some abatement technologies such as speed reductions can be more cost efficient but as standalone measures not possible to reduce a major part of the GHG emissions from a ship.

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[2] General CO_2 emission factor for fuel oil used on-board ships is that approximately 3.2 ton CO_2 is produced in the combustion process per ton fuel oil consumed. At 90 percent capture rate one ton fuel oil will in such case produce 2.88 ton CO_2 to be stored on-board.

3 Carbon capture technologies

This chapter includes a description of CC capture technologies, an overview of their status, development, literature, and research with focus applied to on-board CC, based on Havenstein and Weidenhammer (2021). For a more detailed presentation the reader is referred to Havenstein and Weidenhammer (2021). In general, three methods for CC can be distinguished:

- Post-combustion capture,
- Pre-combustion capture
- Oxyfuel combustion.

Post-combustion CC is applied in the flue gas environments and refers to the capture of CO_2 from a carbonaceous fuel, after the fuel has been combusted. The CO_2 concentration in the exhaust gases is typically low, due to the high dilution with combustion air (Wang & Song, 2020). When fuel cells are applied to convert the fuel, the more applicable term "post-conversion capture" is used.

Post-combustion capture technologies:

- Chemical absorption
- Membrane separation
- Cryogenic separation
- Calcium looping

In **pre-combustion** capture, as the name implies, the CO_2 is removed from the fuel before an energy conversion occurs. This is generally done by converting the fuel into a syngas with a high CO_2 concentration and the subsequent capture of CO_2 from the syngas.

Oxyfuel combustion is using another approach to capture CO_2 from flue gases. This technology combusts fuels in an O_2-enriched environment, to create a flue gas mixture which is ideally only consisting of CO_2 and water vapour. After the condensation of the vapour, the CO_2 is ready for sequestration (Wang & Song, 2020).

3.1 Post-combustion capture

Post-combustion CC typically include the removal of CO_2 from flue gases with low CO_2 concentrations, from combustion of hydrocarbon fuel. There are different technologies available to capture CO_2 from exhaust fumes of which the most common technologies are presented. Some of these technologies are already in commercial operation, while others are still under research.

3.1.1 Absorption by chemical solvents

CC by chemical absorption is the most mature technology of all post-combustion technologies (Sreedhar et al., 2017). It is used in large-scale applications, e.g., coal-fired power plants, for the removal of CO_2 from their exhaust (NRG Energy Inc., 2021). Although this technology is well developed, continuous research is ongoing to improve the processes (Vega et al., 2020).

Post-combustion capture by absorption, using a 30 wt% solution of MEA, is the most mature technology for CC. Therefore, in the consulted literature it is widely used as a benchmark for the comparison of different CC technologies. The high reactivity of this solvent in connection to its low purchase price are main arguments for the wide usage of MEA in different flue gas conditions (Sreedhar et al., 2017).

For further information and data on post-combustion capture by absorption, see *8.1*.

Besides MEA, which is already commercially available, a variety of alternative chemical absorbents has been researched in the past decade (Wang & Song, 2020). A fair amount of them were amine-based, but also ammonia solvents, and other aqueous liquids (water containing dissolved substance) and ionic liquids (a salt in the liquid state) have been under consideration. All these chemicals come with individual benefits and drawbacks in different applications, but also demand distinct boundary conditions, which is limiting their area of application. Furthermore, the usage of blended chemicals to increase the advantages and, at the same time, diminish the disadvantages of the individual chemicals, has been tested (Kothandaraman, 2010; Sreedhar et al., 2017). Table 1 is comprising some of the researched chemical solvents and provides an overview of their specifics.

Table 1. Overview of different chemical solvents

Absorbent	**Advantages**	**Disadvantages**	**Energy demand for regeneration**	**Remarks**	**Literature Source**
Monoethanol-amine (MEA)	Low costs; high reactivity	Degrades in contact with air, SO_x or NO_x; corrosive; volatile	Intense (2,2 – 6 MJ/kg_{CO2})	8,2 - 14 % efficiency penalty for a power plant	Kothandaraman, 2010; Sreedhar et al., 2017; M. Wang et al., 2015
Piperazine (PZ)	Resistant to thermal degradation and corrosion	Can form precipitation and nitrosamine (toxic) during CO_2 capture → concerns regarding environmental friendliness	About 85 % of MEA	Can be used as a blend to MEA to increase efficiency (activated MEA)	Cousins et al., 2014; Feenstra et al., 2019; Sreedhar et al., 2017; X. Wang & Song, 2020
Ammonia (NH_3)	Good availability; lower chemical costs than MEA; resistant to thermal degradation and corrosion	High volatility	Very low, requires only 27 % reboiler duty compared to MEA	Tested in pilot-scale only	Awoyomi et al., 2019, 2020; Sreedhar et al., 2017
Ionic Liquids	Less costs than MEA; resistant to degradation (thermally & chemically stable); non-volatile	Particularly toxic to aquatic organisms	Lower than MEA	Some liquids show high regeneration efficiency (up to 95%); tested in pilot-scale only	Krishnan et al., 2020; Mac Dowell & Shah, 2012; Sreedhar et al., 2017; Y. Zhou et al., 2020
Potassium carbonate (K_2CO_3)	High thermal & chemical stability; non-volatile; no degradation; more efficient than MEA	Low mass transfer rate; higher space demand than MEA	Lower than MEA		Kothandaraman, 2010; Sreedhar et al., 2017; M. Wang et al., 2015

The use of different solvents is affecting the technology setup of the absorption process, which is why space requirements, costs (OPEX & CAPEX) and maturity of the absorption technology will vary.

CC plants in post-combustion applications that utilise chemical absorption by amines are already commercially available since several years. Industrial applications are even scaled up to the usage of absorption technologies for CO_2 removal from power plants. Post-combustion capture technologies are a kind of exhaust gas aftertreatment system and hence provide the possibility to integrate this CC technology into an existing flue gas stream. Amine-based solvents, such as 30 wt% MEA, are the most common and successfully used solvents for the chemical absorption from flue gases (Sreedhar et al., 2017).

The lower the CO_2 concentration in the flue gas and the lower the quantity of flue gas from the source, the higher are the costs per captured ton CO_2 of the respective CC technology, partly due to economies-of-scale (Johnsson, 2021). Another relation is that the more CO_2 that can be captured from the flue gas, the lower are the costs per captured ton CO_2, which means that an increasing capture-rate (e.g., from 60 to 90 percent) significantly lowers the costs per captured ton CO_2 (Feenstra et al., 2019).

The installation of large-scale chemical absorption equipment to power plants is causing large capital costs (CAPEX) for the owner. The costs of the investment originate to a large extent from the costs for the absorber and stripper unit, where especially the packed columns are main contributors to the price (M. Wang et al., 2015). When considering the investment costs, it must be noted that it is possible to reduce the CAPEX when higher operational costs (OPEX) are acceptable. This trade-off between CAPEX and OPEX is also affecting the space requirements. The CAPEX and OPEX are further influenced by the choice of solvent. However, the general technology setup including the main cost contributing units is similar in all chemical absorption processes.

The OPEX of the absorption technology mainly composes of the energy costs for absorption and stripping and purchase price for the utilised solvent. Breaking down the additional energy, the largest share of energy demand is associated to the regeneration of the solvent, if conventional absorption with packed columns is used (Kothandaraman et al., 2009).

The choice of absorbing solvent is influencing the OPEX. MEA has a relatively low-cost price in the purchase but demands immense energy for regeneration (Sreedhar et al., 2017). Several sources refer to a required regeneration energy for MEA between 3.2-4.2 GJ per ton of captured CO_2. In some cases, more than a third of the power output of the power plant is required for solvent regeneration (Oko et al., 2017; M. Wang et al., 2015).

Compared to MEA, K_2CO_3 has a lower purchasing price, at the same time less solvent is needed and the energy demand for regeneration is lower (M. Wang et al., 2015). The absorption process with NH_3 requires up to 73 percent less energy than the MEA process (Awoyomi et al., 2020; Mac Dowell & Shah, 2012). The same fact of lower energy demand also applies for PZ, which directly relates to lower OPEX for the operator, when PZ, K2CO3 or NH_3 are used instead of MEA (Sreedhar et al., 2017). Additionally, favourable for PZ and K_2CO_3 is their high resistance to solvent degradation, i.e., less replenishment of the solvent is required. Contrary to that, MEA is affected by such degradation and requires solvent replenishment when the capture-rate is decreasing. This is contributing to higher OPEX of MEA in comparison to the other solvents (Raksajati et al., 2013). Concluding, in case alternative solvents to MEA are applied in chemical absorption, the OPEX can be lowered significantly in comparison to the MEA process, due to the lower purchase price, lover energy demand and longer service lifetime of specific solvents. Out of the solvents considered in this comparison, NH3 has the least OPEX and is therefore marking the lower end of the range. A study by Cousins et al. (2014) found that the energy demand for solvent regeneration of PZ is about 15 percent lower than for MEA, i.e., the translated OPEX in the PZ process are at a level of 85 percent, compared to the benchmark process.

3.1.1.1 Advantages and drawbacks with chemical absorption

One of the biggest merits of the post-combustion CC technology by chemical absorption is the general possibility of retrofitting it to an existing plant, without major changes to the actual power generating process (Sreedhar et al., 2017). Since this technology has reached high maturity, it can immediately be used in arbitrary flue gas applications. The components involved in the processes have been tested in real flue gas conditions over extended time periods, which contributes to the technology's reliability.

However, the intense energy demand for solvent regeneration is a major drawback of the chemical absorption technology. Additional energy penalties are accounted to the power requirements of the solvent pumps and blower/fans in the exhaust stream, to overcome the pressure drop of the absorber (Wilcox, 2012). Another disadvantage is the toxicity and corrosivity of some solvents and their gradual degradation over time. The CC related equipment is both, space, and weight intensive, which can be limiting for confined-space applications (Feenstra et al., 2019; Sreedhar et al., 2017).

3.1.1.2 Research and development for the application on-board with chemical absorption

Due to its application in land-based industrial processes, absorption by chemical solvents is the most mature process for CC. This is also represented by the number of articles on research for the application in the naval sector. Articles and reports proposing processes and evaluating the feasibility of CC for reducing carbon emissions from shipping has been identified and assessed. The main findings of the papers are summarised in Table 2.

Mac Dowell & Shah published in 2012 a review on options to reduce the carbon emissions from international shipping and introduced post-combustion CC by absorption with chemical solvents as an option to reduce the carbon footprint of the maritime transport sector. Based on the absorption process using MEA solvents and its drawbacks, the authors define four criteria for sorbent materials:

- High CO_2 absorption capacity to reduce the equipment size,
- High thermal and chemical stability to reduce the degradation,
- Low volatility to reduce solvent losses,
- A weak bonding of CO_2 to reduce the costs of solvent regeneration.

Two alternative solvents were proposed, which are showing a better performance than MEA in regards of these criteria. Firstly, NH_3 allowing a reduction of at least 7.5 percent of the energy required for regeneration in comparison to MEA and secondly, ionic liquids offering a saving potential of up to 16 percent, in comparison to MEA. The volatile nature of NH_3 and the low density of ionic liquids are highlighted as critical.

Absorption using MEA

The literature review on EEDI, EEOI and CCS by **Wang et al**. (2017), is studying current policies for carbon emission reduction from shipping and is giving an overview of the different CC techniques. The paper is briefly analysing the feasibility of the described technologies and is discussing impediments and constraints for the application of CC on-board.

Based on the technology developed by Zhou and Wang (2014), **Fang et al**. (2019) presented their model for the optimal sizing of a CC system for on-board application. The model for a so-called *all-electric ship* is determining the optimal size of an energy storage system first and in the second step evaluates the feasible size of the CC system based on the identified constraints. The case study is based on actual operating data from a vessel's voyage and discloses, that the vessels energy system in combination with an energy storage system, can power a CC system capturing up to 60 percent of the CO_2 emissions. For a higher capturing rate, additional power generation would be required (Fang et al., 2019).

The first study for the application of solvent-based CC on-board ships has been carried out by **Luo and Wang** and was published in 2017. The proposed post-combustion capture technology is designed to run with a 30 wt% aqueous solution of MEA for the absorption of CO_2. Based on a middle-sized general cargo ship as an example, the researchers developed a model of the ships energy system to simulate the efficiency and conduct a techno-economic assessment. Without the installation of additional power generation equipment, a CC rate of 73 percent were estimated at costs of €77/ton CO_2. To obtain a capture-rate of 90 percent, additional power is required, which is generated by a gas turbine within the model and is raising the costs to €160/ton CO_2, mainly due to an increased fuel consumption. Limitations of CC on-board technology were identified by the researchers as tank storage of the solvent and captured CO_2, limited space for the equipment, limited supply of heat, electric power, and cooling utilities as well as in the construction due to the constant movement of the ship. In conclusion, this CC technology is feasible for the on-board application but requires additional energy production on-board (Luo & Wang, 2017).

Feenstra et al. (2019) evaluated CC to be a transition solution on the way to zero emission shipping and therefore researched the application of post-combustion CC technology for diesel and LNG fuelled ships. For two dual-fuel reference ships, a 1,280 kW inland ship and a 3,000 kW general cargo vessel, the process for chemical absorption is simulated with 30 wt% aqueous MEA and 30 wt% aqueous PZ as solvents. The process simulation for the inland ship revealed that the cooling capacity from the evaporation of LNG is sufficient to cover the liquefaction of the compressed CO_2 for on-board storage. When the ship is running on diesel, i.e., no evaporation of LNG takes place, an additional refrigeration unit is needed to liquify the CO_2 for intermediate storage and thereby is raising the costs for equipment and operation. Besides the different fuel options, different options for solvents have been compared. Since PZ has a higher desorption pressure, the required compression work for the captured CO_2 is lowered, reducing operational and equipment costs. Another option examined is the difference resulting from a capture-rate of 60 percent or 90 percent, showing that the costs per ton of captured CO_2 are lower, the more CO_2 is captured. In almost all cases, the heat derived from the exhaust gases was sufficient to cover the energy demand needed for desorption. By €98/ton CO_2, the lowest costs were achieved for the 3,000 kW reference ship, when using PZ as solvent and running on LNG. Nevertheless, due to concerns on the environmental friendliness of PZ, the feasibility study for modifying the reference vessel to fit the CC plant was carried out for the use of MEA as solvent instead and LNG as fuel at a capture-rate of 90 percent. It is shown how the additional equipment and storage tanks can be fitted on-board without impacting the ships stability. Feenstra et al. (2019) conclude, that CC might be a more cost-effective option for larger and LNG-fuelled ships, also due to the purer exhaust gas stream reducing the degrading of the used solvent. More research is needed to reduce the initial investment costs and examine the impact of the ship's movement on the ab- and desorption processes (Feenstra et al., 2019).

Chemical absorption with MEA as solvent is applied in the concept for a H_2-powered 3,000 DWT general cargo vessel by **Lee et al.** (2020) as well. Since the volumetric energy density of H_2 is low and there is no infrastructure for supplying vessels with H_2 as of now, the authors propose a system for on-board production of H_2 from two fuel alternatives: LNG (CH_4) and methanol. Energetic and exergetic analyses are carried out to compare the two options, including the integrated CC plant.

The methanol-based system requires 1.1 times more space, and the fuel costs are 2.2 times higher than the CH_4-fuelled alternative. It is concluded that this technology is a feasible alternative on the transition to H_2-fuelled ships, but further development is required (H. Lee et al., 2020).

In connection to the Northern Lights project, **Einbu et al.** (2021) researched the potential of absorption-based CC using a 30 wt% MEA solvent on-board a CO_2-carrier, thus also eliminating the need for additional storage tanks for the captured CO_2. The results of their simulation demonstrate that the waste heat of the engine is not capable to achieve capture-rates above 50 percent. The additional demand of thermal energy can be met by using a fuel afterburner, which would increase the fuel consumption by 6 – 9 percent when running on LNG and by 8 – 12 percent when running on MGO, respectively. The afterburning of fuel in the engine's exhaust gases increases the available heat for regeneration of the solvent and simultaneously increases the CO_2 concentration of the flue gas stream (Einbu et al., 2021).

To reduce the exhaust temperature to the required temperature prior to entering the absorption column, the proposed design includes a direct contact cooler, which could potentially function as SO_x scrubber (Einbu et al., 2021). The conducted simulation achieved the lowest energy penalty with an absorption bed height of about 20 meters, which results in a total absorber tower height of approximately 30 meters. The authors propose that the absorption column could be split in several absorbers in series, to reduce the height, if required by the ships design. Further, the height could be reduced when the solvent flow through the absorber is increased, which would lower the initial investment but raise the operational expenses due to a higher energy demand for solvent regeneration. Reducing the absorption bed height from 20 to 5 m would result in an increase in fuel consumption from 6.5 percent to 8 percent (LNG), at a capture-rate of 90 percent. This trade-off between CAPEX and OPEX is seen as an important degree of freedom in determining the required absorption bed height (Einbu et al., 2021).

In 2020, the **Roadmap to Zero Emission from International Shipping**, funded by the Japanese government, was released. The paper presents a strategy for the transition towards climate neutral shipping. (Japan Ship Technology Research Association, 2020)

Besides concepts for alternative fuel and drive technologies, the **Shipping Zero Emission Project** developed a concept for a 20,000 TEU container vessel, equipped with on-board CC published by **Japan Ship Technology Research Association et al./ JSTRA** (2020). The vessel is designed to operate on routes between the Far East and Europe, using methanol fuel and is equipped with a liquid amine absorption plant for CO_2 capture. Furthermore, other CC techniques have been evaluated for the concept, but according to the authors of the report, these are not feasible, due to the low partial pressure of CO_2 in the exhaust. Considering the membrane technology for CC, a vacuum pump would be required to lower the pressure within the membranes for an efficient CO_2 capturing process, which would significantly increase equipment and operational costs. Therefore, the authors propose liquid amine absorption with KS-1™ as absorption liquid. The technical arrangement is expected to be able to achieve a capture-rate of 86 percent, which might be increased by further development. The captured CO_2 is liquified for temporary storage on-board. Figure 2 shows the general arrangement drawing of the 20,000 TEU concept vessel. The vessel was extended by one additional container bay in comparison to a common 20,000 TEU vessel, to allow for the placement of the CC system in front of the stern funnel and the placement of the CO_2 and methanol tanks below the accommodation. The equipment connected to CC is occupying a space equivalent to 1,820 TEU for a single voyage and 2,550 TEU in case the CC system is designed for a round voyage. Since the study is just presenting a concept, it is addressing issues for the practical use of such technology on-board from a general point of view. (JSTRA et al., 2020).

