Environmental and techno-economic evaluation of carbon capture and storage solutions for the maritime transportation: a review

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Abstract: Maritime transportation contributes to the emissions of greenhouse gas (GHG) worldwide near to 3 % of the total amount. The International Marine Organization (IMO) has the ambition of reaching net-zero GHG emissions from international shipping by 2050. This led to a growing attention to decarbonization techniques applied to the maritime sector. These technologies are widely used in other onshore sectors, with a capture rate up to 90 %, and in recent years they have started to be analyzed for offshore applications. While the utilization of alternative fuels would be a definitive, but long-term solution, one of the most promising short-term solutions is to retrofit existing vessels with carbon capture systems. This study aims to analyze the evolution of the interest for this topic in this century through a systematic literature review. Then an overview of the different carbon capture technologies is given, with a detailed description of the more relevant technologies, such as post-combustion methods. Finally, their strengths and weaknesses are highlighted, based on technical and economic feasibility, and a focus on the environmental aspect. The results show that post-combustion carbon capture with chemical absorption is the most mature and advanced now, but still, these technologies are highly energy-demanding and too expensive to be attractive, although they have the potential to drastically reduce the emissions and guide the transition towards a net-zero emissions scenario.

Keywords: GHG emissions, carbon dioxide removal, CCS, maritime transportation, decarbonization.

1. Introduction

1.1 Background

Anthropogenic greenhouse gas (GHG) emissions have resulted in a 1°C increase in temperature above the pre-industrial level by 2017 (IPCC, 2022). If this trend persists, the average global temperature could surpass 1.5°C sometime between the years 2030 and 2052 (Tollefson, 2018). The primary objective of the Paris Agreement is to ensure that the average global temperature increase remains below 2°C compared to pre-industrial levels, with a more ambitious target of lowering it to 1.5°C (UNFCCC, 2016). As a result of a 1.5°C increase in global temperatures, it is expected that certain regions may experience extreme heat, increased rainfall, and more frequent periods of drought. Limiting global warming to 1.5°C rather than 2°C might potentially alleviate severe heatwaves for a population of around 420 million individuals. This would also decrease occurrences of intense precipitation on a global and local scale (IPCC, 2022). Shipping is a significant source of greenhouse gas emissions. In 2018, its emissions accounted for 2.89% of the total GHG emissions caused by human activities worldwide. If no more measures are taken, the emissions from shipping could potentially reach a level that is 90-130% higher than the global emissions recorded in 2008, which were already at 90% of the emissions recorded in 2018.

Around 70% of worldwide shipping emissions are attributed to tankers, carriers, and containers that transport oil, chemicals, and LNG (liquified natural gas), while smaller boats produce lower emissions (IMO, 2020).

The International Maritime Organisation (IMO) aims to achieve complete elimination of GHG emissions by the year 2050 by reducing the emissions by 20% by 2030 and 70% by 2040, in comparison to the emission levels recorded in 2008 (MEPC, 2023). IMO presents of short-, medium-, and long-term methods to accomplish this objective. Immediate remedies involve measures such as the decrease of the speed, whilst enduring solutions involve transitioning to alternative fuel sources (R. Chen, 2023). The increasing viability of (LNG) as a substitute for marine diesel oil (MDO) and heavy fuel oil (HFO) has initiated the search for alternative fuels. This is attributed to its reduced emissions (Pavlenko et al., 2020), and similar pricing compared to other fuels (Yoo, 2017).

In 2018, HFO accounted for 79% of the overall fuel use in international shipping, as determined by energy content calculations and voyage-based allocation (IMO, 2020). However, fuel composition has changed. HFO use has dropped 7%, while maritime MDO consumption rose 6% and LNG consumption rose 0.9% (IMO, 2020).

Due to the difficulty of making important vessel changes, increasing the energy effectiveness is prioritised. From January 1, 2023, all ships must calculate their Attained Energy Efficiency Existing Ship Index (EEXI) to determine energy efficiency, necessary to submit their annual operating carbon intensity indicator (CII) and rating.

