

Comparative Assessment of Carbon Capture Processes from the Perspective of Selection Criteria

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The Paris Agreement of 2015 aims to keep the global average temperature increase below 2 °C above pre-industrial levels and to limit warming to 1.5 °C if possible. The European Union has set ambitious targets (-55 % by 2030 and Net-Zero by 2050) to support the European Green Deal (EGD). To reach the goals by the deadlines, extensive pre- and post-source measures are necessary. This article focuses on post-source measures and seeks to identify, quantify, and evaluate the selection criteria of the applicability of carbon capture techniques. The specific energy demand (theoretical minimum work required to separate CO₂ from a gaseous mixture) of a capture process can be derived from the first and second laws of thermodynamics. There are, however, other factors that can significantly influence the decision-making process for carbon capture from a given polluting source. The first criterion group is related to the 2nd law efficiency, i.e., the proportionality between theoretical minimum work and real energy demand that can be achieved in practice, while the second group covers the specific separation cost as a primary economic parameter. The research gives comprehensive insights into the different carbon capture methodologies and analyses their dependency on CO₂ concentration, the presence of impurities, and operational conditions such as temperature and pressure. Based on the analysis outcomes, selection criteria are proposed to help match mature technologies (TRL 7–9) to specific gas compositions and industrial applications, primarily for process gases from power plants, chemical industries, and cement production, supporting more efficient and context-dependent implementation and the green transition.

1. Introduction

The separation of greenhouse gases (GHG) from emissions or from the atmosphere is expected to become a key area in the global mitigation effort. While the most effective strategy remains the prevention of emissions, certain processes inherently produce emissions that cannot be avoided. In such cases, only the GHG removal can bring results. The European Union (EU) has recognised the importance of these technologies and has assigned a prominent role to technical carbon removal methods in several of its directives and policy frameworks. The EGD explicitly states that carbon capture and storage technologies (CCS) must contribute to achieving climate neutrality (European Commission, 2021a). As a leading sustainability technology, carbon removal is classified as environmentally sustainable under the EU Taxonomy, provided that specific criteria are met (European Union, 2020). The significance of this field is further underscored by the EU's development of a dedicated regulatory framework for the certification of carbon removal methods and carbon storage solutions (European Commission, 2024). Although the range of technical GHG removal solutions is rapidly expanding, there is a lack of comprehensive analyses assessing the applicability and suitability of these technologies across different use cases. The objective of this publication is to review the carbon removal solutions currently available on the market or under development, and to define selection criteria that can support decisions about the most appropriate technology for a given application. The comparative assessment of carbon capture (CC) processes is essential for determining effective methods to reduce carbon emissions. This comparison can be based on key selection criteria, including efficiency, cost-effectiveness, technological maturity, and environmental impact. The CC technologies vary significantly in terms of the physicochemical mechanisms they use, as well as in the

specific roles they play across the carbon value chain. Among the prominent methods of carbon capture, CCS and Carbon Capture and Utilisation (CCU) form the foundational technologies, while Direct Air Capture (DAC) emerges as a pivotal innovation designed specifically to address atmospheric CO₂ concentrations. Most existing studies focus on individual carbon capture methods or examine their techno-economic aspects in isolated applications. There is a lack of comparative analyses that assess different technologies using thermodynamic, operational, and economic criteria across various gas compositions and process conditions. This paper addresses this gap by defining selection criteria that link theoretical efficiency with practical applicability, with an emphasis on technologies at TRL 7–9 maturity levels.

