

Carbon Capture and Utilization Technologies for Offshore Platforms: a Literature and Industrial Perspective

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Today, fossil fuels remain the most reliable and widely used energy source, with demand projected to rise in the coming years. Approximately 25% of the total fossil fuel production comes from deep and shallow offshore operations, yet its carbon footprint is about twice that of onshore oil rigs per equivalent megajoule (MJ) of methane produced. Accordingly, lowering the carbon footprint in offshore operations represents a key step for reducing worldwide Greenhouse Gas (GHG) emissions. However, conventional Carbon Capture and Utilization (CCU) technologies frequently prove inadequate in meeting the specific demands of offshore operations due to constraints associated with their segregation from land connections, limited spatial availability, and deep process integration. This paper reviews the CCU technologies with potential applications in offshore platforms based on their technological maturity and compliance with offshore operational constraints. In particular, electrified reforming, catalytic hydrogenation, and 2-step carbonylation present a near-term potential for offshore operations, while technologies such as 1-step carbonylation and electrocatalytic and photocatalytic transformations still require substantial advancements for their effective offshore implementation.

Keywords: Carbon Capture and Utilization, Offshore, Carbon Dioxide

1. Introduction

Since 2021, there has been a notable increase in the demand for fossil fuels driven by the post-pandemic economic recovery. According to the International Energy Agency (IEA), oil and gas consumption is expected to continue growing in the coming years, reaching a peak by 2030 (International Energy Agency, 2023). To meet the increasing global energy demand, the exploitation of reservoirs through shallow and deep-sea drilling operations has played a key role. It has been estimated that approximately 25% of worldwide oil and gas production is derived from offshore platforms (International Energy Agency, 2018).

Offshore platforms have shown higher GHG emissions compared to onshore facilities. This is due to the nature of their operations, which encompass activities such as drilling, the maintenance of floating systems, and the transportation of equipment, waste, and personnel. The Carbon Intensity (CI) of offshore operations has been estimated at 5.7 grams of CO₂ per MJ of produced oil in the United States, a value twice the one reported by the US national inventory for onshore operations (Negron et al., 2024). For this reason, reducing GHG emissions in offshore operations represents a crucial step in diminishing the worldwide carbon footprint.

CCU technologies have been widely studied in the literature and effectively applied in industrial environments (Al-Mamoori et al., 2017). However, offshore operations present additional challenges to conventional CCU technologies due to the lack of land connections, limited space availability, and the need for deep process integration. These constraints demand highly efficient CCU technologies with minimal dimensions, low weights, auto-sufficient, and intensified unit operations. Furthermore, research has typically focused on literature applications, with little attention paid to available industrial-scale processes or patents describing potential CCU industrial applications. This review aims to address this gap in the literature by providing an overview of the most promising CCU strategies with transformative potential for offshore platforms. Considering the

consolidated state-of-the-art in Carbon Capture or Sequestration technologies (Al-Mamoori et al., 2017), this work focuses on Carbon Utilization alternatives from already captured CO₂.

2. Methodology

Typical search engines were used for the literature scouting. Concerning patent search, Espacenet and Orbit were used (Espacenet, 2024; Orbit, 2024). To ensure that no potential technologies were overlooked, the scouting considered evaluating several keywords related to offshore technologies or their operative constraints:

- Offshore / Coastal
- Oilfield / Platform / Rig
- Carbon Dioxide / CO₂ / Carbon
- CCU / Utilization / Conversion / Transformation / Feedstock / Reuse
- Hydrogenation / Reduction / Carbonylation / Solidification
- Low weight / Low pressure / Low temperature / Intensified / Light / Compact

The search was refined by combining the results with CCU-related patent Cooperative Patent Classification (CPC) symbols such as Y02C20/40 (capture or disposal of CO₂) or Y02P20/151 (technologies for GHG reduction) and public industrial information from the related companies. The methodology employed for patent and literature scouting is summarized in Figure 1.