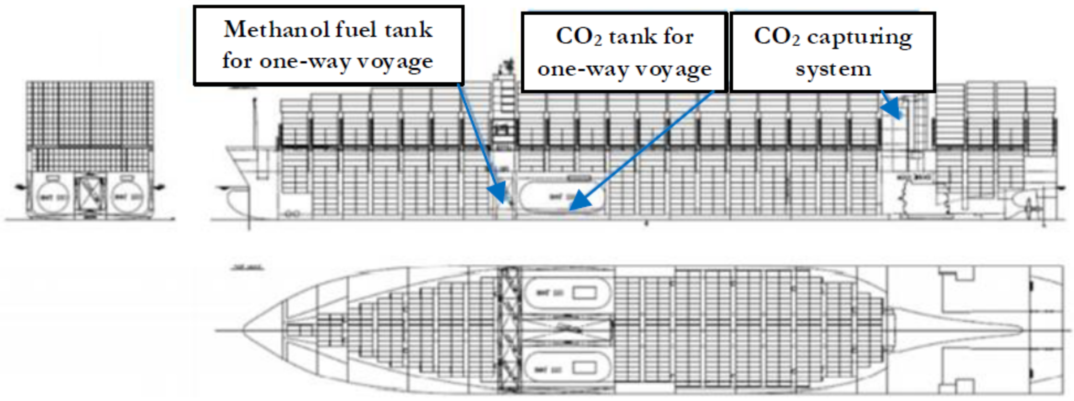


Figure 2. General arrangement of 20,000 TEU Container ship equipped with CC developed by JSTRA et al. (2020)

Utilising a medium range tanker with a capacity of 47,000 DWT and a 9,960 kW two-stroke main engine, **Stec et al.** (2021) conducted simulations to assess to which degree it is possible to capture CO_2 with waste heat as only energy source for the post-combustion CC process. The authors thereby decided to use a 30 wt% MEA-based post-combustion CC for their model, since it can be installed without major changes to the ship's existing propulsion system. To enable the vessel to run on HFO and to protect the amine-solvent from degrading, the model is including a desulphurisation unit, which is installed upstream of the CC plant. The proposed closed-loop system for sulphur removal from the exhaust gases is also in charge of cooling the exhaust gases before entering the absorption tower (Stec et al., 2021).

Since the study aims to merely use waste heat to regenerate the amine-solvent in the stripper, the capacity of the CC process is limited by the available waste heat. Depending on the available waste heat, a certain percentage of the exhaust gases is processed by the CC unit. The remaining exhaust is bypassed, i.e., only treated by the desulphurisation unit (Stec et al., 2021).

The available waste heat is dependent on the area of operation of the vessel, the study of Stec et al. (2021) therefore researched three scenarios: arctic, ISO reference and tropical conditions. The least waste heat is available under arctic conditions, whereas under tropical conditions the most waste heat is available. Based on the results of Feenstra et al. (2019), the simulation is designed to capture 90 percent of the CO_2 lead through the absorber, as this achieves the lowest costs per captured ton of CO_2. Under arctic conditions, 35 percent of the exhaust are passing the CC unit, achieving an overall capture-rate of 31 percent of CO_2 emissions in the simulation. In the best case, under tropical conditions, 62 percent of the exhaust are passing the absorber, achieving a simulation result of 56 percent capture-rate. (Stec et al., 2021).

Absorption rate based on exhaust heat

To include the impact of CC in the formula for the calculation of the EEDI, **Lee et al.** (2021) introduces a factor representing the captured percentage of CO_2. To validate the proposed method, the authors carry out a case study for a 53,000 DWT container feeder with a capacity of 3,840 TEU, fuelled by LNG. The case study is examining three cases: 45 percent, 55 percent, and 70 percent reduction of emitted CO_2. In all cases, only a part of the exhaust stream is passing the CC unit, which is sized to achieve a capture-rate of 92 percent. Due to the low partial pressure of CO_2 in the exhaust stream of the case study vessel, an amine solution is chosen for CC. The simulated process consists of a post-combustion chemical absorption process with activated MDEA as solvent. The solvent consists of MDEA as base component and PZ as activator. (Lee et al., 2021).

The simulation is carried out to investigate the sizing of the required equipment to estimate the cargo loss, which is negatively impacting the EEDI (Lee et al., 2021). The waste heat of the engine is utilised to regenerate the solvent in the stripper and was sufficient in all cases. The compression and liquefaction process consumes more power than the actual capturing process, where the most energy is consumed by the blower required to overcome the pressure drop through the absorber. Irrespective of the differing volume flow of exhaust passing the absorber in the three examined cases, the packing height in the absorber is unchanged since it is more affected by the concentration of CO_2 in the exhaust stream. The solvent flowrate as well as the diameter of the absorption columns are varied, to achieve the targeted capture-rate of 92 percent (Lee et al., 2021).

CC GHG reduction with MEA versus other potential methods

Guler et al. (2021) compared absorption CC technology, using MEA as solvent, with other measures with carbon reduction potential such as speed reduction and usage of LNG. The ships being assessed were a very large crude carrier (VLCC) and different sizes of LNG carriers (Q-Max, Q-Flex, conventional LNG carrier). The study concluded that speed reduction is the best cost-oriented and easiest reduction solution for ships with low freight values like crude oil tankers while CC is more cost-effective for ships with high speed and freight values. The use of LNG along is not sufficient to meet the IMO2050 criteria. In relation to CC technology, chemical absorption is stated the most favourite option for on-board shipping application by considering its maturity and other positive aspects over other technologies, such as cost, high carbon capture rate, acceptable toxicity, etc. Precombustion capture system was not seen applicable and the oxy-combustion system may be expensive. When the cost of absorption CC system was examined by its components, the highest cost was the liquefaction cost. The study investigated the impact of design parameters of the absorber column on the cost and capture CO_2 amount. The carbon capture rate was assessed with a potential to be further improved by adjusting the design parameters of the absorber column.

Absorption using aqueous ammonia

Exploring the potential of a post-combustion CC process using **aqueous ammonia** on-board a CO_2-carrier for simultaneous removal of CO_2 and SO_x emissions from the exhaust, was the motivation of the research of **Awoyomi et al.** (2019). The advantages of using ammonia (NH_3) instead of conventional amine solvents, are the lower heat required for regeneration, the low chemical costs, the thermal stability and tolerance towards pollutants and O_2. Additionally, its ability to release CO_2 at higher pressure is reducing the required power for compression. Further, the integration of SO_x capture allows the production of sellable by-products. Challenges of the NH_3 absorption process have been revealed during the trials at the Munmorah pilot plant. The slow kinetics of CO_2 absorption and the high volatility of NH_3 require larger equipment with regard to capacity and abatement technologies to reduce the ammonia-slip (Awoyomi et al., 2019).

An economical evaluation of the proposed process for post-combustion CC using aqueous ammonia as solvent was conducted by **Awoyomi et al.** (2020) and published as a separate paper. Contradictory to the foregoing study, it was assumed that the engine is running on LNG. This makes the pre-treatment column redundant since LNG contains almost no sulphur. To achieve the required temperature of the exhaust gases prior to entering the absorber, a direct contact cooler is replacing the pre-treatment column. Besides the utilisation of cold energy from vaporising the LNG before combustion, the economic effect of exhaust gas recycling (EGR) and the optimum concentration of the NH_3 solvent are investigated (Awoyomi et al., 2020).

The optimum solvent concentration is determined as 10 wt% ammonia, minimising the required energy for solvent regeneration (Awoyomi et al., 2020). Due to the reduced volume flow of exhaust gases and increased CO_2 concentration when applying EGR, the costs per ton of captured CO_2 could be lowered from $13 /ton CO_2 to $117/ton CO_2 at a capture-rate of 90 percent. Further, it is concluded that the costs per ton of captured CO_2 are rising when the capture-rate is lowered, even if capital expenses are reduced (Awoyomi et al., 2020).

Calcium oxides absorption

In 2014, **Zhou and Wang** published their proposal for a new technology for post-combustion capture applications on-board vessels. Rather than other CC technologies applied ashore, this technology consists of chemical processes for carbon solidification. A solution out of the reactants sodium hydroxide (NaOH) and calcium oxide (CaO) is used to bind CO_2. The product of this process is calcium carbonate ($CaCO_3$), which can be filtered from the solution and stored as solid powder on-board, until its discharge. Apart from the advantages in reduction of power and space requirements as well as the avoidance of stability issues due to storage of liquified CO_2 on-board, the authors see a financial advantage. Based on a 16-days voyage of a 157,500 DWT bulk carrier, from port of Qinhuangdao to San Francisco, a cost estimation has been carried out. The study was based on laboratory experiments. Including the costs for required energy, chemicals and freight reduction, the authors cost analysis comes to the result, that the profits from a sale of the produced $CaCO_3$ would exceed the running costs of the capturing plant.

Another review on options for decarbonising shipping has been conducted by **Balcombe et al.** (2019). CCS is named as one potential course of action to reduce the carbon intensity of shipping and the concept of **Calix RECAST** is presented as an example for a CCS technology. Calix RECAST is also using CaO for binding CO_2 but other than the concept of Zhou and Wang (2014), the CaO is added as powder into the exhaust stream, rather than being contained within a solution. The resulting $CaCO_3$ is assumed to be dumped into the sea, where remaining non-reacted CaO is going to bind further CO_2 from the ocean. Balcombe et al. highlight, that the shoreside production of CaO would emit significant amounts of CO_2 and if these emissions are not captured, the technology would just lead to a shift of emissions from one sector to another. Furthermore, additional research is needed to address the impact of an increased pH-value on the ocean when disposing unreacted CaO (Balcombe et al., 2019).

In late 2022, a feasibility study, led by the **research institute RISE**, started to assess if a carbonate-based CC technology, earlier tested in land-based applications, would be beneficial on-board ships. The intention is to use the captured carbon dioxide and refine it into calcium carbonates ($CaCO_3$), which is a valuable commodity used in different industry processes and assessed easier to handle than liquid or compressed CO_2. To this date, laboratory tests has been conducted and the results will be analysed going further. Also included are assessments of the value chains and circular business models linked to a maritime application of the CC system. The study is planned to be finished early 2024. (RISE, 2022; Forsström, 2023).

Process improvement and cost reduction potential

Van Duc Long et al. (2021) conducted a study related to improvement of marine carbon capture on-board diesel fuelled ships. The technology being studied was absorption with improved processes and blended MDEA/PZ solvent, with intercooler, multiple feeds, and heat integration on a 3 MW diesel engine. Main findings were that the CO_2 removal for the final configuration solvents Mono-ethanolamine/piperazine (MEA/PZ) and N-methyl-diethanolamine (MDEA)/PZ could improve the CO_2 removal compared to the MEA solution by 1.7% and 2.8% in terms of, respectively.

In the study by **Ji et al.** (2021), This study investigated the effect of modified solvents for absorption CC with three aqueous amine options: MEA, DIPA, and MDEA-PZ in terms of the carbon capture performance. The scope of the study was tank to propeller performance for LNG dual-fuel engine via process modelling and simulation. Also including the optimised dimensions of process units, variant lean solution flows, and intensified absorption/desorption reactions with least negative effects. The MDEA-PZ showed the highest CO_2 capture efficiency. The required regeneration energy of MDEA-PZ is between MEA and DIPA. The criteria of solvent selection were fast kinetics, minimal energy penalty, less prone to degradation, less corrosive, and neglectable toxicity, and high cyclic capacity.

Ros, et al., (2022) studied advancements in ship-based CC technology with absorption with MEA as solvent on-board the LNG-fuelled ship Sleipnir owned by Heerema Marine Contractors. The total carbon capture cost calculated in the study was between €119 and €133/ton CO_2 associated with CO_2 product pressure (€119 for 20 bar case and €133 for 7.2 bar case). It was concluded that further solvent development for the CC should focus on high pressure desorption and lowering oxidative degradation of solvents. Further demonstration and integration will be done in the EverLoNG project.

Buirma et al. (2022) performed a supply chain feasibility study on on-board absorption CC and storage for a single offshore heavy lift vessel.
Main findings were that emission and financial targets can be met by aligning the offshore transportation distance with the capacity to store CO_2 on board and the available means of transport to the final user. And that adsorption technology can best be integrated on-board vessels that sail on LNG (available of cold matter), the costs of the system are estimated at between €100 and €150 per ton of CO_2 captured. The offshore transport distance is more decisive than the onshore distance was also concluded.

Demonstrations and feasibility studies
The **CC-Ocean** project is in line with the conclusion of the Japanese study (JSTRA et al., 2020) presented above. Supported by the Japanese government, K-Line, Mitsubishi Shipbuilding and ClassNK formed an alliance in 2020 to develop and install a small-scale CC demonstration plant on-board a vessel. The test operation of the plant is planned to start in the middle of 2021 ashore, before it is installed on-board of the Corona Utility, an 88,715 DWT bulk carrier, by the end of 2021. The project aimed to develop more compact equipment for the application on-board and to explore the requirements for a stable continuous operation at sea (Offshore Energy, 2020).

The **Oil and Gas Climate Initiative** (OGCI) conducted together with **Stena Bulk** a feasibility study to explore the potential of carbon capturing on-board tankers and LNG carriers within the Stena Bulk fleet. Based on a number of parameters including the large number of installed 2-stroke engines running on heavy fuel oil, a Suezmax tanker with a 16 MW main engine with scrubber was selected as a case vessel. System design of a chemical absorber with monoethanolamine (MEA) solvent was selected and the system was designed to capture up to 90 percent of the CO_2 emitted from the main- and the auxiliary engines as well as the boilers. The system was calculated to be able to capture up to 8 percent of the CO_2 using only available heat from the exhausts. In case that

90 percent of the exhausts should be captured, 53 percent total fuel consumption increase where estimated. Also, capital and operational expenses where estimated and the vessels total operational expenses was estimated to increase with 25 percent to a reference vessel's existing operating expenses whereof increased energy consumption stands for the main part, over 80 percent. (OGCI, 2021). Rough calculations based on information given in the OGCI report gives that the total costs for CO_2 capturing liquification and storage on-board comes at a cost of above €100/ton CO_2 avoided for the specific case. In addition, costs for delivery ashore, further transportation as well as storage needs to be considered.

The **Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping** (2022) has published a paper with results from a work package on on-board carbon capture completed as part of the Green Fuels Optionality Project (GFOP). The study includes case study analysis for CC on-board container, bulk and tanker vessels for newbuilds and retrofit. The technology studied were post-combustion liquid amine absorption with liquid CO_2 storage. For a very large crude carrier (VLCC) newbuild, the best business case studied, CO_2 abatement cost ranges from $220-290/ton CO_2 with a tank-to-wake effective CO_2 emission reduction of 74-78 percent. As example, related to loss of cargo capacity, for the VLCC segment, the lightweight increase due to additional system weight, leads to a deadweight decrease of 3-4% (cargo carrying capacity). In total, up to 45 percent increase of total energy consumption for the on-board CC is estimated. The study also assess that the chemical absorption technology will be commercially available around 2030 and available as small-scale systems for on-board implementation already in 2025. The study concludes that the technologies are still in development and can provide significant emission reductions.

The **EverLoNG** project, led by TNO, will demonstrate the feasibility of CO_2 capture by demonstrating its use on board two LNG-fuelled ships and moving the technology closer to market readiness. The ships are owned and operated by project partners TotalEnergies and Heerema Marine Contractors. Altogether 16 project partners from five countries will participate in the development of full-chain carbon capture, utilisation and storage (CCUS) networks, connecting SBCC with CO_2 transport links, geological CO_2 storage and markets for CO_2 use. The project aims to deliver a decarbonisation solution to the market in 2025 with a marginal abatement cost of between €75 and €100 per ton of CO_2 equivalent and a CO_2 capture rate of up to 90 percent. EverLoNG is funded with €3.4 million by ACT (Accelerating CCS Technologies) under EU Horizon 2020. (EverLoNG, 2023). A briefing report on CO_2 Shipping Interoperability has been published (Parmiter, 2022).