2. Classification of the various carbon removal solutions

The first way of classification of CC-methods is based on the overall outcome provided by the solution. CCS is considered a pivotal technology covering three main sub-processes: capturing CO₂, transporting it, and permanently storing it in geological or other formations (Yu et al., 2023). By capturing CO₂ from large stationary sources (e.g. power plants), CCS can mitigate the effects of climate change while still allowing the use of fossil fuels (Barasa and Olanrewaju, 2023). Despite the potential benefits, several challenges hinder the widespread implementation of CCS. High costs associated with capturing, compressing, and storing remain significant barriers. Estimates indicate that a substantial part of the investment in CCS is allocated to the capture technology itself, which covers around 75 % of total costs (Chen et al., 2022). There are technical challenges regarding the long-term stability of storage sites, too (Sciandra et al., 2022), including concerns about potential leaks (Romanov et al., 2024). The landscape of CCS is continuously evolving, with ongoing research aiming to enhance its efficiency and cost reductions. Improved capture materials and processes, better geological assessment techniques, and comprehensive lifecycle analyses will be pivotal in unlocking the full potential (Yoshida, 2024). CCS is now often discussed in conjunction with CCU, which promotes the conversion of captured CO₂ into useful products, creating additional economic incentives for CCS (Barasa and Olanrewaju, 2023). CCU represents a transformative approach allowing more circular industrial processes (Wegat et al., 2022). The utilisation pathways for captured CO₂ are diverse and can include its transformation into chemicals, fuels, or materials. Captured CO₂ can be converted into methanol, which has garnered significant attention as a renewable fuel and chemical building block (Sankaran, 2023). By integrating CCU technologies into existing processes, companies can offset their carbon footprint and create new revenue (Migdadi et al. 2022). A vital aspect of CCU is ensuring that the energy used comes from renewable sources. Therefore, optimising the energy input to maximise carbon efficiency is a primary focus area in CCU research and development. Technologies such as Power-to-Gas (P2G) and DAC have shown promise in this regard (Oluwadamilola, 2024). The challenges facing CCU technologies include scaling up and addressing economic feasibility. Current research focuses on enhancing reaction efficiencies and developing catalysts that can operate under milder conditions, which may lower energy consumption and overall costs (Siegel et al., 2022). DAC is an emerging technology which captures CO₂ directly from the atmosphere (Bahmanpour et al., 2023). Traditionally, DAC systems incorporate large fans that draw ambient air through chemical adsorbents, which capture CO₂ (Su et al., 2022). These systems often rely on amine-based sorbents that have demonstrated efficiency in both adsorption and thermal desorption processes (Majnoon et al., 2023). Advancements in membrane technologies are under investigation as potential alternatives to traditional solvent-based approaches (Fujikawa and Selyanchyn, 2022). Despite its potential, DAC faces significant challenges. The atmospheric CO₂ concentration is relatively low, making capture processes energy-intensive. The costs associated with high-capacity capture equipment and the energy required for the thermal regeneration contribute to the financial barriers (Delgado and Faba, 2024). Moreover, life cycle analyses of DAC technologies underscore the environmental trade-offs. In carbon-negative DAC systems, the used energy must come from renewables; otherwise, the emissions associated with energy consumption could negate benefits (Chauvy and Dubois, 2022). In conclusion, while Direct Air Capture presents a promising methodology in the fight against climate change, addressing its economic and operational challenges remains critical for its successful deployment. The second option to classify CC-methods is based on the specific physicochemical mechanisms employed in the capture process. Different techniques leverage distinct physical and chemical principles, and these methods can be systematically classified into four main groups: Absorption, Adsorption, Membrane Separation and Cryogenic Processes. The absorption mechanisms of CO₂ involve distinct interactions depending on the medium used and can generally be categorised into physical and chemical absorption. Physical absorption primarily relies on the solubility of CO₂ in different solvents. Chemical absorption involves the reaction between CO₂ and the absorbent, often resulting in the formation of stable complexes. This process is crucial in technologies such as DAC, where air is contacted with strong bases like sodium hydroxide (Garza et al., 2023). This leads to the formation of soluble carbonates through rapid exothermic reactions (Garza et al., 2023). Ionic liquids are being examined as promising solvents in chemical absorption scenarios due to their efficiency and reduced energy