EEXI must be calculated for ships over 400 GT. These ships' energy efficiency is compared against a criterion. The ship meets efficiency standards if its Energy Efficiency Existing Ship Index (EEXI) is below the threshold (IMO, 2022).
The CII sets the annual reduction factor to keep a ship's operating carbon intensity at a certain rating level. It must be calculated for ships over 5000 GT based on their annual fuel consumption. This rates the vessel from A (best performance) to E (lowest performance); the owner must take corrective action and explain its plan to raise the rating to at least C by 2022 if the outcome is E for one year or D for three years (IMO, 2022).
New vessels must have an Energy Efficiency Design Index (EEDI) starting January 1, 2013. EEDI provides a value expressed in grams of CO_2 per ship's capacity-mile: the smaller the EEDI, the more efficient the ship is. Designers can choose their preferred materials and engine specs, if the EEDI threshold is respected for their own ship category (IMO).
These projects aim to promote zero-emission shipping, which will be achievable only through the developing green fuels. During this time, immediate and medium-term solutions like carbon capture and storage (CCS) are crucial. CCS is a technology that removes CO_2 from flue gases for use or storage (S. Chen et al., 2022). This strategy could reduce hard-to-control emissions from heavy industries and maritime traffic (International Energy Agency, 2020). If technologies like CCS are not implemented, the projections report that achieving net-zero emissions would be impossible or at least more expensive (S. Chen et al., 2022; Global CCS Institute, 2020).
A life cycle assessment (LCA) study showed that chemical absorption-based onboard carbon capture reduces carbon emissions by 52%, better than what obtained with direct air capture (DAC) of CO_2 (Negri et al., 2022). Exploring CCS technology is valuable, but a comprehensive framework that summarises its accomplishments in the maritime sector, provides insights, and identifies future growth potential is needed.

1.2 Bibliometric analysis and research objectives

To clearly define the direction of the research and to clarify its scope, this section highlights the bibliometric analysis of the existing contributions. Specifically, scientific, and technical contributions evidence that the attention to CCS applied to the shipping sector grew in the last decades. The overall number of publications is low, but an increasing trend can be noticed: in the decade 2004 – 2013, 66 publications have been issued; while in the last decade, from 2014 to 2023, this number has almost become three times bigger, with two hundred publications. As of the 9th of April 2024, 12 papers have already been published in year 2024.
The inquiry was done with the following string: (TITLE-ABS-KEY ("carbon capture" OR "CO2 capture" OR "carbon sequestration" OR "carbon removal" OR "CO2 sequestration" OR "CO2 removal") AND TITLE-ABS-KEY (ship OR "naval sector" OR "naval field" OR "maritime industry" OR "naval industry" OR "marine sector" OR "shipbuilding industry"). The following subject areas were excluded due to their non relevance: Pharmacology, Toxicology and Pharmaceutics; Immunology and Microbiology; Medicine; Business, Management and Accounting; Agricultural and Biological Sciences; Physics and Astronomy; Computer Science; Mathematics; note, editorial and short survey were excluded; and the year 2004 has been chosen as the 1st, because starting from 2004 there is at least 1 publication per year.
Among these publications, only a small percentage are literature reviews. Sarbanha et al., 2023 provides a comprehensive analysis of the latest advancements in ship-based carbon capture technology research and evaluates several systems based on their performance, level of development, and economic viability. Another one focuses on the utilization of alternative fuels and the subsequent comparison between them, and additionally, attention is given to CCS technology (Mukherjee et al., n.d.).
The other reviews were related to carbon capture not applied to the shipping industry and CO_2 shipping.
Considering these starting points, the absence of a thorough investigation of shipboard CCS systems is noted. Hence, this study aims to evaluate the technological, economic, and environmental feasibility of these technologies. Despite recent studies' significant value, this paper aims to fill the gap in research on CCS technology in maritime transportation by conducting a comprehensive literature review. The review will critically evaluate the existing body of work and identify potential areas for future research.

The structure of the paper is as follows: Section 2 introduces the main carbon capture technologies. Section 3 gives details about the most used carbon capture technologies in the shipping industry. Section 4 is dedicated to the results and their discussion, while Section 5, is for conclusions and potential future research directions.