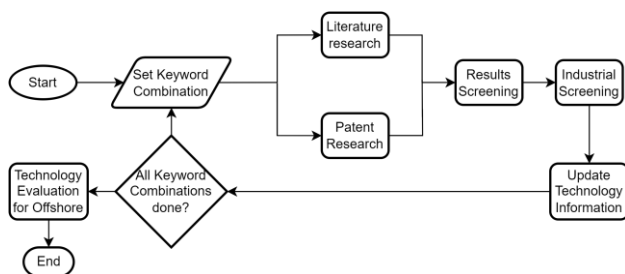


Figure 1. Methodology for the research of potential CCU technologies for offshore platforms.

The offshore potential of the technologies was determined using several factors, including their Technology Readiness Level (TRL). The TRL was determined considering the applications, scouting, and the minimal value for the technology to be considered mature at 6. In addition, the technology compactness, the absence of co-reactants not widely available in offshore facilities (i.e., different from CO, CO₂, H₂O, CH₄, or H₂), the reduced number of reaction steps (as it is related to the dimension of the process and its total weight), or the presence of low pressures (as it is related both to the units' cost and weight) were key evaluated aspects.

3. Results and Analysis

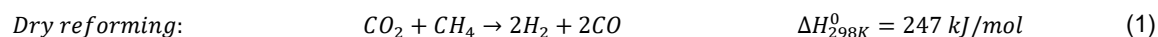
The literature and industrial scouting resulted in CCU technologies that were grouped into four categories:

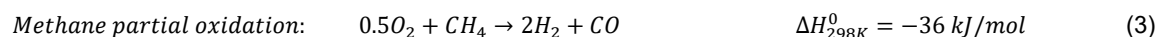
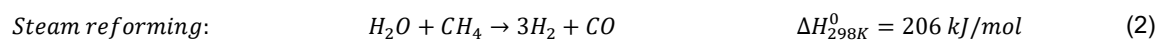
- **Reduction:** Processes that lead to the production of CO.
- **Hydrogenation:** Reactions coupling CO/CO₂ with hydrogen or a hydrogen-rich molecule.
- **Carbonylation:** Reactions involving the insertion or addition of CO to an organic molecule.
- **Solidification:** Technologies that result in the formation of carbon-based solid products.

3.1 Reduction

Reforming

Steam reforming (Eq. 2) is the most widely spread process to produce syngas (a mixture of CO and H₂) from methane in a cost-effective way (Ullmann's Encyclopedia of Industrial Chemistry, 2003). Likewise, reforming may involve CO₂ as feedstock without significantly affecting the total operating costs or the reacting conditions, typically around 800 °C and 20 bar for hydrogen production. CO₂ reacts with methane in the dry reforming reaction presented in Eq. 1. This process may be complemented with steam or oxygen (Eqs.2 and 3) for bi and tri-reforming processes. In particular, dry-reforming technologies require higher operating temperatures (>1000 °C), which, complemented with the absence of steam, may increase the probability of coke formation and catalyst sintering (Usman et al., 2015).





Reforming reactions typically involve the use of supported catalysts based on noble (Ru, Rh) or non-noble metals (Ni, Co, Cu) over metal oxide supports (ZrO₂, Al₂O₃). Noble metals are usually expensive, while non-noble metals often result in low activities, requiring more severe conditions that may increase the likelihood of catalyst sintering and coke formation. This has motivated the development of hybrid bi-metallic catalysts over mixed oxide supports. In particular, Ni-CeO_x-MgAl₂O₃ has demonstrated high activities, reaching CO₂ conversions of up to 85% at temperatures around 800 °C (Vita et al., 2018).

Conventional reformers consist of large heavy ovens, unsuitable for offshore applications. However, electrified reformers have been proposed as a potential solution, given their comparable costs, compact design, and reduced environmental impact. Moreover, their uniform temperature profiles reduce their size by approximately 100 times and minimize hotspots that could cause catalyst sintering or coke formation (Wismann et al., 2019). Electrified reformers pose a promising alternative for CCU in offshore platforms. Nevertheless, no evidence exists of industrial-scale processes using electrified reformers, even though pilot-scale processes have been proposed (Salano et al., 2024). In any case, industrial players have demonstrated their interest with patents for electrified reformer designs by companies such as Haldor-Topsoe (Mortensen et al., 2021) and for dry and bi-reforming catalysts by Saudi Aramco and BASF (Alsolami et al., 2021a, 2021b; Milanov et al., 2015).