requirements for solvent regeneration (Ciriaco et al., 2023). The use of natural materials, such as algal and bivalve aquaculture, demonstrates the role of natural processes in CO₂ absorption. Advancements in material science and biochemistry, focusing on CO₂ absorption, point toward a multifaceted approach that enhances both environmental sustainability and industrial efficiency. Innovations in ionic liquids, biogenic systems, and changes in processing technology are essential in broadening the scope for effective CO₂ management (Bressane et al., 2024). Adsorption, referring to the adhesion of molecules to a solid surface, can occur through physical or chemical processes. Physical adsorption involves the binding of CO₂ to solid surfaces like activated carbon or zeolite via physical forces. Chemical adsorption entails the chemical bonding of CO₂, often facilitated by amines or metal oxides (Peu et al., 2023). To improve effectiveness, a purified gas stream with minimal moisture and a significant CO₂ concentration is necessary. The gas stream must undergo pre-treatment to eliminate water vapour, sulphides, and nitro compounds, as these components can impede CO₂ adsorption by competing for active sites on the adsorbent surface (Karimi et al., 2023). Under optimal conditions, adsorption processes can achieve CO₂ capture efficiencies of approximately 85-90 %. Physical adsorption doesn't involve the disruption of robust chemical bonds. Therefore, the energy needed for regeneration is generally reduced, and it can result in lower energy demands compared to amine scrubbing (Rana and Andino, 2025). Cyclic operations, which necessitate more intricate equipment and alternating processes, face limitations in adsorbent saturation and lifespan. Heavy contamination accumulation can diminish the capacity of the adsorbent, requiring its eventual replacement (Wilcox, 2012). Membrane-based CO₂ separation has emerged as a promising approach due to its operational efficiency, scalability, and lower energy demands (Islam, 2024). Recent research has advanced a variety of membrane materials. Polymeric membranes, including those based on polysilsesquioxane, offer favourable permeability and CO₂ selectivity (Horata et al., 2023), while inorganic membranes, such as ceramics, are valued for their thermal and chemical stability (Hashim et al., 2023). Mixed matrix membranes (MMMs), combining polymeric and inorganic components, have shown enhanced separation performance and operational robustness (Islam, 2024). Another key development is the functionalization of materials, notably the incorporation of Metal-Organic Frameworks (MOFs). Due to their high surface area and tailored pore structures, MOFs improve CO₂ adsorption and are increasingly used in membrane composites (Liu, 2024). Hybrid systems, combining membrane separation with solvent-based absorption, further improve capture efficiency (Asante et al., 2024). In applied contexts like biogas upgrading, membrane technologies support CO₂ removal while enhancing methane recovery (Purba and Safitri, 2023), offering both environmental and economic benefits (Domrongpakkaphan et al., 2024). Cryogenic distillation involves the separation of gaseous mixtures at reduced temperatures, using differential boiling points of the constituent elements. The cryogenic CO₂ capture technology employs liquefied natural gas to produce the necessary cold energy for CO₂ capture. This cryogenic method is capable of yielding CO₂ with a high purity level, reaching up to 99.17 % (Madejski et al., 2022). In cryogenic separation, CO₂-containing gas mixtures undergo compression and pretreatment to eliminate water. The compressed liquid is processed through heat exchangers to a lower temperature, followed by cryogenic distillation to separate liquefied CO₂ from gases like N₂ or H₂. Its application is limited by elevated operational expenses, making it feasible only when CO₂ concentrations are exceedingly high, specifically at or above 60 % v/v. Unlike absorption methods, cryogenic CO₂ capture obviates the need for chemical sorbents and can be conducted at atmospheric pressure (Wilcox, 2012).

3. Selection criteria for carbon removal solutions uptake

In absorption processes, several factors guide the selection of absorbents which require optimization to reach effective operations (Lu et al., 2023). Absorption commonly occurs within a temperature range of 40-60 °C (chemical reactions exhibit maximum efficiency within this range). Crucial parameters include pressure, CO₂ concentration in the feed gas, and the gas/liquid ratio, typically ranging from 0.1 to 0.3 kg solvent/kg flue gas. The dimensions of the absorber tower, specifically height and diameter, are determined by the desired CO₂ removal efficiency, the L/G ratio, and the mass transfer rate. The thermal energy demand of regeneration is a critical factor in the overall system energy efficiency. Solvent recoveries and losses must be considered, alongside economic factors such as payback time, realistically estimated between 8 and 15 y. Additional key factors include pH value and gas velocity (Wang et al., 2023). In the process of adsorption, the extent of CO₂ absorption is contingent upon both pressure and temperature. Elevated temperatures lead to a reduction in the sorption capacity. The presence of humidity in the gas intended for capture diminishes adsorption efficiency, necessitating that the selection and sizing of equipment account for the technological imperatives of potential cooling and moisture condensation. The specific type of adsorbents also influences the temperature at which the process is conducted (Kammerer et al., 2023). The influence of water on CO₂ adsorption warrants thorough consideration, as its presence can either augment or impede CO₂ uptake depending on the sorbent material (Wilcox, 2012). The effectiveness and cost-efficiency of CO₂ separation are significantly influenced by the concentration of CO₂. Specifically, in adsorption processes that rely on temperature-pressure variations, a

higher CO₂ concentration correlates with an enhanced CO₂ sequestration capacity (Ji et al., 2024). Elevated temperatures of flue gas during membrane fusion can rapidly degrade the membrane. Therefore, it is advisable to cool the gas to below 100 °C prior to membrane separation. The membrane needs to exhibit resistance to aggressive compounds found in the flue gas, or these compounds should be removed beforehand. Effective gas separation requires a substantial driving force. To facilitate the application of membrane technology to dilute (low concentration CO₂) end gases, either the CO₂ concentration in the flue gas must be increased, or a selective membrane must be utilised to target other gases present (Brunetti et al., 2010). Elevated moisture levels have the potential to diminish membrane efficiency. Therefore, treating wet end-gases prior to processing or selecting a technology capable of withstanding substantial relative humidity is necessary (Chronopoulos, 2016). Elevated pressure enhances the effectiveness of membrane processes; however, the operational pressure range of 0.7–2.4 MPa commonly employed in industrial settings results in substantial energy consumption and diminished thermal efficiency. Membrane technologies must exhibit durability and high mass transfer flux within compact, cost-effective modules, characterised by a high surface area per unit volume, to effectively compete with absorption and adsorption technologies (Duan and Kai, 2022). In cryogenic separation, compressors are critical, and their selection hinges on the fluid type and volumetric flow rate. Given that CO₂ desublimation occurs between -100 °C and -135 °C, it is imperative to ensure the incoming gas stream is devoid of contaminants (Wilcox, 2012).

