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Carbon capture and utilization for industrial applications

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Abstract

Heavy industries such as cement, iron and steel, oil refining, and petrochemicals are responsible for about 22% of global carbon dioxide (CO_2) emissions. There exist several pathways for global CO_2 mitigation. Capturing, storage, and utilization of CO_2 (CCS and CCU) provide an operational solution for significant emission mitigation. High purity CO_2 streams are the most interesting points for CCS and CCU. Pure CO_2 streams are suitable for compression, transport, and storage. Capture technology categories are typically pre-combustion, oxy-fuel combustion, and post-combustion processes. Moreover, the main challenges of the robust industrial CCS/U development are the high costs of CO_2 separation from flue gas or ambient air and the conversion of CO_2 in various utilization pathways. This research study includes a summary of several CCS technologies and CCU pathways, their current status, cost, and industrial deployment.

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Keywords: Carbon capture technologies and costs; CCS/U; CO_2 stream purity

1. Introduction

Carbon separation, capture, storage, and utilization (CCS/U) aim to reduce global anthropogenic carbon dioxide (CO_2) emissions and tackle climate change [1,2]. Heavy industries, including cement, iron and steel, oil refining, and petrochemicals, are responsible for about 22% of global CO_2 emissions. Among these industries, oil refineries account for 4%–6% [3]. CCS refers to capturing carbon at the emission source and preventing its entry into the atmosphere. In parallel, some studies deal with capturing CO_2 from the ambient air. The captured carbon is then either utilized in industrial processes or sequestered geologically [1,2]. For both utilization and storage, CO_2 capture

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is an essential process. The main challenges of the prospering industrial CCS/U development are the high costs of CO_2 separation from flue gas or ambient air and the high costs of CO_2 conversion in various utilization pathways [4].

CO_2 capture requires employing several methods like the use of membranes, chemical looping, cryogenic distillation, etc. [1]. The collected CO_2 can be stored in geological sites or utilized directly and indirectly (CCU). The direct utilization example is enhancing oil recovery, and the indirect utilization is using CO_2 as a feedstock for chemical industries to produce valuable products such as the manufacturing fertilizers [5] or synthetic fuels. Possible carbon utilization pathways include the usage of CO_2 in oil and gas recovery enhancement, polymer processing, the manufacturing of fertilizers [5], urea [6], methanol synthetic methane, synthetic crude, electrochemical conversion to certain chemicals, and water desalination projects [1,7].

2. Technology status

Different capture and separation technologies via several methodologies exist, and their costs depend on the CO_2 amount, CO_2 concentration, partial pressure, and the concentrations of contaminations such as N_2 [8,9].

Capture technologies are pre-combustion, oxy-fuel combustion, and post-combustion processes [8,10]. These carbon capture technologies use various materials and separation methods depending on the need and demand [1,8]. Fig. 1 depicts a schematic overview of the different CO_2 capture categories.