Table 2. Research articles on post-combustion chemical absorption for the application on-board ships

Authors (Year)	**Title**	**Solvent**	**TRL**[1]	**Ship type**	**Main conclusion**	**Additional information**
Dowell & Shah (2012)	Shipping and CCS: A system perspective	MEA, NH_3, ionic liquids	N/A	Not specified	MEA has major drawbacks, NH_3 and ionic liquids are having energetic advantages	Literature review on alternatives for carbon emission reduction of international shipping, disadvantages of MEA, criteria for solvents in shipping, advantages of NH_3 and ionic liquids
Zhou & Wang (2014)	Carbon capture and storage - Solidification and storage of carbon dioxide captured on ships	NaOH + CaO	3	Not specified	Major advantages in comparison to liquefaction of CO_2, more research needed to increase efficiency	Case ship study for capture of 20 % of CO_2 to meet IMO 2020 goal, profit from selling product of CC is able to exceed running costs
Luo & Wang (2017)	Study of solvent-based carbon capture for cargo ships through process modelling and simulation	MEA	2	General cargo vessel, 12.500 DWT, 17 MW	Ship design bears constraints for CC, additional power needed to gain 90 % capture-rate	Without additional power generation on board a capture-rate of 73 % is possible at a cost of 77,50 €/t_{CO_2}; with additional power installation 90 % capture-rate is achievable at 163,07 €/t_{CO_2}
Wang et al. (2017)	Reviews on Current Carbon Emission Reduction Technologies and Projects and their Feasibilities on Ships	N/A	N/A	Container vessel, 6.300 TEU, 57.059 kW	High energy, material and space requirements as constraints; further development necessary	Review on current situation for emissions, policies and technologies; prediction for future development; comparison of different CC technologies; examples for current incentives for CCS included
Fang et al. (2019)	Optimal Sizing of Shipboard Carbon Capture System for Maritime Greenhouse Emission Control	NaOH + CaO	2	All-electric ship concept	CC needed to meet future IMO GHG emission goals	Including model based on real-life case study for an existing ship; cost/profit calculation
Balcombe et al. (2019)	How to decarbonise international shipping: Options for fuels, technologies and policies	CaO powder	N/A	Not specified	Combination of policies, fuels and technology is needed	Overview of existing/researched technologies and policies to reduce the emissions by shipping
Feenstra et al. (2019)	Ship-based carbon capture onboard of diesel or LNG-fuelled ships	MEA + PZ	2	Inland ship 1.280 kW; general cargo vessel 8.000 DWT, 3.000 kW	CC is technically feasible for onboard application; costs per ton of captured carbon are lower the bigger the ship/plant	Both reference ships are equipped with dual fuel engines (Diesel/LNG); diesel options are more expensive due to additional refrigeration unit for liquifying CO_2
Awoyomi et al. (2019)	CO_2/SO_2 emission reduction in CO_2 shipping infrastructure	NH_3	3	CO_2 carrier, 10.800 kW	Maximum available waste heat is sufficient to achieve a capture-rate of 70 %	NH_3 as solvent allows simultaneous removal of SO_x and CO_2; by-products can be sold; simulation for different operation modes of the vessel; simulation of CC process based on Munmorah pilot plant
Lee et al. (2020)	Comparative Analysis of On-Board Methane and Methanol Reforming Systems Combined with HT-PEM Fuel Cell and CO_2 Capture/Liquefaction System for Hydrogen Fueled Ship Application	MEA	2	General cargo vessel, 3.000 DWT, 3.800 kW	Alternative for hydrogen fuelled ships is feasible, but more extensive research is needed	Energetical analysis of methane/methanol-based systems for comparison; general cargo ship with shaft power of 3800 kW as reference for simulation
JSTRA et al. (2020)	Roadmap to Zero Emission from International Shipping	KS-1™	2	Container vessel, 20.000 TEU, 55.000 kW	Further funding and research are needed to achieve outlined goals	Conceptual design for a 20.000 TEU container vessel trading between Far East and Europe; specific technical issues for onboard installation are identified
Awoyomi et al. (2020)	Process and Economic Evaluation of an Onboard Capture System for LNG-Fueled CO_2 Carriers	NH_3	3	CO_2 carrier, 10.305 kW	Operational profile of the specific ship must be studied to designing the CC system	Economic evaluation of NH_3 process developed by Awoyomi et al. (2019); EGR reduces plant size and increases capture efficiency; lowest cost achieved were 117 \$/t_{CO_2} at a capture-rate of 90 %
Stec et al. (2021)	Reducing the energy efficiency design index for ships through a post-combustion carbon capture process	MEA	2	Medium range tanker, 47.000 DWT, 9.960 kW	Post-combustion CC is feasible to fulfil EEDI requirements just by utilising waste heat	Simulation investigating CC process under various ambient conditions (arctic, ISO, tropical); capture-rate is adjusted to the available waste heat; exhaust gas desulphurisation to protect amine solvent from degrading
Lee et al. (2021)	Novel methodology for EEDI calculation considering onboard carbon capture and storage system	MDEA + PZ	2	Container feeder, 3.840 TEU, 53.000 DWT, 18.200 kW	CO_2 capture-rate needs to be higher than intended EEDI reduction to compensate additional power demand for CC	Waste heat of the engine is sufficient to supply energy required for regeneration of the solvent in all cases simulated; compression and liquefaction consumes more power than CC process itself
Einbu et al (2021)	Onboard CO_2 capture from ship engines	MEA	2	CO_2 carrier, 5675 kW	Available waste heat is not sufficient to supply energy required for capture-rate higher than 50 %	Part of the Northern Lights project; fuel afterburner required to increase available heat for regeneration of solvent; reduction of absorber height and increase of solvent flow rate offer trade-off opportunity CAPEX/OPEX
Ovcina (2020)	K Line to test world's 1st CO_2 capture plant on board its ship	Not specified	7	Bulk carrier, 88.715 DWT, 9.960 kW	N/A	CC-Ocean project is funded by the Japanese government; world's first carbon capture application onboard a vessel; no scientific papers published

[1] The TRL in this table is reflecting the state of the research described in the respective article/report. It is not indicating the TRL of the corresponding technology and does not necessary correspond with assessment within this study.

3.1.2 Adsorption by solid sorbents

Adsorption describes the adherence of atoms, molecules or ions from a gas or liquid to an adsorbent surface, on which a film of adsorbate is formed. When the adsorption is occurring through van der Waals forces at the adsorbents surface, the process is defined as physisorption. Contrary to that, when adsorption proceeds through a covalent bonding of the substances to the surface, it is referred to as chemisorption (Ben-Mansour et al., 2016; Wilcox, 2012).

Chemisorption is proceeding much slower than physisorption, caused by the electron transfer which is required to establish a proper bonding to the adsorbent. Based on the comparably slow pace of adherence, chemisorption is an inappropriate method when large volumes of CO_2 are to be captured from the flue gases. The principle of physisorption is providing a more suitable solution in terms of faster capturing process and lower energy requirements for sorbent regeneration (Ben-Mansour et al., 2016; Wilcox, 2012).

Another difference between these two processes is the temperature, at which the process is occurring. A relatively low heat of adsorption is typically connected to physisorption, whereas high adsorption heat usually refers to chemisorption (Ben-Mansour et al., 2016; Wilcox, 2012).

The adsorption of CO_2 takes place in an adsorber unit, which is containing solid sorbent materials, arranged in columns. Flue gas is perfusing the adsorber where it is contacting with the surface of the adsorbent. The adsorbent itself is specifically designed for a selective adsorption of CO_2 from the gas mixture. Especially CO_2 contained in dilute mixtures, can effectively be separated by adsorption (Wilcox, 2012).

For further information and data on post-combustion capture adsorption by solid sorbents, see *8.2*.

3.1.2.1 Advantages and drawbacks

Drawbacks of this technology in connection with the potential use in flue gases are mostly connected to the properties of the adsorbents. Most of the physical adsorbents are operated at low-temperature conditions, which are unlikely to be prevalent in flue gases (Sayari et al., 2011). Especially at higher temperatures, the capacity of the physical adsorbents is decreasing (Wang & Song, 2020). Amine adsorbents are affected by oxidation and further by thermal degradation.

Another major drawback of these kinds of adsorbents is their incompatibility to SO_x and NO_x contaminants in the flue gas since it causes them to degrade (Wang & Song, 2020). The efficiency of zeolites and MOFs is affected by the presence of water vapour in the flue gas, since these adsorbents preferentially adsorb water before CO_2 (Sayari et al., 2011).

Favourable for physical adsorbents, such as zeolites and MOFs, is their good CO_2 capture capacity at high pressures and low temperatures. Solid amine-based sorbents, however, are able to capture high capacities at low partial pressures of

CO_2. Further, they also show better CO_2 selectivity than physical adsorbents (Wang & Song, 2020). Adsorption technologies in general have a high potential in capturing CO_2 directly from air, rather than from (high temperature) flue gases (Wang & Song, 2020). Nonetheless, advances in the technology as well as in new adsorbents have been made, which is demonstrated by the Svante pilot plant and its capability of CO_2 capture from flue gas (Svante Inc., 2021).

3.1.2.2 Research for the application on-board

Only one single study could be identified, which is exclusively focussing on the application of adsorption by physical solvents in marine applications. The second research presented in this section developed a model for the application in road transport but is claiming that the technology could be sized up to be feasible for the capture of CO_2 from ships exhaust. It is worth noting, that both identified articles are applying Temperature-Swing-Adsorption (TSA).

In 2018, **Erto et al.** published the results of their research, investigating the potential of alumina supported K_2CO_3 for the capture of CO_2 from the exhaust of marine diesel engines. In comparison to absorption with solvents, the authors name several advantages of the fixed-bed adsorption process: use of non-hazardous and non-corrosive materials as well as a high operating flexibility (able to manage variable inlet gas flow and CO_2 concentrations). Further, the chosen sorbent (K_2CO_3) can capture CO_2 at temperatures below 100 °C and in humid conditions. The regeneration temperature is generally lower than 200 °C. Since sulphur dioxide (SO_2) is competing with CO_2 for the adsorption, a sulphur scrubber is needed when the ship is operating on high sulphur fuels (Erto et al., 2018).

Following lab-scale experiments to determine the best operating temperatures and K_2CO_3 concentration, a case study is conducted for a RoPax ferry (Erto et al., 2018). The ferry is propelled by a 4,350 kW engine running on MGO and is operating on a one-hour route. Based on the lab scale results, a conventional TSA unit is designed. The adsorption takes place at 60 °C and the regeneration at 120 – 200 °C using steam. The proposed system consists of two columns: one being in service, one being generated. To handle the exhaust flow of the case study vessel, the sorbent beds are calculated to be 3.89 m in diameter and 0.56 m in height. Unfortunately, the regeneration time is almost double the time required to saturate the adsorbent with CO_2, i.e., the adsorber is operating effectively only for half of the cycle time. Nevertheless, a CO_2 reduction rate of 27.8 to 28.4 percent (including the additional power required to operate the plant) can be achieved (Erto et al., 2018).

Erto et al. (2018) conclude, that the plant design has large margins for improvement, especially in regard of the optimisation of the CO_2 loading capacity of the K_2CO_3 sorbent. Since the proposed process is operating at similar temperatures as the absorption process using MEA, but without the typical drawbacks of such, the proposed method is seen as promising for the marine application (Erto et al., 2018).

Sharma and Maréchal (2019) have developed a concept for an energy self-sufficient CC and liquefaction system. In the centre of the proposed technology is a TSA-cycle using PPN-6-CH2-TETA as adsorption material for CO_2. Besides the adsorption cycle, the system consists of a Rankine cycle, a heat pump and a CO_2 compression and liquefaction unit. Thereby, the Rankine cycle utilises the waste heat available in the exhaust stream to provide the mechanical power required to drive the heat pump compressor and the CO_2 compressor. In the simulation, the system reached a 90 percent capture-rate. Even though the model and simulations have been designed for a truck engine, the researchers claim that this technology can be scaled up to any internal combustion engine within the transportation sector, also including marine diesel engines (Sharma & Maréchal, 2019).

3.1.3 Membrane technology

Post-combustion CC through membrane separation is a widely researched topic with continuously growing interest in the past two decades (Siagian et al., 2019). Membranes are used in various industrial fields due to their high ability for separation, which is one of the biggest merits of this technology (Wilcox, 2012).

For further information and data on post-combustion membrane technology, see 8.3.

3.1.3.1 Advantages and drawbacks

For commercial applications of CO_2 removal from natural gases, polymeric membranes are preferably used, due to their high selectivity, ease of fabrication into different configurations and low manufacturing costs. The downside of the polymers is the physical aging and plasticisation, which occurs when CO_2 is solubilising in the membrane and therefore lowering the permeability of the membrane. This is negatively affecting the efficiency of the separation process (Siagian et al., 2019).

Both membrane technologies, membrane gas separation (MGS) and membrane contactors (MC), require intense pre-treatment of the flue gas. This is due to the fact that impurities in the flue gas are negatively influencing the performance of the membrane. Membrane fouling, membrane degradation and the wetting phenomenon are possible results, if harmful contaminants (including water) are not removed from the flue gas, upstream of the CO_2 capture process (Siagian et al., 2019).

Favourable for MGS systems is the unnecessity of the liquid absorbent in comparison to MC, which means that there is no need of additional equipment for chemical regeneration in this process. Nevertheless, due to the higher energy penalty for flue gas compression, MGS results in higher operational costs than MC. In favour for both technologies is the general possibility of retrofitting into existing systems (Siagian et al., 2019).

3.1.3.2 Research for the application on-board

The membrane technology is not yet readily developed for CC from flue gases, since major problems still need to be solved to increase the lifetime of the membranes. This is also reflected by the consulted literature, where few articles could be identified, that is considering the application of membrane technology for CC from marine exhaust gases.

Thereby, **Su et al. (2020)** mainly focussed on options to utilise waste heat from marine Internal Combustion Engines (ICEs) and integrated the membrane technology for CC in their concept, as it is expected to significantly decrease the required energy for CC, once it is available for commercial use. The simulation is developed based on a marine ICE, fuelled by LNG. The captured CO_2 is liquified by using the cold energy generated from evaporating the LNG, prior combustion. Furthermore, CO_2 is used as working fluid within one of the waste heat recovery cycles (Su et al., 2020). Even though, CC technology is not the focus of this study, it shows that the combination of LNG-evaporation and CO_2-liquefaction has high potential for energy savings.

Oh et al. (2022) investigated the process design of on-board membrane carbon capture and liquefaction systems for LNG-fuelled ships. The study is applied on a 3,800 TEU container feeder. It is concluded that with the application of membrane carbon capture technology on-board LNG-fuelled ships and by varying the liquefaction process, it is possible to achieve similar or even slightly lower energy consumption as reference amine-based system, in addition, by changing CO_2 permeance (transmission rate of the membrane), the major equipment size can be reduced to only 20% of the reference system.

The **HyMethShip** project, a pre-combustion CC concept, is including a membrane reactor, which is combining the conversion of methanol into H_2 and CO_2 and the separation of H_2 in one process step (Zelenka et al., 2019). Nevertheless, the HyMethShip concept is a pre-combustion application of membrane technology.

3.1.4 Cryogenic carbon capture

The technology of cryogenic separation is making use of transformational phase changes of CO_2, when the CO_2 is cryogenically cooled in the flue gas stream from fuel combustion. More precisely, the CO_2 is changing from its gaseous phase directly to the solid phase, so that the solid CO_2 can efficiently be separated from the flue gas stream. Generally, all other flue gas contaminants can be separated in the same way as the CO_2, which is one of the advantages this technology offers. The application of this technology for the specific use in CC increased recently, due to overall good capture performance (Song et al., 2019).

Cryogenic carbon capture (CCC) is making use of the phase change of gaseous CO_2 directly into a solid. This process is called "de-sublimation" and is achieved by cryogenic cooling of the flue gases.

For further information and data on post-combustion capture with cryogenic, see 8.4.

CCC technologies have successfully been tested in pilot plants at different scales (Baxter et al., 2019; Sustainable Energy Solutions, 2021c). CO_2 capture-rates of more than 90 percent were achieved under real flue gas conditions. Further, the capability of the CCC process for successful separation from other flue gas components was proven (Sustainable Energy Solutions, 2021b). Small-scale Compressed Flue Gas (CFG) pilot plants have been running for several weeks at different locations, with capture-rates of up to 95 percent. External Cooling Loop (ECL) systems have been demonstrated in different environments in pilot plants, also in relation to the usage of various fuels such as coal, natural gas, and biomass mixtures. In a coal-fired power plant test of 600 running hours, an average capture rate of the ECL system of 91 percent was proven (L. L. Baxter et al., 2019; Sustainable Energy Solutions, 2021b). The performance tests of the described pilot plants have been carried out at fluctuating concentrations of 5 to 15 percent CO_2 in the flue gas. When steady-state operation was attained, the average flue gas concentration was at 8 percent CO_2.

Compared to MEA absorption technologies for CC, the CCC technology has high potential for cost savings (Lang, 2016). When integrating the CCC process into the design of a newbuild power plant, the CAPEX of a CCC plant is only at 50 percent of the costs of an amine-based absorption process. The same applies for the energy penalty, where CCC technology requires only half of the respective load of an MEA plant (Baxter et al., 2011; Lang, 2016).

Contrary to MEA absorption, CCC requires only the electricity to run the cryogenic processes, but no excessive heat energy for solvent regeneration. Resultingly, the load requirements of the technology are lower, which is decreasing the fuel costs (OPEX) to a lower level than MEA technologies. The CAPEX for a CCC system is lower than conventional MEA absorption technologies (Baxter et al., 2011).

Comparing various options for post-combustion CC, Roberts (2021) states, that the OPEX in CCC are 50 percent lower than in MEA absorption and the CAPEX are 30 percent lower, respectively. This statement of lower costs for CCC than for MEA absorption is supported by an interviewed expert (Malmgren, 2021).

3.1.4.1 Advantages and drawbacks

Provided that an existing energy system is capable of supplying sufficient electric energy for the CCC process, the technology can be retrofitted to any combustion process. In such case, apart from the additional components of the CCC plant which need to be installed, no further changes in the power plant are required (if the existing power plant had flue gas treatment facilities already in place). Furthermore, CCC is less energy consuming than the commonly used CC technology of chemical absorption (Baxter et al., 2011; Safdarnejad et al., 2015). High CC efficiencies of 90 percent and more have been validated in pilot plants (Lang, 2016). This contributes to lower costs for the technology, which is favourable for the operator of the plant.

As stated in the working principle above, the cryogenic process is also able to remove particles and pollutants such as SO_x, NO_x, Hg and HCl from the exhaust gases, even with high efficiencies, which is seen as a major advantage of this technology. Nevertheless, high amounts of impurities in the flue gas still must be pre-treated by adequate facilities (e.g., SO_x scrubbers in the flue gases from fossil-fuelled ICEs) and cannot be replaced by a CCC plant (Malmgren, 2021). Unfortunately, the reuse of waste heat energy from other processes for performance improvements of this technology is not possible, which means that all the required energy for the cryogenic processes needs to be provided by electrical generation. CCC technologies are producing waste heat and can be integrated into the existing waste heat regeneration cycle of a power plant, but for on-board applications the additional waste heat is not desirable, since there is already an abundance of waste heat generated on-board.

3.1.4.2 Research for the application on-board

Cryogenic separation is a mature process in the industry and applied for gas separation but highly energy intense. Therefore, research on CCC is concentrating on ways to increase the energy efficiency of the related processes.

In 2020, **Willson** published a report evaluating the application of an advanced cryogenic carbon capture (A3C) process on-board vessels. The report takes a holistic approach, considering technical and economic impacts as well as the impact on the operation of the vessel and required shoreside infrastructure. Case studies for two example vessels are carried out.

For more information on the A3C technology, see 8.5.