Plasma

Plasma may be generated through different methods such as dielectric barrier discharge, microwaves, radio frequency, and gliding arcs. These technologies are among the most promising ones for the conversion of CO₂ due to their compactness and autocatalytic nature (Qin et al., 2018). Nevertheless, plasma technologies have several inherent limitations regarding offshore operational constraints, which include high temperatures (exceeding 1000 °C), high operational and capital costs, low conversion and selectivity (approximately 20% and 70%, respectively), and scalability issues. Even though the use of nickel-based catalysts in recent years has shown enhanced reaction yields, it should be noted that plasma technologies remain in an early development stage. Consequently, further research is necessary to determine their offshore potential. This is demonstrated by the absence of plasma technologies for CCU at industrial or pilot-scale. Instead, research has focused on lab-scale processes at universities and research centres, particularly in China (Zhang et al., 2019).

Photochemical and Electrochemical Reduction

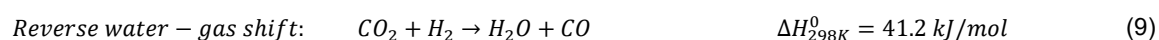
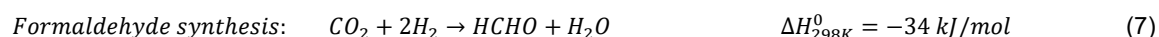
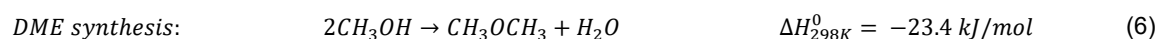
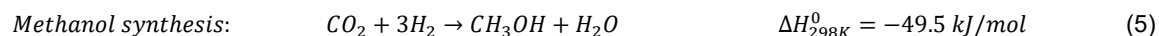
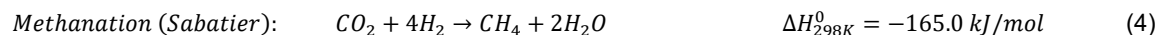
Photocatalysis and electrocatalysis offer a compact alternative for CO₂ reduction using different wavelength ranges within the electromagnetic spectrum. The operating conditions are typically ambient temperatures and pressures or slightly heated systems (up to 80 °C). The reaction path involves electron and proton transfer to generate products including Methane, Methanol, Acetic Acid, Formaldehyde, Formic Acid, Carbon Monoxide, and Ethylene (Wu et al., 2017). The selectivity to any of these products may be tuned to reach 90 – 95 % by adding catalysts, typically based on Ag, Pt, I, Pd, Cu, Sn, Co, Fe, and CeO₂. These catalysts are used as bulk phases (electrodes) in electrochemical applications and supported in TiO₂ in photocatalytic applications.

The compactness and mild operating conditions of photo and electrochemical reduction processes pose a significant potential regarding offshore operating constraints. However, critical drawbacks have been identified, including high catalyst corrosion and cost, low conversion in photocatalytic systems, and low product concentration due to the necessity of diluted solutions to promote ion interaction. Furthermore, scaling up presents a considerable challenge due to the ion mass transfer in large solution volumes. As a result, research has focused on lab-scale and pilot-scale plants. However, research on these technologies has been advancing quickly, and together with the reduction in electricity costs and the improvements in renewable energies, it is expected to grow to industrial levels within the next 5 to 15 years. Remarkable examples include pilot-scale facilities such as Rheticus I, an industrial collaboration between Evonik and Siemens for the production of butanol via photocatalysis in a 3,000 cm² cell (Siemens Energy, 2019), and a 15,000 cm² cell built by OCOchem for the electrocatalytic conversion of CO₂ to formic acid (OCOchem, 2024).