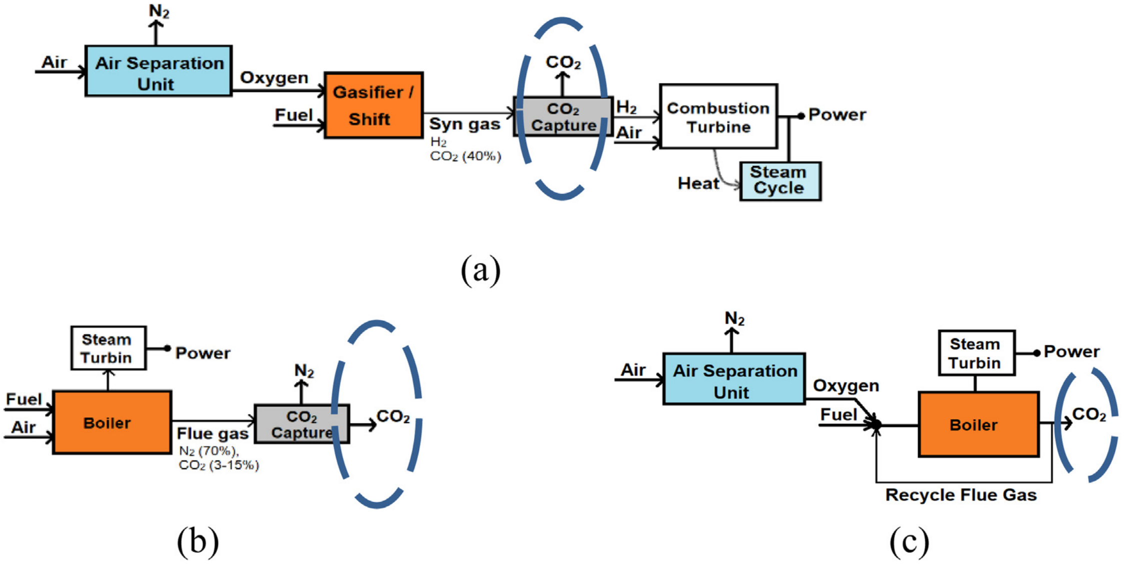

Fig. 1. (a) Pre-combustion, (b) post-combustion, and (c) oxy-combustion carbon capture schematics.

Post-combustion capture refers to capturing CO_2 from the traditional combustion methodologies in which the air supplies oxygen. Therefore, the flue gas contains low concentrated CO_2 diluted in N_2 and NO_x molecules. Hence, the post-combustion CO_2 abatement is a straightforward approach to capturing emitted CO_2 from usual processes and forms the basis of the current infrastructure in CCS [11].

The fundamental implication of pre-combustion capture (PCC) is gasification, where carbonaceous materials such as coal and biomass are reacted at high temperatures to produce synthetic gas [1]. The partial oxidation in pre-combustion leads to the production of CO_2/CO and H_2. Then, H_2 is separated from CO_2 by physical or chemical methodologies to get utilized as fuel with an ultimate combustion product of water [12]. However, the main issue of the pre-combustion route is H_2 combustion. H_2 cannot replace conventional fuels such as methane due to the physics of H_2 combustion. Pre-combustion implies, in many cases, replacing existing kilns or boilers with new kilns and boilers; however, the technology readiness times and its costs are not available yet. Lastly, H_2 combustion with air produces water and NO_x, in which NO_x compounds are environmentally harmful.

Oxy-fuel combustion technology burns fuel in a mixture of oxygen and recycled flue gases (RFG) rather than air. Hence, the end-stage mixture stream consists mainly of CO_2 and condensable water vapor. Separation of the water vapor is possible during the compression process [1,9]. Oxy-fuel combustion is almost an alternative to the post-combustion CC technique [9]. This process is combusting fuel in a mixture of pure O_2 with purity above 95% and CO_2 with a purity of 80%–98%. So, in oxy-fuel combustion, the air is replaced by pure O_2 to decrease the amount of nitrogen in the exhaust gas. The major challenge is the dissociation of pure O_2 in the air separation unit, which is energy-intensive. The other origin of high purity O_2 production is green H_2 production via water electrolysis. So, the H_2 economy will probably impact the O_2 production costs.

The oxy-fuel combustion process is advantageous because the combustion products are mainly composed of CO_2, H_2O, and SO_2. The next step is the separation of H_2O by condensation. Elimination of SO_2 is possible by electrostatic precipitation and desulphurization. These purifications result in a pure CO_2 stream that is suitable for compression, transport, storage, and utilization [8].

Among CCS technologies, post-combustion is the most mature alternative to capture CO_2 and finds use to retrofit existing technologies [13]. Post- and pre-combustion captures rely on methodologies that can separate CO_2 from the mixed stream via (i) Solvent scrubbing, (ii) Solid adsorbent, (iii) Adsorption, (iv) Membrane, (v) Cryogenic distillation [1].