The **decarbonICE** project, on which no scientific papers have been published so far, is developing several conceptual designs for an on-board CC system with an integrated solution for long-term storage (MDC, 2021). The project is developing a CCC plant for the application on LNG and MGO/HFO fuelled ships, making it feasible for retrofit as well as for newbuildings. The captured CO_2 is stored as dry ice on-board and will be shaped in a certain way, to so-called Carbon Decent Vehicles. These vehicles can be released into the sea, where they will sink with high speed and dig themselves into the seabed sediments. Therefore, the decarbonICE project is also including the development of a production system for manufacturing of the Carbon Decent Vehicles, a launching system for these, analysis to find the optimal shape for the vehicles and analysis of the CO_2 storage in seabed sediments (MDC, 2021). Nevertheless, the storage in seabed sediments is seen critical, since the consequences of a concentrated gas leakage into the surroundings are not well researched until now and significant knowledge gaps exist in this regard (Harvey et al., 2012). Besides these environmental and technical issues, also a cost analysis and safety and risks assessments are addressed by the project (MDC, 2021). When the vessel is equipped with the decarbonICE technology and is using carbon neutral biofuels, the system could achieve carbon negative shipping (MDC, 2021).

3.2 Pre-combustion capture

Pre-combustion CC is referring to the removal of CO_2 from a synthesis gas (syngas). The syngas is either obtained by the gasification of carbonaceous fuels, e.g., coal, heavy oils or hydrocarbon fuels, or the catalytic reforming of natural gas with O_2. Fundamentally, the created syngas consists of CO and H_2. With the utilisation of steam, the CO is converted into a syngas of CO_2 and H_2, so that the resulting mixture is (almost pure) H_2 and CO_2. In this gas mixture, the actual CC process is applied (Kanniche et al., 2010).

For further information and data on pre-combustion capture, see 8.6.

The pre-combustion CC technology is mature and in commercial application worldwide. A lot of industrial applications for the gasification of carbonaceous fuels, natural gas reforming and the processing of natural gas are existing since several years already (Global CCS Institute, 2012). In pre-combustion CC by absorption, most mature and highest rated on TRL 9 are the liquid physical absorbents, Rectisol and Selexol, used in natural gas processing and fuel gasification (Kearns et al., 2021).

In recent research, H_2 is considered to be a promising fuel for the decarbonisation of ICEs (Babayev et al., 2021). Currently, H_2 is utilised in fuel cells and gas turbines, but the conversion of carbonaceous fuels to H_2 by pre-combustion capture processes is providing a base for the further H_2 usage in ICEs (Lip et al., 2016).

In conclusion, although the technology of pre-combustion CC for land-based applications for CO_2 removal and H_2 generation is mature, it is not applied in connection with ICEs so far. The functional interaction between pre-combustion

CC from carbonaceous fuels and the subsequent combustion of H_2 in ICEs still need to be proven.

3.2.1.1 Advantages and drawbacks

One of the advantages of the concept of pre-combustion CC is the production of H_2, which can be used for energy generation (Cormos et al., 2018). In this way, Jansen et al. (2015) see the potential of the pre-combustion CC technology to contribute to a faster implementation of H_2 as an alternative fuel. Based on the working principle of this technology, the CO_2 is captured at an elevated pressure, which is decreasing the energy consumption for the subsequent compression for CO_2 storage (Jansen et al., 2015). The energy demand for the capture and stripping process itself is significantly lower than in the post-combustion CC, due to the higher CO_2 content in the syngas, which is ultimately making the capturing more efficient (Eldardiry & Habib, 2018).

Disadvantageous for this technology is the high CAPEX, connected to the components for the syngas generation. Therefore, in comparison to post-combustion CC, pre-combustion capture is less economically favourable for the owner (Jansen et al., 2015).

3.2.1.2 Research for the application on-board vessels

No literature for the application of absorption or adsorption technology in combination with pre-combustion capture on-board seagoing ships have been found. Only one concept for precombustion capture could be identified: the HyMethShip. The HyMethShip concept, which has been named as example for an approach towards a circular economy for carbon, applies membrane separation to separate H_2 from the other syngas components.

The **HyMethShip** project aimed to develop and assess a complete system, i.e., from bunkering of methanol throughout the propulsion, energy generation and temporary storage of captured CO_2 on-board, until the CO_2 is discharged to port facilities (Zelenka et al., 2019). This is also including economic and life-cycle assessments. The project includes the optimisation of a marine ICE for the combustion of H2, to make the technology feasible for a wide range of vessels. The core of the HyMethShip's propulsion system is the pre-combustion CC system (Zelenka et al., 2019), of which a schematic is shown in Figure 3.

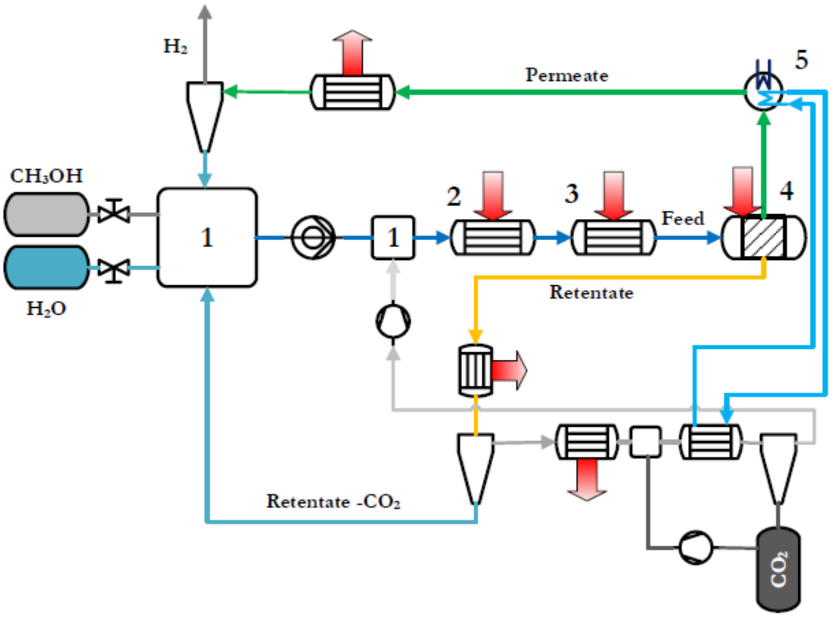


Figure 3. Schematic of the HyMethShip CC system

In the mixing chamber (1) methanol and water from the storage tanks are mixed before being fed into the economiser (2) and afterwards into the evaporator/superheater (3). The resulting gas mixture is then fed to the membrane reformer (4), which is combining two process steps in one (Zelenka et al., 2019). The catalytic methanol reforming as well as the separation process of H_2 via a membrane takes place under the same reaction conditions. All three units (economiser, evaporator/superheater, membrane reactor) are utilising waste heat, generated by the combustion of H_2 within an ICE. The membrane reactor (4) is splitting the mass flow into two streams. The H_2-selective carbon membrane allows generated H_2 to be removed as permeate. The permeate stream mainly consists of H_2 and water. Latter is removed by condensation and fed back into the process before the pressurised gaseous H_2 is supplied to the engine. The other stream, the retentate, is cooled down to condense remaining water and methanol, which are fed back into the process. The remaining gaseous phase is containing the CO_2, produced within the membrane reactor. By cooling down this gas stream to -45 to -55 °C, the CO_2 partially condenses and can be stored in liquid phase. The non-condensed stream of gases is led back into the process. The cooling needed to condense the CO_2 is generated by an absorption chiller, which is utilising waste heat for its operation. The technical key issues within this process are to control the energy transfer into the membrane reactor, to control the chemical composition and the partial pressures. (Zelenka et al., 2019).

The HyMethShip system is expected to achieve 97 percent CO_2 capture-rate and practically eliminate sulphur, PM and NOx emissions (Zelenka et al., 2019). Energy efficiency is expected to be more than 45 percent higher than combusting renewable methanol directly and capture the CO_2 after the combustion. To demonstrate the feasibility of the system, an onshore demonstration plant with an engine in the range of 1,000 to 2,000 kW will be developed. The project ended in in 2021.

3.3 Oxyfuel combustion

Oxyfuel combustion is another approach towards the capture of CO_2. Rather than filtering the low concentrated CO_2 out of a mixture of exhaust gases, this technology allows to produce exhaust gases consisting mainly out of CO_2 and water vapour (Wilcox, 2012).

By combusting the fuel in an O_2-enriched environment, reducing the portion of other gases usually contained within the combustion air, dilution of the CO_2 in the exhaust is avoided. When the water vapour is condensed out, the remaining flue gas ideally consists of CO_2 only. The CO_2 can be captured, compressed, and brought to the intended aggregate phase for storage (Wilcox, 2012).

For further information and data on oxyfuel combustion, see 8.6.

3.3.1.1 Advantages and Drawbacks

The main advantage of oxyfuel combustion is the comparably easy capture of CO_2, since the exhaust stream ideally consists of CO_2 and water vapour only (Wilcox, 2012). Further, due to the absence of N_2 in the combustion, NO_x emissions can almost be avoided completely (Wilcox, 2012).

Disadvantageous are the high investment costs and the electricity demand of the required *Air Separation Unit (ASU)* (Johnsson, 2021; Normann, 2021). The high efforts necessary to avoid a slip of air into the combustion process and the need to replace the engine are the main reasons for this technology not being considered as feasible for retrofit applications (Wilcox, 2012; Johnsson, 2021; Normann, 2021).

Since oxyfuel combustion processes are not requiring heat for regeneration, as chemical absorption processes do, they might be competitive in processes where only little waste heat is available, by achieving significantly lower costs of captured CO_2 (Gardarsdottir et al., 2019).

3.3.1.2 Research for the application on-board vessels

Currently, there are no publications available presenting concepts for the application of oxyfuel combustion on-board internationally trading vessels. **Wang et al.** (2017) evaluated the feasibility of different CC technologies for vessels and concluded that oxyfuel combustion could potentially be applied on-board, once it is ready for commercial use. Nevertheless, they also state that new materials for engine components might be required, to withstand the high combustion temperatures. Further, the high-power demand for the ASU might be disadvantageous for the application of this technology on-board. Additionally, the need to install the equipment in restricted sites is evaluated as a serious problem for the application on-board vessels (Wang et al., 2017). The safety issues connected to the production and storage of large amounts of O_2, which are requiring the installation in restricted sites, are seen as a major problem for marine applications by interviewed experts as well (Normann, 2021).

The feasibility study by **Li et al.** (2020) investigates the conversion of a conventional diesel-driven inland water ship to a propulsion drive powered by oxyfuel combustion. Thereby, the main focus was to reduce the consumption of O_2 and at the same time, to attain the original energy output of the engine. However, the study is limited on the conversion and optimisation of the engine and feasible solutions regarding space requirements and possibilities on-board, as well as economical aspects are not considered. The concept contains the on-board storage in bottles of the required O_2, rather than producing it by an ASU (Li et al., 2020).

4 On-board carbon capture projects

Samskip communicated in 2022 that their ships will use CO_2 capture solution from **Value Maritime** with commissioning in early 2023. The *Filtree system* is stated to capture 30 percent or more of CO_2 emissions. The systems also remove sulphur, particulates (Samskip, 2022). In 2023, it was also announced that a carbon capture solution has been installed on-board the medium range tanker Pacific Cobalt from Eastern Pacific Shipping. The system, which is said to filter out sulphur and 99% of particulate matter, includes a CC module that can capture up to 40% of CO_2 emissions from the vessel's main and auxiliary engines.

The CO_2 is captured in a solvent that is stored on-board tank with storage capacity of over 200 ton of CO_2. Once the tank is full, the chemical will be pumped ashore and further delivered to end users, who will be able to release the CO_2 on demand. The solvent will be returned to the vessel for reuse to further capturing. (Value Maritime, 2023a). In 2022 and 2023, LR respectively ABS has granted approval in principle (AIP) to Value Maritime for their Carbon Capture System onboard seagoing vessels. (Value Maritime, 2023b).

Wärtsilä has demonstrated and run pilot test installations of a scrubber that is presented as CCS-ready with a 70 percentage CO_2 capturing rate which is claimed possible to increase to reach 80 percent capturing rate with a solvent optimised for marine engine exhaust gas. The system will be tested on-board the ethylene carrier Clipper Eos during 2023 with a potential to be introduced on the market 2025 (Wärtsilä, 2023).

In 2021, **Alfa Laval** performed tests in common with Japan's National Maritime Research Institute (NMRI) on-board a ship that belonged to a Japanese shipowner with an Alfal Laval sulphur oxide scrubber installed (PureSOx). The tests showed that a modified PureSOx-system also where able to absorb CO_2 from the auxiliary diesel engines, while the scrubber was operating in closed loop mode. (Alfa Laval, 2021)

Monaco-based tanker operator **Scorpio Tankers** (2022) has entered a memorandum of understanding with Californian company **Carbon Ridge** to collaborate on the development of on-board carbon capture for maritime vessels. The agreement addresses the collaboration for detailed front-end engineering, design, and validation process with a small-scale test unit on-board one of Scorpio Tankers' product tankers. (Scorpio Tankers, 2022).

South Korean shipbuilder **Daewoo Shipbuilding & Marine Engineering** (DSME) has completed a verification test of its carbon capture and storage technology on board an LNG carrier owned and operated by GasLog. DSME has developed the system in common with Hi Air Korea since 2020. The technology uses ammonia water absorbent and dissolves carbon dioxide emitted by the ship's engines into an aqueous sodium hydroxide solution and converts it into a mineral form. The absorbent is regenerated and reused during the process. (Offshore Energy, 2022).

Compact Carbon Capture, a Baker Hughes Venture has developed a CC that uses centrifugal forces to distribute the absorption solvent. Enabling more effective solvent distribution that enhances mass transfer. The technology is intended also for use on-board ships. (Madsen, 2022).

In addition, and as example, also the following companies has announced plans for system development or pilot installations on-board CC:

- Deltamarin
- TECO 2030 & Chart Industries, Inc.
- Langh Tech

5 Comparative technology assessment for on-board carbon capture

5.1 Methodology for the comparative assessment

The master thesis made by Havenstein and Weidenhammer (2021) made within the scope of this project, developed a methodology for technology assessment of on-board CC. The process included the following research questions:

- Which technologies are most promising for CC on-board vessels in combination with internal combustion engines?
- Which limitations, constraints and criteria are important for the applicability of CC technology on-board vessels?
- How well does CC on-board perform in comparison to other solutions for decarbonising shipping?

The methodology developed by Havenstein and Weidenhammer (2021) is not the only way to assess on-board CC but could be used as guidance to find important areas to take into consideration when evaluating CC systems for specific ships or in more general terms.

Post CC with the chemical solvent MEA is the most common technical solution being assessed and described in the literature for carbon capturing in general as well as for on-board CC. Also, CC with MEA is also widely used as benchmark process for comparisons between CC technologies why this process also been used as the base case other technologies being benchmarked towards in this study.

The conducted assessment focussed on the technical feasibility and specifications of CC technologies for the application in combination with internal combustion engines (ICE). This since it is probable that newbuildings are still going to be equipped with ICEs in the foreseeable future (Bullock et al., 2020). Also, only CC technologies that have been developed to a certain technology maturity was included in the assessment.

The feasibility of each included technology for on-board application was evaluated in a first stage with the following criteria's:

1.1 Safety and stability: Are the ship's safety and/or stability negatively impacted when installing the CC technology on-board? Are there additional hazards or an increased risk for the operating crew? How would a failure of the CC plant impact the vessel? How do the additional installations affect the metacentric height (GM) and thereby impacting the stability?
The technology bearing the lowest risk for the ship's safety and having the lowest impact on its stability are rated best.

1.2 Ship's movement and vibration: Is the CC technology negatively impacted by the movement of the ship at sea? Could vibrations on-board reduce the efficiency of the CC plant? The technology impacted the least by movement and vibrations is rated best.

1.3 Fluctuations in energy demand: Is the technology capable to operate reliably when the energy demand is fluctuating? Due to the different operation modes of a vessel the energy demand is changing, i.e., the use of fuel is variable and thereby the generated mass flow of CO_2 is fluctuating. Especially during manoeuvring, the energy demand may change rapidly.

The CC plant must be able to follow these fluctuations, i.e., it has to provide sufficient fuel to deliver the required energy (pre-combustion) or capture CO_2 reliably from a fluctuating exhaust gas flow (post-combustion).

The technology being most capable to meet the fluctuating energy demand and still reliably capture CO_2 under these conditions, is rated best.

1.4 Impurities in fuel/exhaust: How is the technology affected by impurities in the fuel/exhaust stream? Is the technique feasible to capture CO_2 from all kinds of engines and fuels or is it limited to a certain engine or fuel type? The technology being the least affected by and tolerant towards impurities in the fuel/exhaust stream is rated the best.

For each criterion, a ranking of the CC technologies in regard of their performance was established.

To evaluate which CC technology is the most promising for the application on-board vessels, the best-ranked technologies in the first stage were thereafter evaluated in relation to selected constraints set out by the specifics of the on-board application as well as demands from shipowners (e.g., space and energy requirements, weight, cost, and technical maturity). The same ranking system as in the first stage were applied in the second stage. The following criteria were evaluated in the second step:

2.1 **Space requirements**: The vessel's purpose lies in the transport of goods and therefore the value of a ship is strongly dependent on the space that can be utilised for cargo. The less space is consumed for the installation of the CC plant and the related tanks for intermediate storage of CO_2, the more cargo can be carried, and a higher revenue can be achieved. The less space is required, the higher the CC technique is ranked.

2.2 **Additional weight**: Ships are designed to carry a defined weight of cargo, the so-called deadweight tonnage (DWT). Weight added by the installation of a CC plant and the intermediate storage of captured CO_2, as well as required chemicals, is reducing the DWT. Therefore, the technology adding the least weight, i.e., reducing the ships transport capacity the least, is evaluated best.

2.3 **Energy requirements**: All energy required to run the plants on-board a ship needs to be generated on-board, i.e., the energy required to run the CC plant needs to be produced by generators on-board. A higher energy demand is increasing the operational costs (fuel, maintenance). Therefore, the assessment is ranking the technique with the least energy requirements best.

2.4 **Capture-rate**: Which CO_2 capture-rate can be achieved? Considering the additional energy consumption: what carbon reduction rate can be achieved? The more CO_2 is captured, the better the technology is evaluated in the assessment.

2.5 **Investment costs**: The initial investment costs are of high importance for the shipowner. High investment costs may make it uneconomical to invest in such technology and will increase the payback period of an investment. The lower the investment costs, the higher the technology is ranked.

2.6 **Operational costs**: How expensive is it to capture one ton of CO_2? The operational costs mainly originate from consumed energy and consumables. The lower the operational costs, the more economical the operation of the CC plant, the better the technology is ranked in the assessment.