3.2 Hydrogenation

The direct hydrogenation of CO₂ is challenging due to the molecule's stability, typically leading to low single-pass conversions, large recycles, and high capital expenses. In addition, the reacting hydrogen must be derived from renewable sources such as water electrolysis to guarantee carbon neutrality, which is still a developing field for industrial-scale applications (Terlouw et al., 2022). However, important advances have been made in the production of single-carbon products, including methane (Eq. 4), methanol (Eq. 5), formaldehyde (Eq. 7), or formic acid (Eq. 8) (Ye et al., 2019). In these cases, conversions and selectivities of around 95% have been

observed when using catalysts based on transition metals such as Pd, Pt, Co, Fe, Ni, Rh, and Ru at temperatures and pressures around 300-450 °C and 1-30 bar, respectively. Regardless the drawbacks, hydrogenation is a relatively simple technology which has been brought to industrial scale by companies such as Sekisui Chemical Co LTD and Saudi Aramco, presenting compact processes for CO₂ conversion to methanol (Dasanayake et al., 2023; Imran et al., 2014), or the Daewoo Shipbuilding & Marine that presented an industrial-scale process for methanation in offshore production facilities (Yoo et al., 2017).



Enhanced Oil Recovery

Enhanced Oil Recovery (EOR) is a cheap and well-known Carbon Capture and Sequestration (CCS) technology. It involves the injection of CO₂-rich fluids in oil rigs to improve the oil and gas extraction and productivity. Still, due to potential high pressures and temperatures inside oil rigs (around 300 °C and 90 bar), the CO₂ may be hydrogenated following Eqs. 4 and 9. These reactions may increase the quality of the gases extracted from the wells and reduce the heavier oil fractions. Reactive EOR requires a typical reverse Water-Gas Shift catalyst such as Cu-ZnO-Al₂O₃. Catalyst injection and recovery, the reaction conditions control, and the variability of the reservoir conditions present critical limitations for this technology, which has been studied at laboratory scale, underscoring the need for further research (Aliev et al., 2022).

3.3 Carbonylation

Several organic compounds of interest may be produced from carbonylation, such as carboxylic acids, aldehydes, and anhydrides. This may be accomplished through a dual-step reaction by producing CO from CO₂ following a reduction step (Sec. 3.1) or a rWGS (Eq. 9). Subsequently, conventional carbonylation or hydroxycarbonylation processes may take place (Eq. 10) (Sang et al., 2022). Acetic acid is the most relevant product from carbonylation reactions. Its Industrial-scale production requires the use of expensive iridium-based complexes (such as [Rh(CO)₂I₂]⁻ for the Monsanto process or [Ir(CO)₂I₂]⁻ for the Cativa), along with high operating pressures (around 30 to 60 bar) and relatively low temperatures (around 200 °C). These are highly consolidated industrial processes, with conversions and selectivities approaching 100% (Ullmann's *Encyclopedia of Industrial Chemistry*, 2003).

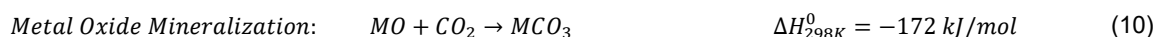


CO₂ carbonylation may also follow one-step approach through the implementation of photocatalytic or electrocatalytic processes (Sec. 3.1), or the utilization of specific homogeneous or heterogeneous catalysts such as three-ethylamine, Ni/Zn or RuCl₂(PTA)₄ at pressures ranging from 10-50 bar and temperatures between 80-200 °C (Kaczur et al., 2018; Park et al., 2020). At the industrial scale, only the dual-step carbonylation of CO₂ has been implemented by companies such as Saudi Aramco and Mitsubishi (Al et al., 2022; Kobayashi et al., 2004). In contrast, only pilot plants have been proposed for one-step approaches (Park et al., 2020). All in all, the chemical and the electrochemical paths present substantial limitations in offshore. On the one hand, the chemical path requires expensive catalysts and high pressures, resulting in high costs and heavy equipment. On the other hand, the electro and photocatalytic processes are subject to the limitations discussed in Sec. 3.1.