3. Carbon utilization pathways

CCU is the utilization of CO_2 as a raw material for the production of valuable products [1,4]. For scaling up the carbon capture technologies, CO_2 utilization is a promising pathway and will offset CO_2 capture and conversion costs [4]. CO_2 utilization is possible via direct and indirect trajectories. CO_2 of high purity is suitable for direct utilization in many food and beverage industries [1].

As reported in the literature, the most prevalent product of CO_2 conversion is methanol, followed by CO_2-based chemicals and synthetic fuels [14]. Green methanol production, based on oscillating renewable energy sources, requires a flexible operation mode through integration with other sections such as the electrical grid and electrolysis processes [15]. The electrolyzer utilizes green power, CO_2, and water to produce a synthesis gas consisting of carbon monoxide and hydrogen. The electrolyzer includes a steel cylinder of eight-meter height in an adjoining hall. The cylinder contains bacteria to convert the synthesis gas into chemical molecules such as hexanol and butanol.

The electrochemical enhancement of CO_2 to fuels has a two-fold benefit. First, this process reduces CO_2 to value-added molecules. Second, it stores excess renewable at the peak production period into energy in chemical molecules. The existing designs of CO_2 electrolyzers range from microfluidic flow cells to polymer-membrane-based reactors [16].

In addition, novel technologies are under development for CO_2 utilization. As the fossil-based energy cost continues to climb, the interest in CO_2 utilization will intensify [4]. For example, microalgae production is a main CO_2 sink [1]. The CO_2 bio-fixation maximization requires optimization of microalgae growth rate and biomass productivity [17]. Fuel cell (FC) is the other promising technology for CO_2 fixation. FCs efficiently produce energy via an electrochemical process. As a case in point, an algae-based microbial fuel cell is an electrochemical device for capturing and converting carbon dioxide through the photosynthesis process using algae strains to organic matters and simultaneously power generation [9].

As a hindering aspect, CCS and CCU installation will increase the energy input of the plant per unit of product. This excess energy requirement is called the energy penalty [18,19]. In the case of coal power plants, the reduction in energy penalty of CO_2 capture is around 50%, compared to the installed capacity of renewable power (solar PV and onshore wind power) [20].

4. Investment and production costs

CO_2 is not a free substance. Its capturing, purification, and transportation require costs and financial investments, which depend on the site location. Costs of CCS depend on the capturing method. In general, 70%–80% of the total cost of post-combustion treatment comes from the capturing stage [8]. The cost of CCS depends on the partial pressure of CO_2, storage scale, energy costs, and technology innovation.

CCS costs vary widely depending on a case-by-case basis [21]. CCS costs increase by decreasing the storage size and the CO_2 patricidal pressure [22]. Moreover, the costs of CCS are higher in the case of additional required treatments such as purifying CO_2 and removing toxic or hazardous chemicals [8]. As a case in point, the potential of CCS in the EO (ethylene oxide) plants in the Dutch industry is abating $\sim$0.1 Mt_{CO2} at an abatement cost of $\sim$25 $€_{2013}/t_{CO2}$ [23].

Direct Air Capture (DAC) is more expensive than capturing CO_2 from point sources, and they require large amounts of energy. The current average of atmospheric CO_2 concentrations is globally around 400 ppm. Air transportation and sorbent regeneration also require energy. The minimum theoretically needed energy is about 3.4 times higher than the point sources with a 10% CO_2 concentration [8]. As various kinds of literature report, the costs for DAC are about 200 to 1000 €$_{2018}$/t$_{CO2}$ [8,24]. Various studies follow different CCS cost calculations. The general term of CO_2 capture cost refers to the sum of operational and capital expenditures for CO_2 capturing divided by the total amount of captured CO_2. The other cost calculation methodology is the CO_2 avoided cost, which obtains the cost of captured CO_2 divided by the amount of saved CO_2 compared to the reference plant. The avoided cost includes CO_2 release during capture and is usually higher than the capture cost. Avoided costs are the target of studies on environmental impact assessments [8]. A summary of the costs related to the CCS is available in Table 1. Capturing costs do not include transport and storage costs in Table 1.

