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Current Opinion in Chemical Engineering

Carbon capture and storage technologies: present scenario and drivers of innovation

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Carbon capture and storage (CCS) technologies are being developed to comply with the intensification of environmental laws and policies. Techniques for carbon capture from exhaust gases include post-combustion, pre-combustion and oxy-combustion. CO_2 separation in gas processing is also a relevant application, employing alternatives commonly used in post-combustion, sharing developments and pulling innovations (additional to innovations pushed by knowledge from basic and applied research). The high volume of exhaust gases and expanding reserves of natural gas defy the state-of-the art in chemical and physical absorption (the most mature technology). The review identifies technological gaps and drivers of innovation in the CCS chain. In the context of offshore natural gas processing, this work reports a recent and massive technological niche for commercial use of membrane based processes.

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Current Opinion in Chemical Engineering 2017, **17**:22–34

This review comes from a themed issue on **Energy and environmental engineering**

Edited by **Heriberto Cabezas**

http://dx.doi.org/10.1016/j.coche.2017.05.004

Introduction

Carbon capture and storage (CCS) comprises separation of CO_2 from industrial sources, compression and transportation to a geologic site for storage, or to enhanced oil recovery (EOR). Its uses cover a variety of industrial applications, outstanding abatement of CO_2 from process or exhaust gases and in natural gas (NG) processing. In the former, depending on the technology, CO_2 is separated from H_2 (pre-combustion), N_2 (post-combustion) and H_2O (oxy-combustion, which burns hydrocarbons with pure O_2) [1], while in NG processing CO_2 is separated from CH_4 and light hydrocarbons [2].

Flue gas is released from carbon-fired power plants at moderate temperature (50–100°C) and low pressure (<1.5 bar). Post-combustion with chemical absorption or physical absorption are the technologies closest to full scale realization and preferred for retrofitting [3••]. Although post-combustion and NG processing may employ different technologies, capture of CO_2 by chemical and physical absorption are their leading options, where the solvent loading (α, mol CO_2 per mol of active solvent, *AS*) is a capture response while the capture ratio (*CR*, kg of total solvent per kg of fed CO_2) and the solvent regeneration heat ratio (*HR*, kJ per kg of fed CO_2) are input factors [4••]. In chemical absorption, CO_2 and the *AS* chemically bond giving high selectivity and low hydrocarbon losses (NG processing) with maximum stoichiometric α of 1 molCO_2/mol at *CR* 10–15 kg/kgCO_2 and reversibly requiring high solvent regeneration *HR* (2000–4500 kJ/kgCO_2). In physical absorption, weak physical binding of CO_2 to solvent reduces selectivity, but can give $\alpha > 1$ molCO_2/mol of *AS* at low *CR* (1–5 kg/kgCO_2) and low *HR* (0–500 kJ/kgCO_2) for solvent regeneration. In chemical and physical absorption, the equilibrium α increases with CO_2 fugacity (CO_2 partial pressure) and decreases with increasing temperature [86••].

Pre-combustion firstly reforms fossil fuel to synthesis gas (syngas, $H_2 + CO$), and, in a second step, to H_2 and CO_2 via water-gas shift (WGS) reaction. H_2 is purified via chemical or physical absorption of CO_2 (easy separation due to high CO_2 partial pressure) and can fuel supercritical boilers, gas turbine (in H_2-fired power plants) or promisingly used in integrated gasification-combined cycle (IGCC) power plants [5]. In H_2-IGCC, high capital expenditure (CAPEX) of syngas, WGS and capture units are drawbacks, and H_2 as fuel requires development of new power machines, another H_2-IGCC risk [6]. In typical coal-fired power plants, the power efficiency reduces from 38.4% without CO_2 capture to 31.2% with CO_2 capture [7], a susceptibility eliminated by changing to full Coal-H_2-IGCC. The capture energy penalty in a carbon-fired power plant is the fraction of power output lost by implementing CO_2 capture.

Oxy-combustion eliminates N_2 in oxidizer of carbon-fired power plants [5], substituting CO_2–N_2 post-combustion separation by O_2–N_2 fractionation via cryogenic distillation, the most cost-effective commercially available route, though with refrigeration energy penalties, in the same range as that for fossil fuel de-carbonization [8]. As oxy-combustion flame temperature [5].

Oxy-combustion is not yet commercial, posing greater technical risks than pre-combustion or post-combustion for large-scales [6]. Porter *et al.* [9] discuss cost and CO_2 purity variations for oxy-combustion and pre-combustion scenarios.