3.4 Solidifications

Solidification aims to recover carbon-based solid products via polymerization, mineralization, carbonization, vitrification, or petrification reactions. However, the focus in the literature (Hills et al., 2020) has been exclusively on mineralization (Eq. 10). This reaction involves Ca, Mg, or Na oxides or hydroxides to produce carbonates at temperatures ranging from 30 to 90 °C (in aqueous phase) or 300 to 500 °C (in direct carbonation). This technique has been widely applied at the industrial level to incorporate CO₂ into concrete mixtures (Hills et al., 2020). However, there is no evidence of mineralization in offshore facilities, even when metal oxides are typically

available in oil wells. This can be attributed to the substantial reaction volumes required due to slow kinetics and the challenges associated with the solid products' recovery from wells. These limitations pose critical impediments to the offshore application of these processes (Hills et al., 2020).



The technologies reviewed in this Chapter are grouped in Tab. 1. This table reports operating conditions for single-carbon products, which typically prompt higher yields (Ye et al., 2019). In addition, the table presents key information regarding the offshore operating constraints defined in Chapter 2. Technologies that have demonstrated sufficient maturity for offshore applications have been labeled “Yes”, while technologies that still require significant advancements for their industrial application have been labeled “Future”.

Table 1: Summary of potential carbon utilization technologies for offshore platforms

Technology	Operating Conditions	Conversion / Selectivity (%)	Catalyst	Cost	Compact	TRL	Offshore Potential
Conventional Reforming	800 °C 8-30 bar	70-90% / 90-95%	Ni, Co, Cu-based	Mid	No	9	No
Electrified Reforming	800 °C 8-30 bar	70-90% / 90-95%	Ni, Co, Cu-based	Mid	Yes	8	Yes
Plasma	+1000 °C 0.1-1 bar	20-40% / 80-90%	Autocatalytic or Ni-based (NiO)	High	Yes	4	No
Photocatalysis	20-80 °C 1 bar	5-10% / 40-80%	Transition metals over TiO ₂	High	Yes	5	Future
Electrocatalysis	20-80 °C 1 bar	20-50% / 70-95%	Bulk transition metals	High	Yes	5-6	Future
Hydrogenation	300-450 °C / 1-30 bar	80-95% / 95-99%	Transition metals	Mid	Yes	9	Yes
Enhanced Oil Recovery	300 °C 90 bar	80-95% / 95-99%	CZA	Mid	No	4	No
Carbonylation (2-step)	180-200 °C / 30-60 bar	90-100% / 90-100%	Noble metal complex	Mid	Yes	8	Yes
Carbonylation (1-step)	80-200 °C / 10-50 bar	50-90% / 80-90%	Ni/Zn or metal complex	Mid	Yes	4	Future
Mineralization	30-500 °C / 1-30 bar	60-90% / >90%	Autocatalytic	Low	No	9	No

4. Conclusion

This study has reviewed the most attractive technologies for offshore applications, based on their maturity and compliance with typical offshore constraints such as small dimensions and transport limitations. Some technologies have been highlighted as viable near-term solutions for advancing offshore CCU, such as electrified reforming, catalytic hydrogenation, or 2-step carbonylation. However, it is crucial to acknowledge that other technologies, such as 1-step carbonylation and electrified and photocatalytic processes, still require substantial advancements in materials, catalysts, and reactor designs to be implemented in offshore platforms.

Nomenclature

CCU – Carbon Capture and Utilization	EOR – Enhanced Oil Recovery
CCS – Carbon Capture and Storage	GHG – Greenhouse Gases
CI – Carbon Intensity	IEA – International Energy Agency
CPC – Cooperative Patent Classification	TRL – Technology Readiness Level
CZA – Copper/Zinc/Alumina catalyst	WGS – Water-Gas Shift

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