2.7 **Maturity leve**l: How far is the technology developed? When is the technology ready to be applied in commercial on-board operation? Since actions for the mitigation of climate change need to be conducted as soon as possible, the technology with the highest maturity level is preferred i.e., ranked best in the assessment.

The technology which was rated the best when combining the seven criteria above were considered the **most promising technology for newbuildings**. However, ships have a long lifespan and retrofitting of new technology for emission reduction of existing vessels is also essential. Therefore, additional criteria were added to the assessment, to evaluate the feasibility of the technologies as retrofit solutions. The technologies have therefore also been ranked according to the intensity of required changes in the technical installation on-board. The less changes needed, the higher the technology is ranked. The following aspects was considered for retrofit:

2.8 Engine: Is it possible to modify the installed engine(s) or does the engine need to be replaced to run with the CC technology?

2.9 Fuel: Does the fuel and/or fuel system need to be changed to meet the requirements of the CC technology?

2.10 Repowering required: As already described in criteria 2.1, all power required to run the CC plant needs to be generated on-board. Is the installed equipment on-board able to provide sufficient power, or does additional generators need to be installed, increasing the investment as well as the operational costs?

The technology rated the best in the criteria of both second steps overall, is the one requiring the least changes to the existing design and technical systems of the ship and at same time performing satisfactory in the general criteria for CC technologies and been evaluated as the **most promising technology for retrofitting** of existing vessels with CC technology.

5.2 Comparative assessments

Most of the criteria for the evaluation of the CC methods are depending on each other. For example, the capture-rate of each technology could be increased by scaling up the complete installation, but this would increase the space and energy requirements. Furthermore, the data retrieved from literature review and expert interviews is lacking comparable figures. Consequently, the assessment is discussing the properties of the included technologies for each criterion, providing a reasoning for the performed ranking.

In general, almost all CC technologies can be adapted in some manner to run in combination with an ICE.

It needs to be pointed out that there are numerous other solvents which could be used in post combustion CC. Apart from the MEA benchmark solvent, the assessment is taking NH_3 and PZ into consideration as well. Studies for all these solvents have been carried out to evaluate the application on-board vessels.

Post-combustion adsorption in general is developed quite far (TRL 6) for the application in industrial processes, but this technology is not effective to capture CO_2 from such low concentrations as prevalent in the exhaust gases of ICEs, i.e., it is not feasible to run in combination with ICEs. Nevertheless, Erto et al. (2018) conducted proof-of-concept tests for an adsorption process using alumina supported K_2CO_3 as sorbent, to be applied on-board a small ferry. The problems that occur in this research are similar to the problems found by other researchers for adsorption technology and are hindering the technology to achieve a higher TRL.

Membrane technology has not yet been researched for the application on-board, but its general characteristics allows it to be applied in surroundings with a confined space. Membrane appliances for separation of CO_2 are still under development (TRL 5) and require extensive flue gas pre-treatment to capture CO_2. However, with such pre-treatment they are feasible to run in combination with ICEs.

CCC has been tested in pilot-scale for CC from industrial processes and power plants and achieved TRL 6 for such appliances. However, these tests do not consider the constraints of the application on-board a vessel. The study by Willson (2020) assessed the appliance of the A3C process for shipboard application in combination with ICEs. Hence, the A3C process is included in the assessment to represent cryogenic separation, since it is a feasible way to apply CCC on-board, although the TRL is lower than for other CCC technologies.

All pre-combustion technologies have in common, that they convert fuel into a syngas. The H_2 fraction out of this syngas is used as fuel for a connected engine, i.e., the ICE needs to be able to run on H_2. Such H_2 engines are still under development and have currently achieved TRL 7.

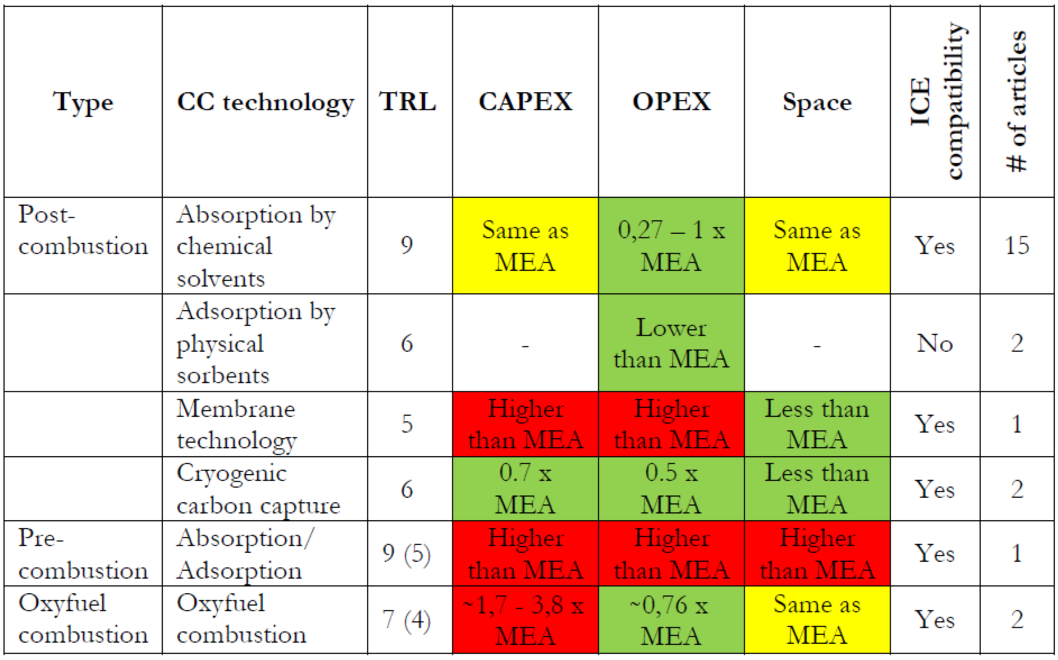
Although, the pre-combustion CC process is mature in coal-fired power plant applications, it has not yet been applied in combination with ICEs. Since the subsystems of the pre-combustion CC technology have been validated, it is assigned TRL 5. Absorption and adsorption technology for pre-combustion capture is assessed in common in stage 1 of the assessment.

Whereas pre-combustion absorption- and adsorption processes remove CO_2 and other pollutants from the syngas stream, leaving an almost pure stream of H_2 for combustion, the membrane-reactor of the HyMethShip concept works conversely. The H_2 contained in the syngas is removed as permeate, leaving a CO_2-rich retentate stream. The difficulties to control the process in the membrane reactor, combining several steps of the common pre-combustion capture process, are currently limiting the HyMethShip concept to achieve a higher TRL, resulting in an exclusion from the assessment (TRL < 4).

Similar to pre-combustion capture technologies, oxyfuel combustion requires a specialised ICE that is able to combust fuel in an oxygen-enriched environment. Difficulties in keeping the parameters of oxyfuel combustion in a manageable range require further development, before the oxyfuel combustion process can achieve a higher TRL. Nevertheless, ICEs for oxyfuel combustion have achieved TRL 4. Therefore, the technology is considered in stage 1 of the assessment. The required ASU is not a limiting factor since those are already commercially available (TRL 9).

An overview of information gathered around the different CC technologies presented in chapter *3* forming the basis for the comparative assessment, can be found in Table 3.

Table 3. Overview of key data of included CC technologies. From Havenstein and Weidenhammer (2021).



Type	**CC technology**	**TRL**	**CAPEX**	**OPEX**	**Space**	**ICE compatibility**	**# of articles**
Post-combustion	Absorption by chemical solvents	9	Same as MEA	0,27 – 1 x MEA	Same as MEA	Yes	15
	Adsorption by physical sorbents	6	-	Lower than MEA	-	No	2
	Membrane technology	5	Higher than MEA	Higher than MEA	Less than MEA	Yes	1
	Cryogenic carbon capture	6	0.7 x MEA	0.5 x MEA	Less than MEA	Yes	2
Pre-combustion	Absorption/ Adsorption	9 (5)	Higher than MEA	Higher than MEA	Higher than MEA	Yes	1
Oxyfuel combustion	Oxyfuel combustion	7 (4)	~1,7 - 3,8 x MEA	~0,76 x MEA	Same as MEA	Yes	2

5.2.1 Stage 1: Feasibility for shipboard application

Stage 1 of the assessment is evaluating the technologies, included in the assessment *(which have passed the excluding criteria, see Havenstein and Weidenhammer, 2021),* regarding their feasibility for the application on-board ships. This stage is not deciding which technology is the most feasible for marine applications, rather it addresses which technology is impacting the ships safety and vice versa which technology is impacted by the movement of the ship. Further, the impact of the fluctuating energy demand, for instance during manoeuvring, and the tolerance towards impurities in the fuel and exhaust are assessed. The results of stage 1 are summarised in Table 4.

Table 4. Results for stage 1 of the assessment Havenstein and Weidenhammer (2021). Lower ranking numbers indicates better performance and vice versa.

Technology	**(1.1) Safety and stability**	**(1.2) Ship's movement and vibration**	**(1.3) Fluctuations in energy demand**	**(1.4) Impurities in fuel/exhaust**	**Overall score**
Cryogenic separation (A3C)	1	2	3	1	**7**
Absorption by NH_3	3	5	1	2	**11**
Membrane separation	2	1	3	7	**13**
Absorption by PZ	3	5	3	4	**15**
Oxyfuel combustion	4	3	2	6	**15**
Absorption by MEA	3	5	3	5	**16**
Pre-combustion	5	4	4	3	**16**

A detailed description of the conducted ranking can be found in Havenstein and Weidenhammer (2021).

Only the top 3 technologies are considered in more detail in the second stage of the assessment. For this reason, oxyfuel combustion as well as absorption by MEA or PZ and pre-combustion has not been regarded in stage 2 assessments. The safety issues related to the large amounts of high concentrated O_2 as well as the high fuel requirements disqualified oxyfuel combustion as a feasible solution for the shipboard application in this assessment. Although pre-combustion CC technologies can be adapted to a wide range of fuels, it is not able to work under unsteady conditions as they are usually occurring on-board vessels. When a failure occurs in the pre-combustion CC plant, this may lead to a complete loss of propulsion, which is further disadvantageous in regard to the safety of ship and crew. The general drawbacks of the absorption process are leading to the exclusion of the solvents PZ and MEA for the second stage of the assessment. Only ammonia-solvents will be included in the second stage, due to the individual advantages regarding energy demand and the resistance towards solvent degradation by impurities in the exhaust gas. Furthermore, membrane and cryogenic separation will be considered for the second stage of the assessment, both being advantageous for appliances, where only a limited amount space is available.

5.2.1.1 Safety and stability (1.1)

While evaluating the impact on the ship's safety and stability, several factors are to be considered. Firstly, additional hazards originating from the CC process, which may affect the safety of crew and ship, need to be taken into account.

Oxyfuel combustion for ICEs demands large amounts of highly concentrated O_2. The required O_2 either needs to be bunkered and stored or produced on-board the ship. However, both scenarios include the storage of O_2 in concentrations far above 30 percent, making the handling very delicate (Johnsson, 2021). The threat is related to the highly oxidizing effect of O_2, which requires protection of all metal surfaces against the contact with the O_2 stream. Even though, the O_2 is not hazardous to the ships personnel when a leakage occurs, the high fire and explosion risk is the main threat, connected to this technology. Fire is in general a major threat to vessels.

Another factor to consider is the so-called "safe return to port" regulation, which is compulsory for passenger ships. While this regulation does not apply for cargo vessels, its reasoning still urges the need for a back-up propulsion system. Hence, one needs to consider the case, how a ship's propulsion system will be affected by a failure of the CC system. Whereas in post-combustion capture the CC plant can be bypassed easily, oxyfuel and pre-combustion capture are requiring a different fuel system and combustion engines. If there is a failure in the fuel system, it may cause the ship to lose its propulsion completely and thereby posing a major threat to ship and crew.

Pre-combustion capture relies on the conversion of fuel into syngas, out of which the CO_2 is separated and the remaining H_2 is used as fuel. If a failure occurs in the syngas production or treatment process, this may cause the production of H_2 to be stopped, leading to a loss of fuel to drive the propulsion and auxiliary generators. H_2 is highly explosive, i.e., the amount produced and stored in advance should be kept as small as possible to limit the risk. In addition to these risks, which are similar to the ones posed by oxyfuel combustion, the impact of the absorption or adsorption plant for CO_2 removal from the syngas needs to be considered. Even though the equipment can be designed smaller than for post-combustion CC due to the lower gas-flow and higher CO_2 concentration, a negative impact on the ship's stability might not be avoided. It can be concluded that the potential negative impact of the pre-combustion CC technology is higher than for oxyfuel combustion.

The hazards of post-combustion technologies are mainly related to the used solvent. Either the solvent is harmful or toxic to the environment (e.g., ammonia) or the degradation products formed by the solvent in contact with the flue gases are harmful. While precautionary measures can reduce the total risk, the use of such solvents still leads to an increased risk for the ship's personnel.

A fact being valid for all CC technologies, is that the installation of such plants is resulting in additional weight of the ship. Whereas the additional weight can be addressed in the design of a newbuilding, e.g., by additional ballast water tanks, the impact on the ship's stability might be an exclusion criterion in retrofit appliances. In general, all weight added above the metacentric height (GM) is negatively impacting the stability of the vessel. Since the sources of the flue gas, the ship's engines, are placed in the back of the vessel, the CC equipment needs to be installed there as well. This is impacting the weight distribution and could also affect the trim of the vessel, which may cause an increased fuel consumption. Furthermore, the additional weight added by fixed installations needs to be deducted from the ship's transport capacity and is therefore reducing the economic value of the vessel. In conclusion, technologies being compact and having a reduced weight are potentially less impacting to the ships' stability.

The post-combustion absorption plants using chemical solvents are bulky and weight intensive.

The main weight is contributed by the absorber, the stripper, and the cross-heat exchanger. Even though, the absorber column could be split into a series of columns to reduce the height of the equipment, it is likely impossible to avoid a negative impact on the stability of the vessel. Additionally, the liquid solvent can have a negative impact on the stability. The large amounts of solvent in the absorber and stripper could start to swing from one side of the column to the other, once the ship is moving due to weather conditions, e.g., wind, waves, and swell. The free surface of the liquid column above the GM poses a threat to the stability of the vessel at sea (Brian, 2003). Regarding the vessel's safety and stability, all absorption technologies have the same impact and are therefore all ranked the same.

5.2.1.2 Ship's movement and vibration (1.2)

Criterion 1.2 is evaluating the impact of the ship's movement and vibration, caused by the ICE as well as the weather conditions impacting a vessel.

The impact of vibrations caused by an ICE and the weather conditions affecting the vessel have not been considered in the available literature either.

5.2.1.3 Fluctuations in energy demand (1.3)

Compared to industrial and power plants with mostly steady state operation, shipboard engines are often operating in an unsteady state since the energy demanded on-board is fluctuating.

Depending on the required speed, operation mode and energy demand from auxiliaries, an alternating amount of energy needs to be converted from fuel, resulting in a varying mass flow of CO_2 to be captured. Especially during manoeuvring, the power demand and corresponding CO_2 flow is changing fast.

5.2.1.4 Impurities in fuel and exhaust gases (1.4)

Some technologies are more sensitive to impurities in the exhaust fumes than others. As example, PM emissions could accumulate in the CC plant, which can reduce its efficiency and increase costs due to degradation.

5.2.2 Stage 2.a: Most promising technology for newbuildings

Stage 2.a aims to evaluate which technology is most promising for the appliance on-board newbuild vessels. Therefore, the three technologies deemed as the most feasible for the application on-board vessels in stage 1, are evaluated in relation to typical constraints set out by the application on-board.

Furthermore, financial aspects which are of high interest for ship-owners, are included as well. The ranking for each criterion is based on a discussion of facts that are presented in chapter *3*. Table 5 is summarising the results of stage 2.a, showing that the absorption process using aqueous NH_3 as solvent has achieved the lowest score, i.e., it is the most promising technology for newbuildings.

Table 5. Results of stage 2.a of the assessment. Lower ranking numbers indicates better performance and vice versa.

Criteria	**Absorption by NH_3**	**Cryogenic separation (A3C)**	**Membrane separation**
(2.1) Space requirements	3	2	1
(2.2) Additional weight	3	2	1
(2.3) Energy requirements	1	3	2
(2.4) Capture-rate	2	1	3
(2.5) Investment costs	2	1	3
(2.6) Operational costs	1	2	3
(2.7) Maturity level	1	3	2
Overall score	**13**	**14**	**15**

5.2.2.1 Space requirements (2.1)

The limited space is the main obstacle for the installation of CC equipment on-board a vessel. Space occupied by the CC plant and all related installations cannot be utilised for the transportation of goods, which is the purpose of a vessel and defines its economic value. Since the EEDI calculation is including the amount of cargo transported, less cargo capacity will also negatively impact the attained EEDI. Therefore, a CC unit for the application on-board ships should take up as little space as possible.

5.2.2.2 Additional weight (2.2)

A vessel's design allows for a specified amount of cargo and provisions to be loaded, the so-called deadweight. When retrofitting a CC plant to an existing vessel, the weight of the installation needs to be deducted from the DWT and is thereby reducing the ship's capacity. In the design of newbuildings, the additional weight can be addressed by the design of the hull. Nevertheless, the lower the weight of the technical installations on-board, the higher the DWT allowed with the same hull design. Hence, also the attained EEDI can be improved due to a higher capacity of the vessel.

5.2.2.3 Energy requirements (2.3)

All types of energy required for a CC unit on-board a vessel needs to be converted from fuel, e.g., to electric and thermal energy. The more energy required by a CC unit, the more CO_2 is produced due to the increased fuel consumption and is thereby negatively affecting the carbon reduction rate of the CC technology. Furthermore, the fuel consumption is the main cost driver in the operation of vessels and an increasing energy demand would thereby directly impact the OPEX.

5.2.2.4 Capture-rate (2.4)

In general, all capture technologies can achieve a capture-rate of 99 percent, but this is not seen as economically feasible in the consulted literature. Due to severe cost increases to capture the last 10 percent of CO_2, most research is carried out to achieve a capture-rate of 90 percent. The increase in cost for a complete capture mainly results from the required equipment size to capture CO_2 with a very low partial pressure. However, technical and energetic efforts required to achieve a higher capture rate differ for all technologies, which are considered in this assessment.