2. Carbon capture technology

This section provides a general description of carbon capture. Research classifies into pre-combustion, post-combustion, oxy-fuel combustion, and chemical looping combustion.

2.1 Pre-combustion carbon capture (pre-CCC)

Extracting CO_2 from fossil fuel before burning it is its main feature. First, gasification and steam reforming turn fossil fuel into a gas composed by H_2 and CO. Gasification uses heat, pressure, and steam to transform carbon-based or organic compounds into syngas, which is 85% H_2 and CO, and minor amounts of CO_2 and CH_4 (Rogoff & Screve, 2011), while steam reforming increases H_2 and CO by injecting water at high temperatures, causing an endothermic process (B. Zhang et al., 2019):
Before CO_2 separation, the water-gas shift reaction converts CO and water into H_2 and CO_2. This reaction is exothermic, and it increases the ratio H_2/CO (Idriss et al., 2015). The current composition of the stream consists primarily of H_2, which undergoes combustion, and CO_2, which needs to be captured. The gas's elevated CO_2 concentration reduces the cost of capturing it compared to scenarios where CO_2 is chemically removed but at a lower

concentration (Zincir et al., 2023; Thaler et al., 2022). Pre-CCC can reach a capture rate of up to 95%, depending on the technology used (H. Wang et al., 2017). On the other hand, the plant is complex, and its cost is high (Zincir et al., 2023; Thaler et al., 2022; H. Wang et al., 2017). Furthermore, the high H_2 temperature may damage the engine (Zincir et al., 2023), and the gas turbine has low efficiency and large NO_2 emissions (H. Wang et al., 2017), making pre-CCC a less attractive technology. However, a study (Law et al., 2023) made a comparison between four technologies, both in pre- and post-CCC, and found out that the pre-CCC captured same or more CO_2 with lower energy requirements.

2.2 Post-combustion carbon capture (post-CCC)

It removes the CO_2 from the flue gas after the combustion. The flue gas, composed by CO_2, N_2, oxygenated molecules such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and O_2, undergo a pre-treatment process to remove particulate, nitrogen, and sulphur oxides (Basile et al., 2011). After that, the CO_2 can be captured.
This is the most mature and studied method for on-board applications (Zincir et al., 2023; Thaler et al., 2022). Among the post-CCC technologies, chemical absorption is the most used. The main advantage is that it is the easiest way to retrofit the vessels. A post-CCC CO_2 capture rate of 95% is possible, however it depends on the technology and engine load (Kwak et al., 2024). Its cost depends on the conditions and technology.

2.3 Oxyfuel-combustion carbon capture (oxyfuel-CCC)

The process involves the extraction of CO_2 following combustion, utilizing pure oxygen instead of air during the combustion phase (Stanger et al., 2015). The combustion product is made of water vapor and CO_2, which can achieve a level of purity up to 90% (Mitra et al., 2022). This high CO_2 concentration makes its separation easier; in addition, NO_x emissions are low, efficiency can exceed 100%, (Mitra et al., 2022) and plants can be easily retrofitted (H. Wang et al., 2017). For these reasons, some authors (Luján et al., 2023) proposed a membrane-based system with oxy-fuel CCC applied to an engine.
However, oxyfuel-CCC is extremely energy-demanding (Mikulčić et al., 2019a), reducing the interest of practitioners towards its implementation.

2.4 Chemical looping combustion (CLC)

The CLC uses air and fuel separate reactors. Solid carriers carry oxygen from the air to the fuel reactor. In the air reactor, metal oxide carriers oxidise. Its oxygen content is then used to burn fuel in the fuel reactor, restoring the process to its previous condition (Mikulčić et al., 2019b). Since the combustion does not happen in direct contact with air, it produces CO_2 and water vapor. The high content of CO_2 in the flue gas makes the efficiency high (Mikulčić et al., 2019b). This technology has initially been employed for gaseous fuels, but its interest is developing in liquid and solid fuels, making it viable in the maritime transportation (Nandy et al., 2016).
Due to the significant capital expenditure and the need to produce a carrier with reduced sensitivity to abrasion, high fuel conversion ratio, high oxygen transport capacity, and good stability, only a limited number of plants employ this technology (Raganati et al., 2021).