Table 1. Summary of main CCS costs.

Plant	Cost[a]
Ethylene oxide	25 €$_{2013}$/t$_{CO2}$ [23]
Natural gas and bio-ethanol processing	17.7–23.9 €$_{2017}$/t$_{CO2}$ [25][b]
Cement	92–171.7 €$_{2017}$//t$_{CO2}$ [25][b]
Iron and steel	62.8–105.3 €$_{2017}$/t$_{CO2}$ [25][b]
Coal-fired power plants	20–40 €$_{2018}$/t$_{CO2}$ [8][b]
Direct air capture	200–1000 €$_{2018}$/t$_{CO2}$ [8][b]
Large CO_2 exhaust sources	18–90 €$_{2015}$/t$_{CO2}$ [24]
CO_2 transport and storage	10 €$_{2017}$/t$_{CO2}$[c] [21]
Offshore transport and storage	14.2–32.7 €$_{2017}$/t$_{CO2}$ [26]
Truck transportation of the CO_2[d]	0.22 €$_{2018}$/t$_{CO2}$ per km [8]

[a] Capture costs refers to the post combustion.

[b] CO_2 avoided cost [26].

[c] Increasing the annual transport flow rate from 0.5 to 5 Mt$_{CO2}$/y would reduce average transport cost more than three times, from over 20 €$_{2017}$/t$_{CO2}$ to around 6 €$_{2017}$/t$_{CO2}$ [21]. Moreover, the cost of CO_2 storage is a relatively small part of overall project costs [26].

[d] Typically, at 17 bar and −30 °C.

5. Potential for CCS deployment

The highest global potential and market size for CO_2 utilization is in the chemical and oil industry, with the Enhanced Oil/Gas Recovery (EOR/EGR), urea production, polymer processing, and fuel/chemical synthesis. The cement sector has a considerable uptake potential, while the potential of the food sector is medium. Carbonation, packaging, and horticulture are some cases of CO_2 utilization in the food sector [25].

Achieving mid-century CO_2 net neutrality in Europe requires large-scale expansion of renewable energy and electrification of end-use sectors. Moreover, hydrogen and synthetic fuels are necessary for emission mitigation in hard-to-abate sectors [27]. Therefore, CCU will probably have an increasing role in producing e-methanol, e-methane, or e-crude.

Most scenarios in IPCC's Special Report on Global Warming of 1.5 °C (SR15) show a significant increase in the use of CCS technologies over this century. CCS technologies are costly, but innovative technologies such as CycloneCC [28] could reduce the costs.

Carbon capture technologies are case-dependent, and each case has its own set of challenges and engineering problems. Every process has specific emission points with different quality and quantities, which are the effective parameters for choosing a capture technology [1].

In pre-combustion methodologies, the possibility of adapting kilns and boilers to burn H_2 is unclear and remains at a very low TRL. In the case of oxy-combustion and chemical looping, O_2 purification is necessary, and most conventional plants require a dual fluidized bed system. Moreover, SO_x and NO_x for CO_2 removal impose considerable costs and decreased carbon capture efficiency [1]. For some other sectors, the carbon captures installation has hindering problems such as the distant and uncertain future. Moreover, there exist several gaps in the CCS demonstration and deployment, such as data and information voids, knowledge shortage, and policy gaps.

6. Conclusion

This study discusses the current CCS/U pathways and their differences. In addition to describing the applicable capturing technologies (e.g. post-combustion) and utilizations (e.g. methanol), this paper also includes some of the recent novel technologies for CCS/U. This study also summarizes the costs related to the CCS/U technologies. All data are coming from recent literature and projects. Hence, the provided data are up to date and include practical information for potential users. Overall, the content of this paper will train the reader with the main concepts regarding CCS/U. Moreover, the provided data are beneficial for the research groups engaged with modeling the CCS/U via different scenarios.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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