5.2.2.5 Investment costs (2.5)

The payback period is one of the most important criteria for ship-owners to decide in which energy efficiency measure to invest. The longer a payback period, the higher the financial risk connected to the investment since the development of the market can only be foreseen for a short period of time. Ship-owners would therefore prefer a technology, with the lowest investment costs and the shortest payback period.

5.2.2.6 Operational costs (2.6)

Lower operational costs are contributing to a shorter payback-period, which is more attractive for ship-owners. Operational expenses include costs for power consumption, chemicals, and maintenance. Hence, the main contributor to the operational costs is the fuel consumed for additional power generation on-board.

5.2.2.7 Maturity level (2.7)

A higher TRL makes a commercial application in the nearby future more likely and figures on cost estimates are getting more precise, since more experience regarding these has been gained.

5.2.3 Stage 2.b: Most promising technology for retrofitting

Integrating CC technology into the design of a newbuild vessel allows to accommodate all requirements of a CC plant. When a CC plant is installed as a retrofit solution, it needs to be integrated into the design of an existing vessel. The more changes are necessary, the higher will be the costs of such an investment into a CC technology. Therefore, this assessment stage is considering additional criteria, which are of high interest when installing CC technology on-board an existing vessel.

5.2.3.1 New engine (2.8)

CC technologies such as pre-combustion capture and oxyfuel combustion are requiring extensive changes to the engine. In pre-combustion capture applications, an engine needs to be able to combust H_2. The conversion of a conventional marine diesel engine is probably uneconomical (i.e., prohibitively expensive) or even impossible (from a technical point of view). Therefore, precombustion capture technology would require a replacement of the entire engine, which would significantly increase the costs for the installation of CC technology. The same applies to oxyfuel combustion, which also requires an engine replacement.

However, all technologies, which are considered in stage 2 of this assessment, are post-combustion capture technologies and thereby do not affect the engine. Post-combustion technologies can be retrofitted relatively easy into an existing exhaust gas aftertreatment system, e.g., like SO_x-scrubbers today. Since none of these reviewed technologies has a negative impact regarding this particular criterion, all are rated to a score of 1.

5.2.3.2 Conversion of fuel and fuel system (2.9)

In general, the same applies for this criterion, as for criterion 2.8. All technologies included in this assessment can capture CO_2 resulting from any kind of fossil fuel combustion, but also all require pre-treatment to do so. In criterion 1.4, it has been discussed how impurities in a flue gas stream would affect all CC technologies and which technologies require more effort in pre-treatment when low-grade marine fuels are combusted.

5.2.3.3 Repowering (2.10)

If it is likely that the installed power system on-board is not able to meet the power demand of an additional CC plant, repowering is required. The installation of additional engines to convert fuel into electricity, is increasing the CAPEX as well as the OPEX, due to an increased fuel consumption and higher maintenance expenditures. Depending on the vessel, this might make the installation of CC on-board uneconomically or even technically unfeasible.

5.3 Feasibility discussions

The comparative assessment, made by Havenstein and Weidenhammer (2021) revealed post-combustion CC by absorption with aqueous ammonia solvents as the most promising solution for newbuildings, as well as for the retrofit case.

The selection of the optimal CC technology for a specific vessel depends on several factors such as available space, available power on-board, possibilities to add weight, total energy consumption and other running costs as well as total investments.

Also, the integration with other systems on-board and the level of increased complexity of the entire system needs to be taken into consideration. When installed on-board a vessel, the plant needs to be operated, serviced, and repaired by the ship's crew.

The conducted assessment considers a variety of constraints and criteria for the applicability of these CC technologies on-board vessels. Safety concerns towards ship and crew as well as peculiarities of the shipboard application (e.g., ship's movement and vibration, fluctuating energy demand) and circumstances set out by marine fuels are regarded. As specific constraints of the shipboard application, the occupied space, additional weight, and energy demand have been identified and assessed. Additionally, the costs related to each CC technology as well as the maturity level and feasible capture-rate have been considered. For retrofitting CC technologies on-board, measures regarding the conversion of the fuel system, the potential replacement of the installed engine and constraints in the available power to operate the CC unit were examined.

Three post-combustion CC technologies have been identified as most feasible for the application on-board in combination with ICEs; absorption by NH_3, cryogenic separation (A3C) and membrane separation. All were found to be promising solutions for on-board CC.

- Cryogenic separation offers the highest economically feasible capture-rate but is lacking maturity and additionally shows the highest energy demand.
- Whereas membrane separation is deemed the least space consuming and weight adding technology, it demands extensive pre-treatment of the flue gases, which is also related to an intense energy demand of this technology.
- Absorption by NH3 was found to be the most space consuming technology in the comparison, but it shows a low power consumption and has advantages in connection with sulphurous fuels, apart from that, it also achieved the highest TRL so far.

Overall, post-combustion capture by absorption with aqueous ammonia solvents might not be a feasible solution for small ships, but due to its high energy efficiency and low OPEX it is the most promising solution for CC on-board large vessels.

6 Conclusion and discussion

In general, Carbon Capture (CC) represents a potential solution to reduce the CO_2 emissions from international shipping. Nevertheless, CC in combination with fossil fuels can only be a transitional solution, to overcome the time until renewable propulsion options are developed, since it is not feasible to capture 100 percent of the emissions with CC technologies. However, in combination with renewable fuels, CC on-board ships with the captured CO_2 delivered to permanent storage could result in negative CO_2 emissions.

While a large-scale production capacity of fossil free fuels for ships has not really started and might become difficult to scale up fast; on-board CC might present a solution, that under certain circumstances can be faster to implement, both as retrofit and on-board new ships. However there also need to be a market for the CO_2 or storage available.

In this report, a broad spectrum of CC technologies has been presented including information on the current applications, costs, space requirements as well as specific advantages and drawbacks of each technology. Also, the research on application of the identified technologies on-board ships is presented in a summarised form.

The reviewed literature and collected data on CC technologies included ashore and on-board CC. Thereby, it was found that the parameters of CC from industrial processes and power plants vary in several factors from the application on-board vessels. Besides the low concentration of CO_2 in the exhaust of ICEs, the confined space on-board and the impact of the weight are criteria not considered in the design of shoreside processes.

Within the assessment process for on-board CC, three post-combustion CC technologies have been identified as most feasible and also promising for the application on-board ships in combination with ICEs; absorption by NH_3, cryogenic separation and membrane separation. In relation to investment costs, the cryogenic separation seems most promising and in relation to operational costs it is absorption by NH_3 that seems most promising.

However, in the current state the mature CC technology (i.e., post-combustion absorption) is economically not yet competitive, but currently less mature technologies could have lower costs, making them profitable even with low carbon emission prices. While absorption technologies are the most promising technology in the short term due to their high TRL, the future of CC technology is seen in less energy consuming and more efficient processes (Nazir, 2021).

Since no full-scale systems on-board ships has been installed yet, it is still difficult to fully assess the total costs for on-board CC. It is also clear that costs for CC on-board ships will depend not only on the choice of technology setup but also with the development of the specific technologies, cost development of components, energy / fuel cost, size of the installation (economy of scale), energy system integration etc.

In addition to the uncertainties for CC cost estimates, it is also still difficult to assess the cost for on-board storage of CO_2, for the delivery ashore, and for transportation to either further utilisation or permanent storage. Transportation and storage (or utilisation) costs will largely affect the total business case for on-board CC, but also, the costs for other decarbonisation options for shipping as well as the development of GHG policies will very much affect the business case for CC on-board ships.

The articles and reports published on research for the application on-board take different base assumptions and have different system boundaries, making a quantitative comparison of technologies subject to high uncertainties. Further uncertainties derive from the low TRL of CC technology for small and mobile sources, such as vessels. Due to the missing comparability and the high uncertainties, the assessment was based on a qualitative evaluation of data.

To allow a quantitative comparison of CC technologies on-board, future research should address the constraints of the application on-board on a common basis. Furthermore, a common basis should include the same source of exhaust and the same available energy (thermal as well as electric), considering that the waste heat of the engine is already partially utilised on-board current vessels. A technoeconomic assessment based on simulations of the identified CC processes on such a common basis could resolve this issue, since it would be based on unbiased figures rather than qualified assumptions comparable data. Further research for each of the identified technologies will also improve the data quality, since with a higher TRL also the certainty of the data is rising. New insights and an improved data quality might change the outcome of the assessment, when assumptions taken in the current assessment are disproved.

To determine which CC technology is the most suitable for a specific ship, the available space and energy need to be considered as well as other ship specific circumstances. In any case, the potential of various solutions to reduce carbon-emission, not limited to CC, must be assessed for the specific case, to decide which technology is the most suitable.

To summarize:

- Several CC technologies seem technically possible to install on-board ships.
- The costs assessments for on-board CC in the literature that is presented within this report vary substantially from approximately €80 up to €290/ton CO_2. The cost estimates for on-board CC found is also estimated with different assumptions and made over time from 2017 to 2022.
- The CC technologies are still under development, and more assessments of final economic feasibility is still needed.

- On-board CC is developing along with ashore systems, where shipping CC will benefit from a further developed CO_2 infrastructure.
- The uncertain total cost and the business case for on-board CC is probably the main barrier to overcome before CC on ships can be introduced at large scale.

Follow up from this study could for example be:

- A digital twin (computer model as an available digital copy) of CC on board a ship together with the handling of CO_2 in a port and subsequent CO_2 pathways such as utilization or storage in order to be able to simulate new process steps and different operational conditions.
- Pilot installation on-board ships for full scale technology verification.
- Start-up of industrial cooperation with companies already engaged in the technology. This could include research, development, manufacturing, installations.
- Further analyses of possibilities and business opportunities related to the CO_2 life cycle and how this will affect ports and terminals, energy companies, shipping sector at large etc.
- Further cost and technological assessments of specific CC technologies.
- Further comparisons with alternative solutions such as switch to renewable fuels.
- Further comparisons on total energy system efficiencies for running ships with CC compared to other measures such as renewable fuels.

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8 Appendixes

The following appendixes contains additional relevant information related to the specific technical carbon capture technologies presented in section *3. Carbon capture technologies*. Appendix information contains both additional technical descriptions and assessment found in the literature related to the specific technologies.

8.1 Appendix - Post-combustion capture by absorption

The general setup in the conventional post-combustion absorption technology is rather straight forward. Two main units are primarily required to establish a working CO_2 capturing cycle. Firstly, the absorber unit, comprising a lean absorbing solvent and secondly, the stripper unit for regeneration of the solvent (Sreedhar et al., 2017).

Both processes, absorption, and regeneration of the solvent, are based on the mass transfer of CO_2 from gas to liquid or vice versa, respectively. The CO_2 absorber is installed in the exhaust stream. As a result of this, the flow resistance in the exhaust will be higher. Additional exhaust fans or blowers may therefore be required to overcome the pressure drop (Sreedhar et al., 2017).

Before the flue gases reach the absorber unit in which the CC process occurs, they are usually led through a complex flue gas aftertreatment system, to remove other undesired flue gas contaminants such as NO_x and SO_x (especially valid for exhaust gases from marine diesel engines).

Depending on the available space, the absorber might consist of several columns, which contain the absorbent. These columns are perfused by the flue gas from below. To improve the efficiency of the absorber, the columns are packed in specific structures. The structured packing of the columns is increasing the contact surface between the absorbent and the flue gas (Wilcox, 2012). Especially in post-combustion CC, the flue gas pre-treatment system is also comprising a direct contact cooler, to lower the temperature of the gas mixture before entering the absorber. Contaminants in the flue gas, as well as excessive heat, can lead to solvent degradation (Rieder et al., 2017).

The feeding-point for the lean absorbent is located on the top of the absorber unit, creating a counter-current between the exhaust gas and the solvent stream. This counter-current is supporting a better diffusion between the two streams. CO_2 contained in the flue gas is reacting with the lean solvent from the feed and is thereby removed from the gas. This occurrence is the actual absorption process, where a mass transfer from the solute CO_2 to the liquid solvent takes place. The chemical bond between CO_2 and solvent is reversible. The CO_2 concentration in the gas phase is increasing, the lower the solvent sinks in the absorber column, allowing the solvent to bind more CO_2 (Kothandaraman, 2010; Wilcox, 2012). At the bottom of the absorber, the CO_2- rich solvent is discharged and pumped into the coupled stripper unit. On the gas outlet of the absorber, the treated flue gas with low-CO_2 content is passed on to the funnel of the plant.

For the technology setup, a simplified schematic, including the process flow, is presented in Figure 4. CO_2-rich solvent is forwarded from the absorber to the stripper and regenerated CO_2-lean solvent is returned from the stripper to the absorber. In this way, a circulation of lean and rich absorbent between these two units is established. To pre-heat the solvent before the stripper and to prevent heat losses from the stripper, a cross heat exchanger is installed in the circulation of lean/rich solvent. Subsequently, after the heat exchanger, before the lean solutions is injected in the absorber, it is cooled by a cooler unit.

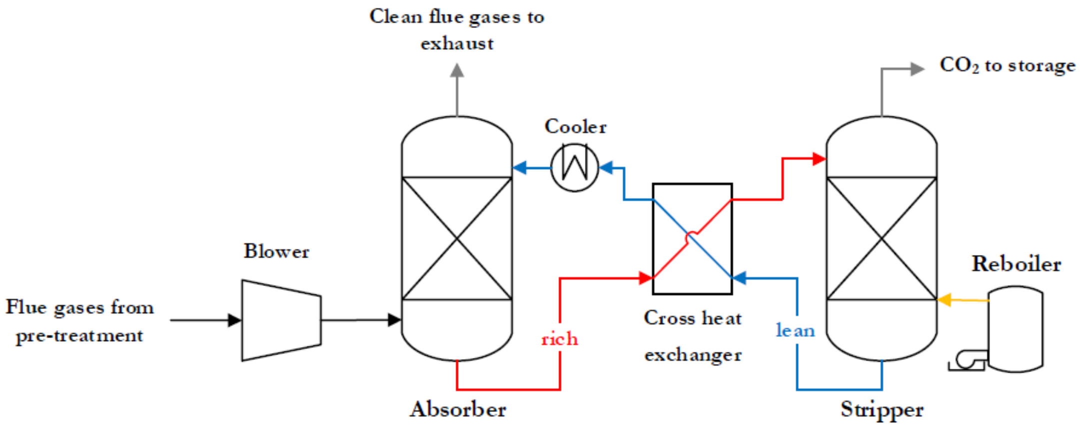

Figure 4. Simplified schematic of the chemical absorption process.

Equivalent to the absorber, the inside of the stripper is filled with packed columns. However, the operating principle in the stripper is opposite to the absorber. When the CO_2-rich solvent enters the upper section of the stripper, it is led through the packed columns. From below, a regeneration steam by a reboiler is created, acting as the counter-current to the rich solvent. When both streams converge, the CO_2-rich solvent is absorbing energy from the so-called stripping stream and CO_2 is released from the solvent feed stream (Chen & Lai, 2019). The mass transfer of CO2 from the liquid to the gas phase is declared as the desorption process (Wilcox, 2012). The released gaseous CO_2 is fuming to the top of the stripper, where it exits the unit on the gas outlet. After the CO_2 got separated, the regenerated solvent is lean again. It is collected at the lower part of the stripper and returned into the feed cycle to the absorber (Chen & Lai, 2019). The pure stream of CO_2 on the gas outlet of the stripper is further pressurised in a compressor to a desired level and finally forwarded to the dedicated CO_2 storage.

Depending on the intended rate of captured carbon from the flue gases, the physical dimensions of the absorber and stripper unit may vary. The higher the desired fraction of captured CO_2, the higher the columns of the absorber need to be, to allow for a longer mass transfer zone. The diameter of the columns is defining the maximum allowed flow rate of the different streams. Additional factors, influencing the rate of mass transfer, are the solubility and the diffusivity of CO_2 in the absorbing solvent, as well as the chemical reactivity of the solvent with CO_2 (Wilcox, 2012).

Also, the cross-heat exchanger in the lean/rich solvent circulation between absorber and stripper takes up space (Normann, 2021). Further, the weight of the components needs to be considered as well, since the individual parts are heavy. Especially for on-board applications, these issues need to be faced and overcome.

The immense packaging height of absorber and stripper units (packed columns), particularly in large-scale applications, is contributing to the space demand of this technology. For a description of alternative systems with potentially lower space demand. Rotating packed-beds could be a key alternative to conventional systems, since they show similar capture performances at reduced unit sizes. However, the technology of rotating packed-beds was still in lab-scale and therefore not available for commercial use (Zhao et al., 2014). In 2022, the EU Horizon funded HiRECORD project started, in order to demonstrate the possibility for of a modular CO_2 capture plant comprising a rotating packed-bed absorber and advanced rotating packed beds desorber. The aim with the project is to reduce capturing costs and also enables a reduction in absorber and desorber sizes (CORDIS, 2022).

Another possibility to reduce the equipment size, is to increase the flowrate of the solvent in the reboiler and the connected electrical auxiliaries (circulating pumps for the solvent). Thereby, the size of the absorber and stripper can be reduced but electric consumers, such as pumps, are requiring more energy. Further, the reboiler duty needs to be increased, to allow for a faster regeneration of the solvent in the stripper. A lower height of stripper and absorber equals to lower CAPEX and less space demand but at the same time the OPEX of the process are increasing (Einbu et al., 2021).

It can be concluded that the space requirements of the components in absorption technologies are dependent on the CC application and are subject to numerous degrees of freedom. Higher mass flows and/or velocities of the flue gas are accounting for bigger sizes of the components. However, the general setup in absorption is not differing much between the alternative solvents and the benchmark MEA process. For this reason, it has been estimated that the space demand of the compared absorption processes is about the same.

8.2 Appendix – Post-combustion capture adsorption by solid sorbents

There are two general technology setups of CC Post-combustion capture adsorption by solid sorbents identified in the consulted literature, namely fixed-bed adsorbers and moving-bed adsorbers.