3. Post-CCC applied in the marine industry

Currently, post-CCC is the most advanced and feasible approach as it can be easily integrated into existing plants, unlike the other methods which necessitate a complete overhaul, resulting in substantial expenses and time requirements (M. Wang et al., 2011; H. Wang et al., 2017; Raganati et al., 2021; Mitra et al., 2022b).
This is still valid for the shipping industry (Hua et al., 2023), making post-CCC technology the most advanced solution. The main post-CCC technologies are now analyzed based on the on-board applications.

3.1 Adsorption

Adsorption exploits the physical phenomenon according to which a gas or liquid adheres to a solid surface. In carbon capture, the adsorption phase is followed by a regeneration of the sorbent. To meet both economic and performance requirements, the sorbent must fulfil multiple criteria: CO_2 adsorption capacity, CO_2 selectivity, moisture/impurities tolerance, CO_2 adsorption/desorption kinetics, ease of regeneration, mechanical and thermal stability (Raganati et al., 2021).
Adsorption can be physical, or chemical based on the material used. Physical sorbents can be classified in (Raganati et al., 2021): carbon-based sorbents, available as activated carbons (AC) and carbon nanotubes (CNTs); zeolites and zeolite-like sorbents; and metal-organic frameworks (MOFs).
Chemical sorbents have been developed to increase the CO_2 adsorption capacity and selectivity at low CO_2 partial pressure by means of amines (Raganati et al., 2021).
Regarding the possible application in the maritime sector, authors (X. Zhang et al., 2023) assessed that Fe-doped CaO-based sorbents have the best performance. Others (Erto et al., 2018) used K_2CO_3 as a sorbent in a lab-scale environment, simulating the conditions of a ship engine, and assessing that carbon dioxide emissions could be cut by 30%. Both studies concluded that adsorption can be a valid alternative to MEA-based absorption, but further in-depth study need to be performed.

3.2 Chemical absorption

It refers to the process in which CO_2 reacts with a chemical solvent to produce an intermediate product. This product is then regenerated by heating, resulting in the recovery of the original solvent and CO_2. The plant can be categorised into two sections: the absorption section, where CO_2 is transported from the flue gas to the amine aqueous solution, and the stripping one, where the solvent is regenerated.
Before entering the system, SO_x and NO_x need to be removed to avoid salt formation, and so it is O_2, which can cause amine degradation and corrosion, enhanced by the presence of the amine itself (M. Wang et al., 2011). The flue gas needs to be cooled, because the best performance in

terms of absorption is at around 50°C (M. Wang et al., 2011; Chao et al., 2021).
In recent years, the application in the maritime industry has been explored. The most used solvent is monoethanolamine (MEA), usually used in an aqueous solution in 30 wt%. A case study (Luo & Wang, 2017) has been presented involving a cargo ship working at a constant value of 85% of its maximum load on the engine. Results show that the on-board carbon capture system can remove 90% of the emitted CO_2 at the cost of 163.07 eur/tonCO_2, considering the additional fuel consumption due to the weight and the energy demand of the plant, which is 22.2% higher than the case with no carbon capture. In another study (Mc-Kinney Møller Center for Zero Carbon Shipping, 2022), it has been found that the additional fuel consumption can reach up to 45% in the case of low sulphur fuel oil (LSFO) powered engines. Another paper (Ros et al., 2020) uses the same technology, with a constant load of 75 %; the results showed a lower CO_2 capture rate, but it agrees with the cost of the technology, attesting a value of 168 eur/tonCO_2.
Although MEA is the most used solvent, there are several concerns to be considered in its utilization, such as the CO_2 emissions related to the production of MEA itself, which should be considered in the assessment of the captured CO_2, but also the high energy requirements of the regeneration phase (Luis, 2016) and the high potential in corrosion of MEA, a primary amine, with respect to secondary and tertiary amines. These reasons led the researchers to find alternative solutions to the use of MEA.
Several works compared the performance of MEA with other amines: in one of these (Archetti & Bosio, 2022), methyldiethanolamine (MDEA) has been considered, despite its lower absorption power, for its lower energy required for the regeneration phase and lower corrosive potential. In another one (Ji et al., 2021), MDEA has been combined with piperazine (PZ) and compared with MEA and with diisopropanolamine (DIPA) under different conditions. DIPA has shown low absorption rate compared to MEA, but lower reboiler duty for the regeneration; MDEA+PZ has shown the best performance and a middling reboiler duty. The good results of MDEA+PZ are confirmed by other authors (Lee et al., 2021): they used a solution of 22%wt MDEA with 8%wt PZ, finding an absorption rate up to 93.1% with an estimate of the additional power required and a cargo loss assessed between 2.9% and 5.3%.
Finally, in Feenstra et al., 2019 a comparison is made between the use of MEA and PZ at different and fixed carbon capture rates (60% and 90%) on different vessels. The result showed that the carbon capture is economically more convenient when applied to larger vessels at a higher capture rate and with PZ as a solvent.
However, these papers report results based on laboratory-scale tests, and not data from real on-board systems, and the real conditions may affect the process.