4. Results

The analysis of the selection criteria indicates that the applicability of carbon capture technologies primarily depends on the CO₂ concentration of the gas stream, the energy required for separation and regeneration, and the presence of impurities. Absorption methods are generally suitable for post-combustion flue gases with moderate CO₂ content (10–15 %). Adsorption techniques may be more practical in smaller-scale or modular systems, particularly where space is limited and humidity is low. Membrane separation tends to work best when the CO₂ concentration is high or can be increased, and when the gas stream is relatively clean. Cryogenic separation is usually only practical at very high CO₂ concentrations (above 60 %), due to its high energy consumption. In terms of technological maturity, absorption and adsorption processes have already been implemented at TRL 8–9 in sectors such as the cement industry and power generation. Membrane systems are under development for applications including biogas upgrading and hydrogen purification, while cryogenic technologies are mostly applied in specialised settings with high-purity gas requirements. Overall, each method has specific advantages and limitations, depending on the operating conditions. In addition to the technical aspects discussed, economic criteria are also very important when considering measures to reduce GHG emissions. Economic decisions are multidimensional and must consider corporate climate protection policies and permissible costs in relation to these. Figure 1 shows the decision-making process for selecting CC procedures based on specific investment and operational costs.

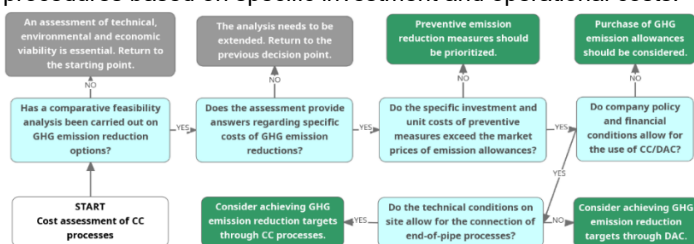


Figure 1: Decision tree for assessing the economic applicability of CC procedures (own edited)

5. Conclusions and further research steps

The suitability and implementation of carbon capture technologies are highly dependent on several key factors, including the specific application, the concentration of CO₂ in the gas mixture, the chemical composition of the CO₂ environment (e.g., presence of water vapor, acidic substances, and solid particles), and the prevailing physical conditions such as temperature and pressure (Thiedemann and Wark, 2025). The concentration of CO₂ in the resultant gases holds significant importance. An elevated CO₂ level diminishes the theoretical thermodynamics necessary for separation, consequently reducing the practical effort needed. As a consequence, separation becomes more straightforward with a higher CO₂ concentration in a gas mixture (Sexton et al., 2015). Beyond CO₂ concentration, the surrounding chemical milieu significantly influences the selection of appropriate separation technologies. Certain processes exhibit heightened selectivity towards specific chemicals within the gaseous mixture. Consequently, water vapour and acid gases can potentially

impede CO₂ binding in solutions or on solid surfaces. The presence of solid impurities poses a risk of damaging solutions, adsorbent micropores, and membranes and could even preclude the feasibility of direct cryogenic processes (Murugan et al., 2020). When selecting production conditions, temperature and CO₂ partial pressure are important factors. When a process occurs at high temperature or pressure, the thermal and pressure work stored under these conditions can be used in the separation process. However, high temperatures can negatively affect separation processes, such as absorption and adsorption, due to their exothermic nature (Sexton et al., 2015). Beyond selection criteria, the aspects of scaling must be considered. The critical determinants include the volumetric flow rate, the flow rate, and, as previously noted, the partial pressure of certain constituents within the resultant gases undergoing purification or separation. Furthermore, the reaction rate significantly influences the sizing process, acting as a primary factor in establishing the separation duration and, consequently, the efficacy of the selected equipment (Porter et al., 2015). Decision-making aimed at reducing greenhouse gas (GHG) emissions cannot ignore economic considerations. The authors propose an algorithm for decision-making based on financial criteria. The decision tree incorporates a range of factors relevant to corporate climate protection policies, investment opportunities, emissions trading markets, and the technical compatibility of CC technologies. A subsequent phase of the research could involve algorithmising the technical selection criteria, employing analogous logic. This approach could streamline decision-making processes, particularly concerning the compatibility of emitting and capture technologies, following a thorough examination of financial viability.

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