In a **fixed-bed adsorber system**, one adsorber unit (one bed) is in charge for adsorbing CO_2 from a feed stream at a time. Another bed is kept off the gas stream as long as there is an ongoing adsorption in the first unit. When saturation of the adsorbent in the first bed is reached, a switch-over to the second unit is conducted. To allow for the time of regeneration of the beds, a cyclic alternation in each unit between capturing and desorption is required (Wilcox, 2012). A simplified schematic of the general setup of a fixed-bed adsorber is displayed in Figure 5.

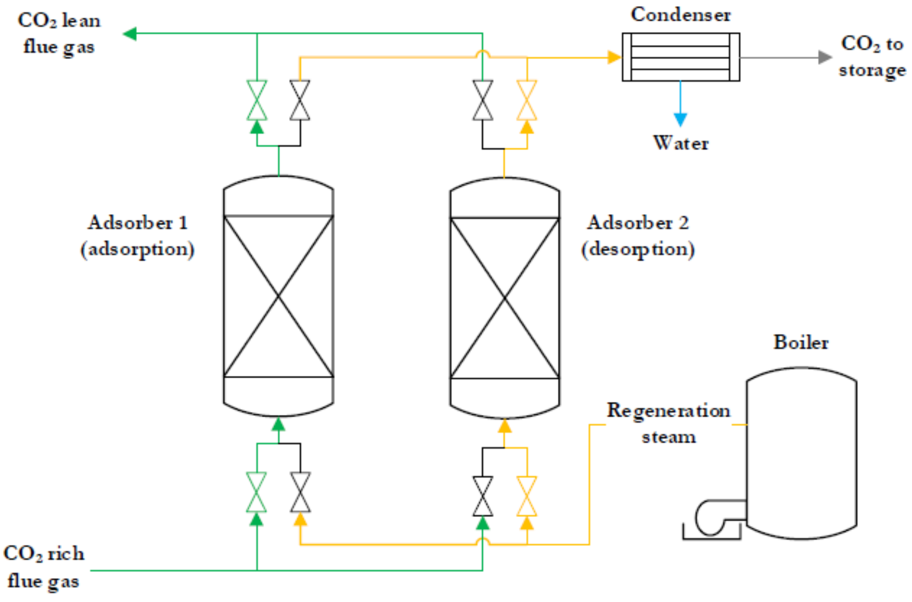

Figure 5. Simplified schematic of a fixed bed adsorber using TSA

Moving-bed adsorbers use a different component setup. Contrary to the fixed-bed system, the adsorption and regeneration processes are not performed in the same unit. As soon as it reaches saturation the solid adsorbent is transferred from the adsorber to a regeneration unit. In return, regenerated adsorbent from the regeneration unit is added to the adsorber in a cyclic process. The CO_2 feed stream is perfusing the adsorber unit in a counter-current to the adsorbent, which enters the adsorber from the contrary end of the unit (Wilcox, 2012). Favourable for this system is the continuous exhaust gas stream in the adsorber, without required interruptions for regeneration of the adsorbent. Additionally, the undesirable pressure drop of the flue stream within the adsorber unit is lower than in the fixed-bed system (K. Kim et al., 2013). A drawback of this system is the occurring wear and tear, due to the movement of the adsorbent within the system. This is reducing the lifetime of both, the solid adsorbent and the contacting components, which ultimately leads to additional costs for the operator (Wilcox, 2012)

Same as the absorption system, the adsorption setup involves a variety of auxiliary equipment, such as blowers/fans to overcome the pressure drop of the adsorber and to elevate the flue gas pressure before it reaches the adsorber. In addition, heat exchangers are used to cool down the inlet flue gas of the adsorber.

The CO_2 adsorption and sorbent regeneration within the adsorption beds can be executed through different adsorption cycles. The most common cycles in fixed-bed systems are:

- **Pressure-swing adsorption (PSA) cycle**, where the CO_2-containing gas mixture is led into the adsorber unit at an elevated pressure, typically between 6-10 bar (Ben-Mansour et al., 2016). While the gas mixture perfuses the adsorber, the adsorption of CO_2 is proceeding. CO_2-lean gas is leaving the adsorber unit while the captured CO_2 is retained in the solid adsorbent. When saturation of the sorbent bed is reached, the feed-valve to this bed is closed and a switch-over to another sorbent bed is conducted. The regeneration of the saturated sorbent bed is done by lowering the pressure into the unit, which releases the captured CO_2 from the adsorbent. The displaced CO_2 is then discharged from the unit for storage. After successful desorption of the CO_2 from the adsorbent, the regenerated sorbent bed is ready for the takeover of the next adsorption cycle (Ben-Mansour et al., 2016; Wilcox, 2012).
- Similar to the technology of PSA, **vacuum-swing adsorption (VSA)** can be applied. Instead of pressurising the flue gas when entering the adsorber, the pressure is lowered to a level below the atmospheric pressure for the adsorption process, and contrary, elevated again for the desorption process (Ben-Mansour et al., 2016).
- Temperature differences can be used for adsorption and desorption cycles as well. Figure 5 is showing a fixed-bed adsorber, utilising **temperature-swing adsorption (TSA).** In TSA, the gas feed is cooled down by utilising a cooling gas stream before it reaches the adsorber. After the adsorption occurred, the adsorber bed is changed over to another unit in the same manner as in the other adsorption cycles, when CO_2 saturation is attained. Desorption in TSA is done by heating up the sorbent bed in the regeneration process with a hot gas stream, generated by an additional heater unit, which is setting free the CO_2 from the sorbent bed (Creamer & Gao, 2016). The regeneration process in PSA and VSA is working similar to TSA but instead of a steam regeneration, compressor units or vacuum pumps are used to elevate or lower the pressure in the adsorber bed.

Different technologies of adsorption and desorption demand different properties of the sorbent (Creamer & Gao, 2016). According to Ben-Mansour et al. (2016), crucial properties for a sorbent, that decide the suitable adsorption concept, are: “adsorbent selectivity, adsorbent capacity, ease of and energy required in desorption”. Liu, Shi, Wang, Gao, & Xu (2021) further added, that a good mechanical strength, which equals to a longer lifetime of the sorbent.

Simulations and experimental modelling of moving-bed adsorption systems for CC in flue gas environments were carried out in various research (Jung et al., 2018; Kim et al., 2013; Mondino et al., 2017). In simulated flue gas environments of coal-fired power plants, high purities of CO_2 were achieved. Further, the total energy demand of the simulated processes was much lower than in conventional adsorption systems, therefore the potential for costs savings of this setup has been demonstrated.

No specific price-linked statements have been found in the available literature. Nevertheless, a range of the additional load which arises by the CC technology, is stated in a study by Wang et al. (2015). Between 5.4 to 9 percent energy penalty is added, by installing an adsorption technology. As aforementioned, the main energy demand is dedicated to the sorbent regeneration, which in this case is between 0.5 - 3.12 MJ/kgCO_2 (Wang et al., 2015). The same study also comprises data of the energy penalty for the comparison with a MEA absorption technology (8.2 – 14 percent additional load), and an energy demand of up to 6 MJ/kgCO_2 (Wang et al., 2015). It is apparent, that the adsorption technology is less energy demanding than the benchmark process, which directly relates to lower OPEX for the operator.

8.3 Appendix – Post-combustion capture with membranes

For the purpose of CO_2 removal from a feed gas with membranes, two main technologies can be identified:

- Membrane contactors (MC)
- Membrane gas separation (MGS)

MC technologies are operated with microporous membranes, acting as a separating wall between a CO_2-rich gas stream and a liquid phase of absorbing solvent. The solvent, which is often amine based, is meant to selectively absorb CO_2 once it diffused through the membrane. The selectivity for the explicit removal of CO_2 from the feed gas is, for the greater part, achieved by the properties of the solvent and lesser by the membrane itself. (Siagian et al., 2019).

The operating principle of the MC technology is rather simple. Flue gases containing CO_2 are entering the gas side of the membrane and are treated and separated by contacting the membranes surface. On the gas outlet, the retentate, a gas stream with lean CO_2 concentration is leaving the unit. Whereas on the sorbent side of the membrane the absorbing solvent is circulating, which is referred to as the permeate, after the CO_2 has been absorbed (Khalilpour et al., 2015). The liquid sorbent in the MC process is regenerated in a regeneration unit in the same way as described in *Absorption by chemical solvents*.

The pores of the membrane are ideally only filled with feed gas but no absorbing solvent.

Hydrophobic membrane materials are used in MC, to prevent the so-called wetting phenomenon of the membrane where liquid solvent is soaked into the membrane and therefore lowering the mass transfer rate by raising the resistance

(Siagian et al., 2019). Generally, the higher the porosity the lower the resistance in mass transfer but at the same time the higher the risk of wetting of the membrane. Furthermore, the utilised membrane material needs to withstand the characteristics of the chemical solvent and the feed gas as well as thermal and chemical influences. All of those in sum could lead to the degradation or fouling of the membrane (Khalilpour et al., 2015; Siagian et al., 2019).

In the **MGS system**, the general technology setup is similar to the MC technologies. The main difference is that the permeate side of the membrane is a gaseous phase too. To enhance the effectivity of CO_2 removal from the flue gas, a compressor unit is elevating the pressure of the feed gas before entering the membrane unit. Some systems use vacuum pumps on the permeate side of the membrane, to achieve similar effects of increased efficiencies (Xu et al., 2018).

It is possible to recirculate the CO_2-enriched permeate stream into a second or third membrane unit and thereby increase the CO_2 capture-rate, as it is shown in Figure 6(Khalilpour et al., 2015). On the other hand, this will result in additional costs for compressors or vacuum pumps and membranes, higher space requirements and extra energy consumption (Siagian et al., 2019; Xu et al., 2018). The principle of serial or parallel use of multiple membranes can be applied for the MC system as well.

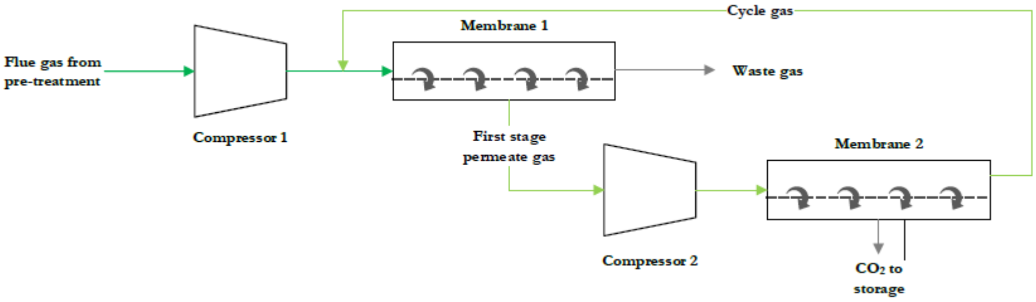

Figure 6. Schematic of a multi-stage membrane CO_2 separation process

In MGS, the membrane design is slightly different than in MC, as the membrane is denser and non-porous (Siagian et al., 2019; Wilcox, 2012). Contrary to MC technologies, the CO_2 selectivity in MGS is only attained by the membrane, which means that the appropriate choice of membrane design, configuration and material is crucial for a high selectivity and efficiency of the process (Siagian et al., 2019). The separation of CO_2 can occur through different mechanisms, e.g. via *molecular sieving*, where larger molecules are excluded by the membranes' dense design and the virtue of their size (Siagian et al., 2019; Wilcox, 2012). Another mechanism is the *solution diffusion* through polymeric membranes, where CO_2 molecules are absorbed by the membrane, subsequently diffuse through the same and are desorbed on the permeate gas side. Solution diffusion is the most commonly used mechanism at the present day (Siagian et al., 2019).

MGS technologies for CO_2 removal from natural gas are used in industrial-scale applications since several decades. Numerous natural gas on- and offshore applications have successfully been upgraded by a membrane-based CO_2 capture plant (Siagian et al., 2019).

However, several challenging factors are retaining membrane technologies from the use in flue gas separation. The large volume of feed gas with typically low CO_2 concentration of less than 20 percent in flue gases from power plants is making the use of MGS membranes uneconomically. The flue gas compression, required to achieve the driving force of separation, causes high operational costs. MC technologies are capable of capturing CO_2 in lower concentrations (< 20 %) but are affected to membrane degradation caused by the flue gas (Siagian et al., 2019).

Even though research has shown that membrane technologies in general have high potential to be applied in commercial CO_2 separation from flue gases, they are not used in large-scale applications yet. However, both membrane processes have been used in research and development stages e.g. pilot plants, but are retained (Han et al., 2020; Khalilpour et al., 2015; Siagian et al., 2019).

8.4 Appendix – Post-combustion capture with cryogenic

Two potential technology setups of Cryogenic carbon capture (CCC) from flue gases and their respective operating principle are (Sustainable Energy Solutions, 2021a, 2021c):

- Compressed Flue Gas (CFG)
- External Cooling Loop (ECL)

In the **CFG system**, flue gases from a power plant are firstly sent through a dryer unit, to condense water contained in the exhaust gases. After this pre-separation, the flue gas stream pressure is elevated by a compressor to the operating pressure required for further processing (Sustainable Energy Solutions, 2021a). With the compression, the temperature of the flue gas is raising. Subsequently, the flue gases are cooled in a heat exchanger unit while attaining the operating pressure. Specific components of the flue gas such as SO_2, NO_2, Hg, HCl are then removed in a condensed phase by a separator unit (see Figure 7) with high efficiencies. After this separation, the remaining flue gas is mainly consisting of N_2 and CO_2. Via an expansion valve (in some systems turbines are used for the expansion of the gas), the gaseous stream is expanded and cryogenically cooled to solidify the CO_2. The solid CO_2 and the left gaseous N_2 stream are then separated in a solid-gas separator. The solid CO_2 is pressurised to 70 – 80 bar. Both streams, solid CO_2 and gaseous N_2, are sent back and utilised at the low-temperature side of the heat exchanger, to cool the incoming flue gases and, at the same time, melting the solid CO_2. At the output of the CFG system, CO_2 is present in a pressurised liquid phase and can be stored or further utilised. The remaining N_2 gas-stream can be released into the atmosphere at ambient air pressure (Baxter et al., 2011).

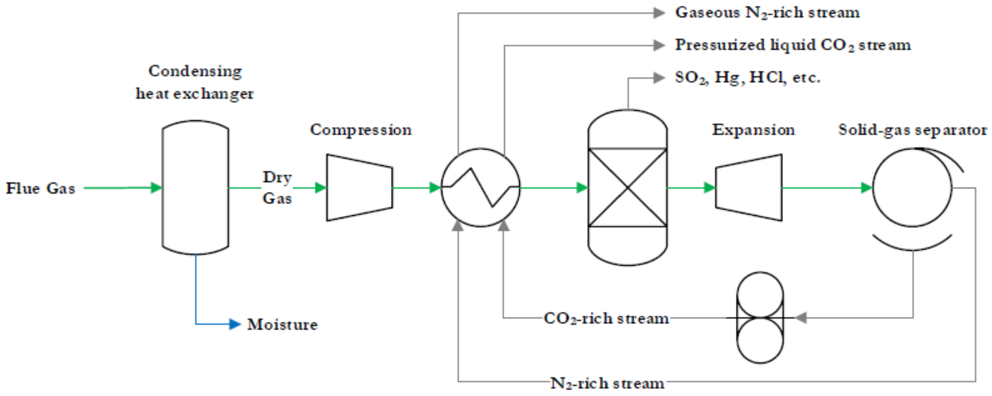

Figure 7. Simplified schematic of the CFG system developed by Baxter et al. (2011)

The general setup in the **ECL system** is similar to the CFG system. However, the main difference in the setup and working principle of the ECL system is, that it does not require flue gas compression. Generally, the system consists of a two-stage CO_2 cooling process, a multi-stream heat exchanger and a desublimating heat exchanger. A simplified schematic of the ECL system can be seen in Figure 8. Firstly, the flue gas stream, supported by a blower, is passed through a dryer unit to strip off moisture. The dry flue gas is further led into the multi-stream heat exchanger for precooling. The cooling energy for the multi-stream heat exchanger is drawn from an external cooling cycle, that is operated by refrigerant compression and expansion. Additional cold energy is provided from the recirculation of solid CO_2 and liquid nitrogen from the outlet of the desublimating heat exchanger into the multi-stream heat exchanger.

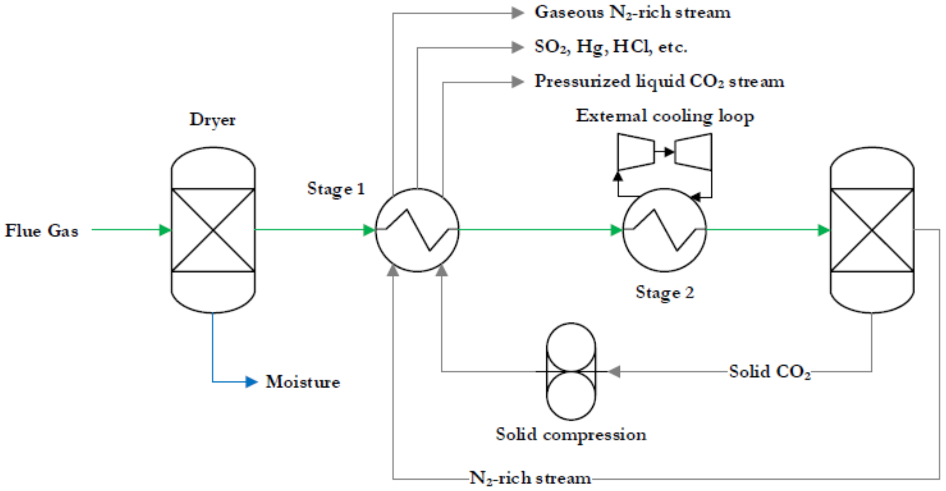

Figure 8. Simplified schematic of the ECL system developed by L. L. Baxter et al. (2019)

After the precooling in the first stage, the cold dry flue gas is forwarded to the second stage, the desublimating heat exchanger, in which CO_2 is condensed and thereby cooled until the CO_2 is precipitating in solid form. As aforementioned, the solid CO_2 is recirculated into the multi-stage heat exchanger, where it liquefies during the heat transfer, and subsequently ejected from the heat exchanger unit. During the cooling process in the desublimating heat exchanger, other flue gas contaminants such as SO_2, NO_2, Hg, HCL are condensed and separated from the flue gas stream (Sustainable Energy Solutions, 2021c). The liquid CO_2, which is exiting the multi-stream heat exchanger, is pressurised, and sent to storage. The flue gas treated by the ECL system is an N_2-rich light gas at near ambient temperature, that can be released into the atmosphere directly.