3.3 Chemical processes for carbon solidification (CPCS)

This method also involves absorption, but it deserves a separate section due to its outcome, which is the precipitation of CO_2 into other products, in most of the applications $CaCO_3$. So here the final product is solid.
In one study (Zhou & Wang, 2014), the application to a ship case study is done with a different approach, i.e. it is referring to a fixed 20% of CO_2 emissions captured, and the main result is that, considering the selling of the CaCO3, the OPEX cost has a negative sign, which means profits. A more recent study (Fang et al., 2019) assessed that GHG emissions can be reduced up to 55.8% with an incremental OPEX of 10.6%. Considering the sale of $CaCO_3$, the real incremental OPEX is around 6.8%.
One utilization of limestone is in the production of cement, both to enhance its properties and reduce its environmental impact (Jin et al., 2024). Finally, the increase of CO_2 presence in the oceans led to a decrease of its pH so, the produced limestone could potentially be diluted in the ocean to increase its pH level (Kheshgi, 1995).

3.4 Cryogenic separation

This method exploits the different condensation properties of CO_2 and of the other components of the flue gas. The main advantages of this approach are that high CO_2 purity can potentially be obtained, as well as high CO_2 recovery, both up to 99.99% (Song et al., 2019).
However, the main challenge that limit the use of this method is the high energy consumption that causes extremely high OPEX (Song et al., 2019).
Regarding its application to the maritime industry, some authors (Sridhar et al., 2024) made a comparison between this method and the other technologies and confirmed that the cost for the cryogenic separation is extremely high if compared to the best technology, which it was demonstrated to be the chemical absorption (682 \$/tonCO_2 vs 76 \$/tonCO_2).
In another paper (Lebedevas & Malūkas, 2024), authors focus their attention on cryogenic separation on board and they found a CO_2 capture rate of 57% in the condition of 20°C temperature for an LNG fuelled ship.

3.5 Membrane separation

Membrane technology is a well-known technology used for separation.
For what concerns CO_2 capture, membranes are increasing their utilization due to their low operational cost, energy consumption, and environmental footprint (Kárászová et al., 2020). These advantages inevitably led to a growing interest in such technology in the maritime sector too.
As reported in Sridhar et al., 2024, in a medium tank vessel, the cost of the membrane carbon capture would be three times the one with MEA, considering MEA's carbon capture cost being 82 \$/tonCO_2. In Oh et al., 2022, instead, the technology is applied to an LNG fuelled ship, showing that the dimension of the plant is much smaller compared to a chemical absorption plant, and the higher the gas permeance unit (GPU) of the membrane, the higher is the space reduction, with 54% reduction with 3000 GPU membrane; on the other hand, due to the low concentration of CO_2 in the flue gas, there is no reduction in cost compared to the chemical absorption. This fact is reported also in Hou et al., 2022, in which the energy requirement is related to the CO_2 concentration in the flue gas, and it

shows that membrane technology becomes more convenient with higher concentration, with the breakeven point set at 10%; this represents one of the major limitations of the membrane technology in this application, in which in flue gas has a CO_2 concentration within 10%.