In NG processing, CO_2 must be removed to comply with treated gas specifications. A determinant change in the technological scenario is pulled by offshore NG processing, mainly at ultra-deep waters on FPSO (Floating Production, Storage & Offloading) platforms. Membrane permeation offers advantages over conventional chemical or physical absorption for NG processing: small footprints, modularity and easy scale-up. The treated NG is the membrane permeation retentate at high pressure, which fits the final compression for pipeline dispatch.

Considering the state-of-the-art, Figure 1 depicts the CCS scenario, contemplating CO_2-EOR and other CO_2 sources (*e.g.*, fertilizers, cement and steel production), including bioethanol plants producing food grade CO_2 from fermenters, which can be directed to downstream CCS. This work analyzes the main technologies involved, focusing in identifying technological gaps requiring innovations and technology drivers in the big CCS scenario. Table 1 presents a compilation of state-of-the-art and advanced processes, including those at lower Technology Readiness Level (TRL) [72], from proof-of-concept to small pilot plants.

Carbon capture from exhaust gases

Capture energy penalty on carbon-fired power plants is significant (≈15–30%) [10] representing 65–80% of CCS costs [11,12••]. To retrofit carbon-fired power plants with 33% power efficiency, a decrease of 12% of efficiency represents more than 1/3 of power output [13], with a capital expenditure (CAPEX) increase of ~77% [14]. Carbon-fired power plants face large variations in CO_2 emissions due to differences in efficiency and employed fuel: coal-fired power plants emit 1116 gCO_2/kWh at 30% and 669 gCO_2/kWh at 50% of efficiency [15,5].

Despite coal being the most CO_2 intensive option, capacity expansion plans [67] indicate that carbon mitigation initiatives are insufficient to outweigh the economic incentives of a relatively cheap fuel. Concerning CAPEX, NG-fired power plants configure the best alternative with half CAPEX of coal-fired power plants and 1/5 of nuclear plants [16]. Impacts on operational costs (OPEX) are quantified mainly by simulation [17]. Uncertainties in overall performance are estimated probabilistically [18]. CAPEX estimation uncertainties are high (±40%), though variability has little influence on the levelized cost of energy (LCOE) [19], suggesting that OPEX dominates CCS.

Boot-Handford *et al.* [20••] present extensive review on leading CO_2 capture technologies, available in the short and long term and their maturity. Post-combustion CO_2 capture employing chemical absorption remains the most efficient and cost-effective capture [21], with heat demand (OPEX) for solvent regeneration as main drawback, reducing power capacity (capture energy penalty ≈10–30%), despite recent improvements lowering heat ratio (*HR*, energy penalty for solvent regeneration) from 5.5 to 2.6 GJ/tCO_2. Carbon-fired power plant repowering or hybridization using solar-assisted post-combustion may conciliate capture and power plant load targets [22]. Limitations of driving force indicate that state-of-the-art membrane permeation are unlikely to compete with chemical absorption in capturing CO_2 from exhaust gases [21].

The deployment of renewable energy substitutes partially the need of (fossil) carbon-fired power plants, reducing the amount of fossil-fuel burned. However, renewable energy dispatch is intermittent, demanding flexible operation of the capture unit to improve the economics of CCS power plants [23]; flexibility allows exploring this transient pattern to reduce CAPEX up to 28% [73]. With chemical absorption, flexibility can be achieved by solvent storage, exhaust gas venting (decoupling energy generation from CO_2 capture, to meet peak energy prices) and time-varying solvent regeneration (allowing CO_2 to accumulate in the solvent at peak energy prices) [24]. Variable capture aligned to energy demand and dispatch [25] results in temporary reduction of capture energy penalty, increasing net efficiency and capacity [26]. For instance, the absorber sized for a time-average condition costs ~4% less then when sized for peak energy generation [27].

Capture energy penalty can be minimized by new solvents or flowsheet modifications, reducing power losses by 25% [28••], conciliating the tradeoff of sensible heat loss (to raise the temperature of the stripper feed) at high solvent rate (high lean loading) and stripping steam use at low solvent rate (low lean loading) [20••]. Additionally, low solvent thermochemical stability [29•] leads to accumulation of degradation products and toxic emissions [30].

Evolving from the first commercial plant (first of a kind, FOAK) to the *n*th commercial plant (*n*th of a kind, NOAK) reduces OPEX and CAPEX [31]. Alternative technologies are sought, posing greater risk because of their earlier stage of development [6]. Emerging technologies (*e.g.*, new membranes and solvents) with potential for 'game-changing' improvements are still scheduled to large-scale testing by 2025 and complete demonstration scale testing by 2030 [64]. Besides low TRL (Technology Readiness Level), a major issue in post-combustion