8.4.1 A3C technology Cryogenic carbon capture

The A3C technology is a cryogenic CC which has been developed and patented by PMW Technology in 2016 (Willson, 2020). In a foregoing study, the A3C process in connection with shoreside industrial and power plant applications, is estimated to reduce the costs of CC by up to 70 percent compared to the absorption by MEA, for scales below 10 ton CO_2/h (Willson et al., 2019). This range is typical for marine applications, where a capture-rate of 90 – 95 percent is expected to be achieved (Willson, 2020).

The A3C process (Figure 9) itself consists of two stages, each containing a moving-bed of metallic beads (Willson, 2020). In the first stage, the cooler-drier removes the water contained in the exhaust gases. The second stage is further cooling down the gases and contained CO_2 is forming a solid coating on the metallic beads. Due to the fineness of the moving-bed material, the surface for heat exchange is increased, allowing a compact design of the process. For comparison, a metallic beads bed of 50 – 100 mm is able to achieve the same separation results as a 15 m high column in chemical absorption (Willson, 2020).

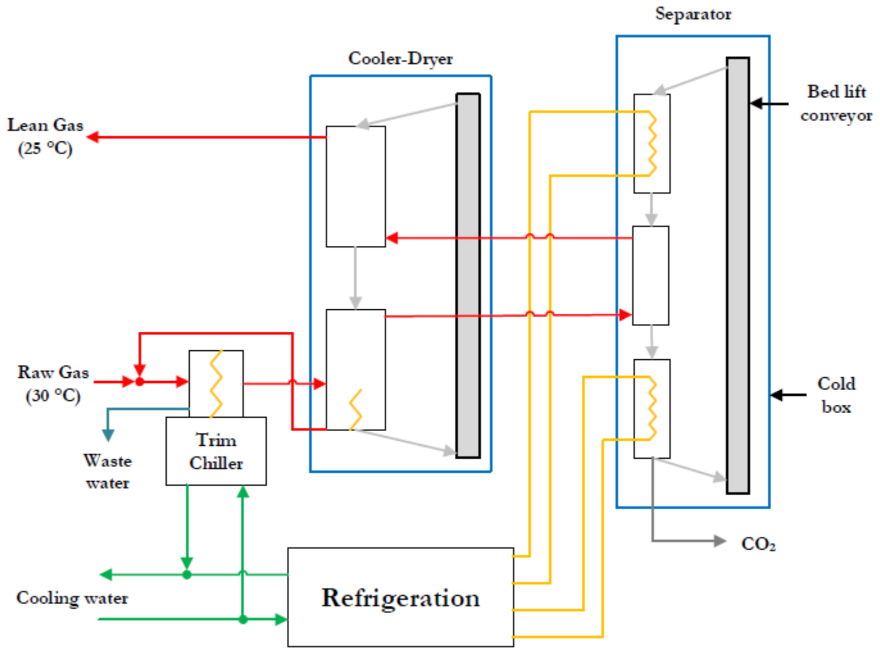

Figure 9. Schematic of the A3C separation process

The solid CO_2 on the metal beads is vaporised using the waste heat of the refrigeration unit, enabling the refrigeration unit to recuperate the cold energy and thereby significantly lowering the energy required for the cryogenic system (Willson, 2020). The CO_2 stream is transferred to the compression and liquefaction unit, whereas the metal beads are transported by a screw conveyor to the top of the separator, where they are cooled down again. The cold CO_2-lean flue gases leaving the separator are cooling down the moving-bed of the cooler dryer in the first stage (Willson, 2020).

As it can be seen in Figure 9 the A3C process requires a gas inlet temperature of 30 °C, which requires further cooling of the exhaust gases prior entering the CC process. Therefore, the concept of Willson (2020) includes a direct contact cooler upstream of the CC unit, which is also utilized to scrub contaminants such as SO_x, NO_x, and particulate matter (PM) from the exhaust stream. Willson (2020) states, that the resulting wash water is treated to remove contaminants before discharge into the sea but does not specify this process in further detail. The separated CO2 is liquified by compressing it to 30 bar and afterwards condensed by cooling. The pressure of the liquid is reduced to 10 bar, causing a small part to vaporise, and thereby further cooling the remaining liquid phase. The liquid CO_2 is stored in tanks at about -40 °C, whereas the gaseous phase is recompressed.

To evaluate the impact and feasibility of the A3C process, Willson (2020) carried out simulations based on two case studies. Even though the case studies refer to specific vessels, the implementation of A3C on-board was considered for the development of a newbuild ship design, not as a retrofit solution. The first case study is carried out for a car carrier, propelled by a dual fuel two-stroke engine being able to run on LNG and MGO.

For the first case-ship, three cases are assessed using LNG as fuel: no CC, CC only from the main engine and CC from all engines (Willson, 2020). The same cases are assessed using MGO as fuel, resulting in six cases overall. Depending on the case, the dimensions and weights of the A3C unit vary. Results are summarised in Table 6.

Table 6. Results of the car carrier case study for A3C application (Willson, 2020)

Case	**LNG**			**MGO**		
	No CC	**ME only**	**All engines**	**No CC**	**ME only**	**All engines**
Reduction rate (%)	0	60	88	0	57	87
Effect on cargo space (%)	0	-5	-6	N/A	1	-1
Auxiliary power consumption (kW)	1854	3543	4278	1854	3918	4973
CAPEX (£1000)	0	11541	14801	0	10139	15117
OPEX (£1000)	0	1152	1632	0	1457	2205
LCCC (£/t_{CO_2})	0	82,3	75,1	0	69	66,9

The second case study is carried out for a small RoPax ferry, driven by a hybrid diesel-electric–battery propulsion system with four four-stroke engines running on MGO (Willson, 2020). Two cases are assessed: No CC and CC from all engines. Willson (2020) is concluding, that the A3C process is a competitive alternative, noting that the LCCC of conventional amine processes are typically around 100-£150/ton CO_2.

8.5 Appendix - Pre-combustion capture

The pre-combustion capturing of CO_2 from a syngas can occur via different technologies. Two mature CC technologies in pre-combustion are the absorption via chemical and physical solvents and the adsorption via chemical and physical sorbents. Apart from the difference that pre-combustion technologies capture CO_2 from a syngas instead of combustion flue gases, the capture process via ab- or adsorption functions in the same way as described in the respective post-combustion chapter.

The same applies for the related regeneration, with a varying working principle of the desorption process in dependence to the applied sorbents and solvents. However, the general technology setup, which is required for the pre-combustion CC process, is more complex.

Pre-combustion CC is applied in a syngas, produced from carbonaceous fuels. This process is referred to as gasification (Vaseghi et al., 2012). In the gasifier, the fuels are partially combusted, while O_2 from an air separation unit (ASU) is added to the process (partial oxidation). The gasification is occurring under pressurised conditions and at high temperatures, caused by the partial combustion (Oresome Resources, 2010). Resulting from the gasification process, a pressurised gas stream rich of CO and H_2 is leaving the gasifier. PM and sulphur contaminants from the partial combustion are also diluted in the gas mixture. The PM are subsequently separated from the gas by a downstream cyclone unit (Lip et al., 2016). A simplified technology setup of the entire pre-combustion CC process is shown in Figure 10.

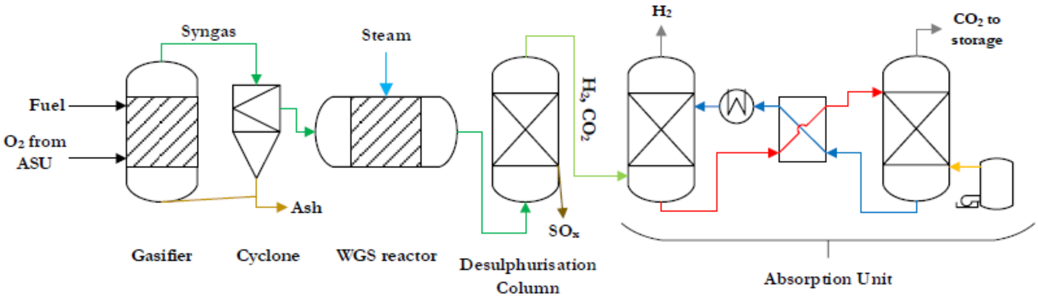

Figure 10. Simplified schematic of the pre-combustion CC process

The O_2 which is added in the gasification process is obtained from the separation of ambient air in an ASU. In the ASU, not only O_2 is separated from ambient air also N_2 is removed. Since N_2 is the major component of the ambient air and does not contribute to the combustion process, it is separated. In this way, a high-concentrated stream of CO_2 and H_2 is produced in the gasification process. Beneficial for this N_2 separation is that it simplifies the CC process and reduces the energy demand for the adsorption/desorption of CO_2 (Kotowicz et al., 2019). The ASU can be any version of a potential air separator. Nowadays, membranes, absorption by chemicals and cryogenic processes are applied (Kotowicz et al., 2019).

In the further processing, the pressurised gas stream is forwarded to a water gas shift reactor (WGS), were the CO and H_2-rich gas is mixed with water vapour, to convert CO to CO_2 and H_2O to H_2. By this, the efficiency of the syngas production is increased, and CO emissions are lowered. After the WGS, the emerged syngas stream is sent through a desulphurisation unit, to remove remaining sulphur contaminants. The desulphurisation is occurring through a selective separation of sulphur from the syngas, utilising either a suitable absorption or adsorption technology (Lip et al., 2016). The final syngas, after the separation of all contaminants, consists of almost pure H_2 and CO_2, with a CO_2 which can contain about 40 percent and a pressure level at 65 bar (Vaseghi et al., 2012). These conditions are highly favourable for the subsequent CC process, which is applied right after the desulphurisation of the syngas (Vaseghi et al., 2012). The capturing of CO_2 from the syngas can occur through the utilisation of similar absorption and adsorption technologies as described in the *post-combustion*. Different absorbents and adsorbents can be applied in pre-combustion CO_2 capture due to the higher partial pressures of CO_2 in the syngas. For such applications, physical sorbents are usually used (Nazir, 2021). Finally, the CC unit is splitting the syngas stream into two separate gas streams: H_2 from the process is used as fuel, whereas the captured CO_2 is compressed and stored.

Rubin et al. (2015) examines estimates on additional costs which arise when a pre-combustion CC technology is used in connection with integrated coal gasification combined cycle (IGCC) power plants with gas turbines as main consumer of the produced H_2. When a pre-combustion CC plant is installed, the total efficiency decreases from 41 percent to 33 percent (8 percent reduction), with additional energy requirements for the capture of 25 percent. Jansen, Gazzani, Manzolini, Dijk, & Carbo (2015) specify, that 44 percent of the total 8 percent efficiency penalty are caused by the WGS.

The CAPEX for the base case power plant increase by 93 percent when a pre-combustion CC technology is installed. Further, the LCOE increase by 80 percent with the use of CC in the system. The average costs of CO_2 captured are estimated to be at $63/ton, when pre-combustion CC is applied in an IGCC power plant (Rubin et al., 2015).

Rubin et al. (2015) applied the same cost estimation as used for pre-combustion CC technologies, to compute the cost figures for coal-fired power plants equipped with post combustion CC technologies. With the installation of a CC plant, the total efficiency decreases to 31.6 percent (9.8 percent reduction). The additional energy requirements sum up to 32 percent more energy input for the CO_2 capture (Rubin et al., 2015).

An increase in total CAPEX of 75 percent is estimated between the base case power plant (without CC) and the same power plant when a post-combustion CC technology is installed. The LCOE are increasing by 62 percent. However, the costs of CO_2 captured are at $46/ton, with the usage of a post-combustion CC plant in coal-fired power plants (Rubin et al., 2015).

The statement of costs of the two cases above allows for a general cost comparison between the post-combustion and pre-combustion CC technology. It is clearly shown that the CAPEX as well as the LCOE for the post-combustion CC technology are lower than for a comparable precombustion CC technology. Lower costs per ton of CO_2 captured are also shown by the post combustion CC technology, compared to the pre-combustion technology.

8.6 Appendix - Oxyfuel combustion

To achieve oxyfuel combustion, the combustion in pure O_2, an ASU is required to separate the O_2 needed for the oxyfuel combustion from other gases contained within the air. However, a typical stream from an ASU still contains about 3 percent N_2 and 2 percent argon, which are diluting the exhaust (Wilcox, 2012). Figure 11 is showing a schematic of the process.

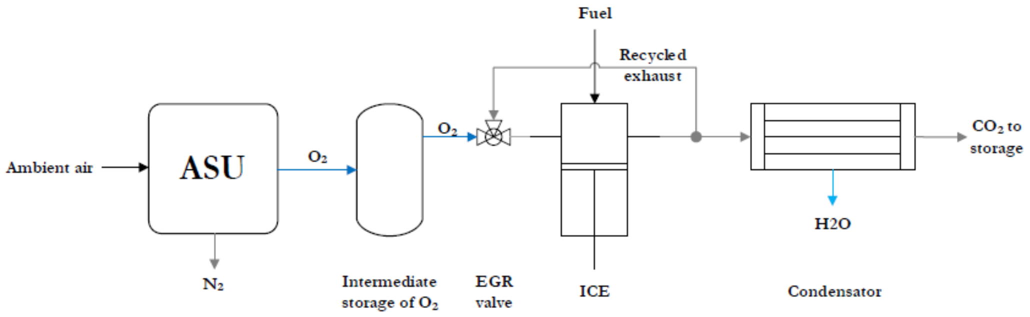

Figure 11. Schematic of the oxyfuel combustion process

Especially in retrofit applications, air slip into the exhaust can lead to further dilution. Furthermore, the initial investment for an ASU and its operating costs are high, making it often uneconomically for retrofitting (Wilcox, 2012).

Chemical looping combustion is an alternative technique to achieve oxyfuel combustion without the need for an ASU but is only feasible for the combustion of solid fuels such as coal (Wilcox, 2012). Instead of adding gaseous O_2 to the combustion process, metal oxides are used as O_2 transporter. In the combustion chamber, the metal oxide is reduced, supplying the required O_2 for the oxidation of the fuel. After the combustion, the metal ions are separated from the exhaust stream by a cyclone filter and are transported into an air reactor, where they are oxidised and afterwards added to the combustion process again (Wilcox, 2012).

The combustion of fuel in an oxygen-enriched environment causes the reaction-speed to increase, since non-reactive atoms like N_2, which are delaying the reaction, are absent (Kang et al., 2018).

Further these non-reactive atoms would act as a thermal buffer by absorbing some of the heat released during the combustion. Their absence is resulting in a faster and hotter combustion of the fuel, which is having a negative impact on the thermal efficiency of the engine (Li et al., 2020). Therefore, different strategies are developed to keep the combustion at manageable temperature and pressure levels and to increase the efficiency of the engine.

In coal-fired power plants, where oxyfuel combustion is already applied to reduce the NO_x emissions, around 70 percent of the exhaust gases are recycled to dilute the O_2-enriched environment in the combustion chamber. This lowers the temperature of the combustion process to levels similar to conventional combustion in air (Wilcox, 2012). Exhaust gas recycling (EGR) is an effective measure to lower the combustion temperature in ICEs as well. Nowadays it is mainly utilised in order to reduce the formation of NO_x during combustion (Verschaeren et al., 2014).

Oxyfuel combustion, particularly chemical looping, has mainly been researched for the combustion of solid and gaseous fuels in power plants for energy generation. Several projects have developed pilot plants, achieving the demonstration state (ZEP, 2017). However, due to an unforeseen development of the electric energy market and the emission trading market, oxyfuel combustion is not commercially competitive and therefore further efforts for most of the pilot plants have been stopped (Johnsson, 2021). As described above, oxyfuel combustion processes for ICEs are still under development (Wu et al., 2014).

Cryogenic ASUs are mature in the O_2 production and therefore have achieved TRL 9 in industry applications (ZEP, 2017). However, these ASUs are energy intensive and further development is required to increase the energetic efficiency of such. Besides cryogenic ASUs, vacuum-pressure swing-adsorption and membranes are being researched for O_2 separation (Abanades et al., 2015).

Due to the low technical readiness of oxyfuel combustion processes in ICEs, currently no predictions on the costs of such technology are available.

Gibbins and Chalmers (2008) compared the costs for equipping a gas-fired power plant with three alternative CC technologies: post-combustion capture by amine solvent, pre-combustion capture with PSA and oxyfuel combustion. The costs of CO_2 avoided, for oxyfuel combustion (\$102/ton CO_2) was estimated to be lower than for pre-combustion capture (\$112/ton CO_2) but not as low as for post combustion capture (\$58/ton CO_2) (Gibbins & Chalmers, 2008). This means, that the variable expenses of oxyfuel combustion are 1,7 times higher than for post-combustion capture with MEA.

Gardarsdottir et al. (2019) carried out a comparison of several CO_2 capture technologies, including absorption by MEA as reference, and oxyfuel combustion for CC from cement production. The costs of CO_2 avoided for the oxyfuel process (€42/ton CO_2) are about half of the costs for the MEA CC process (€80/ton CO_2).

The interviewed experts agreed with these findings, stating that oxyfuel combustion has the highest investment costs in comparison to other CC technologies, but lower operational costs (Johnsson, 2021; F. Normann, 2021; Nazir, 2021). The experts added that the required ASU and a completely different setup for fuel combustion are the main reasons for the high capital investments.

Lighthouse samlar industri, samhälle, akademi och institut i triple helix-samverkan för att stärka Sveriges maritima konkurrenskraft genom forskning, utveckling och innovation. Som en del i arbetet för en hållbar maritim sektor initierar och koordinerar Lighthouse relevant forskning och innovation som utgår från industrin och samhällets behov.

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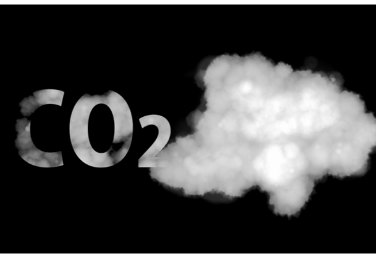

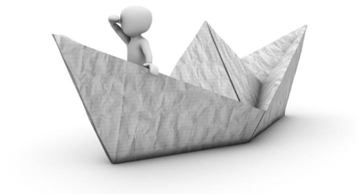

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