4. Results and discussion

Chemical absorption is, according to the current state of the art, the best technology to be implemented as a post-combustion carbon capture on-board. This is because of its maturity and its performance. Indeed, the capture rate is highly effective, overcoming the 90%, and it is achievable at a competitive capture cost (i.e., maximum 300 eur/tonCO_2). However, despite the readiness of the chemical absorption, the main limitation is related to its investment cost and the energy requirements. This is the main reason the technology is still not attractive on a large scale, as evidenced by Ji et al., 2021. Other technologies have been assessed too, but without finding a tangible alternative with comparable performances.

Adsorption did not find application in the maritime industry, even though preliminary assumptions and lab-scale tests have been made by Erto et al., 2018 and X. Zhang et al., 2023. The lack of a comparative cost measure makes this technology difficult to position in a potential future scenario. Cryogenic separation is in its preliminary stages too, and its prohibitive costs make it a step behind the other technologies (Sridhar et al., 2024), even though the capture rate could be acceptable (49% - 57%) (Lebedevas & Malūkas, 2024).

Carbon solidification and membranes look more promising; their capture rate is still far from chemical absorption, and their costs are higher, but carbon solidification showed limited OPEX expenses and an effortless way to use the captured CO_2, while membranes have potentially the lowest environmental impact and the easiest retrofitting (Fang et al., 2019). Membrane separation is an evolving technology due to its high presence in different sectors but, as of today, the limit of the low CO_2 concentration in the flue gas makes the technology too expensive.

In Table 1, a quantitative comparison between the costs and the performances of the so far investigated technologies applied in the maritime sector is provided.

Table 1: comparison between carbon capture technologies' costs and performances in on-board applications

Technology	CO_2 capture rate	Cost
Adsorption	30%	-
Chemical absorption	> 90%	77.5 eur/tonCO_2 – ≈300 eur/tonCO_2
CPCS	≈ 55%	OPEX > 6.8% compared to no carbon capture
Cryogenic separation	49% - 57%	682 $/ton$CO_2$ – 752 $/ton$CO_2$
Membrane separation	-	> 500 $/tonCO2

5. Conclusions

Since maritime transportation accounts for approximately 3% of GHG emissions, the IMO aims to achieve carbon neutrality in GHG emissions from global maritime transportation by the year 2050. Carbon capture technology is becoming increasingly popular as a temporary solution in the transition for achieving zero-emissions. Among the methodologies, the post-combustion carbon capture is the best solution for the on-board application, due to the limited modification required on the vessel compared to the other technologies. In turn, post-combustion carbon capture can be classified in different technologies, with chemical absorption being the preferred, due to several reasons: CO_2 capture rate that can achieve values higher than 90%; the lowest cost of captured CO_2 among all the technologies; maturity of the technology and easy retrofitting. Chemical absorption is not free of limitations, due to its high CAPEX required, and high energy demand, especially in the solvent regeneration phase. Studies demonstrate that using blended amines instead of single amines may improve the overall performance of the system (Ji et al., 2021). As an alternative, carbon solidification and membranes are potentially the most promising, but still far from chemical absorption, due to lower capture rates and higher costs.

Although there is a growing body of study on this subject, the technology is not sufficiently appealing due to its excessive costs and energy demands. Furthermore, only a small number of studies prioritize investigating the environmental consequences of carbon capture technology in comparison to the current situation. Future studies should focus on two primary areas. Firstly, optimising current technology by decreasing expenses and energy demands, and improving efficiency. Possible ways to do so include avoiding low engine loads and, above all, standardizing the equipment (Ros et al., 2020). This will enhance the competitiveness of carbon capture technologies in the market for decarbonizing shipping. Moreover, it is imperative to prioritize the assessment of the environmental consequences of these technologies through LCA evaluation to gain a deeper comprehension of their benefits. This assessment should not consider just the removal of CO_2 from the gas stream. Since the final goal is to reduce the impact and emissions, the entire process and its integration with other processes should be considered in the environmental analysis (Luis, 2016).

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