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Research article

Life cycle assessment of carbon capture and utilization from ammonia process in Mexico

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ABSTRACT

Post-combustion CO_2 capture (PCC) of flue gas from an ammonia plant (AP) and the environmental performance of the carbon capture utilization (CCU) technology for greenhouse gas (GHG) emissions to an enhanced oil recovery (EOR) system in Mexico was performed as case study. The process simulations (PS) and life cycle assessment (LCA) were used as supporting tools to quantify the CO_2 capture and their environmental impacts, respectively. Two scenarios were considered: 1) the AP with its shift and CO_2 removal unit and 2) Scenario 1 plus PCC of the flue gas from the AP primary reformer (AP-2CO_2) and the global warming (GW) impact. Also, the GW of the whole of a CO_2-EOR project, from these two streams of captured CO_2, was evaluated. Results show that 372,426 tCO_2/year can be PCC from the flue gas of the primary reformer and 480,000 tons/y of capacity from the AP. The energy requirement for solvent regeneration is estimated to be 2.8 MJ/$kgCO_2$ or a GW impact of 0.22 $kgCO_{2e}$/$kgCO_2$ captured. GW performances are 297.6 $kgCO_{2e}$ emitted/barrel (bbl) for scenario one, and 106.5 $kgCO_{2e}$ emitted/bbl for the second. The net emissions, in scenario one, were 0.52 tCO_{2e}/bbl and 0.33 tCO_{2e}/bbl in scenario two. Based on PS, this study could be used to evaluate the potential of CO_2 capture of 4080 t/d of 4 ammonia plants. The integration of PS-LCA to a PCC study allows the applicability as methodological framework for the development of a cluster of projects in which of CO_2 could be recycled back to fuel, chemical, petrochemical products or for enhanced oil recovery (EOR). With AP-2CO_2, "CO_2 emission free" ammonia production could be achieved.

1. Introduction

In the oil and gas industry, in 2013 CO_2 emissions from fuel combustion oil were 10.8 Gt and 6.3 Gt from natural gas, accounting for 50% of global energy-related CO_2 emissions (IEA, 2015a). CO_2 represents the highest greenhouse gas (GHG) emissions along the whole production chain in the oil and gas downstream industry. These are due to the combustion of fossil fuels as well as process streams in the refineries and petrochemical complexes (Kuramochi et al., 2012). However, in the petrochemical industry where the CO_2 capture unit is part of the industrial process, the CO_2 emissions of high purity from processes streams have already been used as feedstock for chemicals. (Aresta et al., 2013).

Four basic strategies have been considered for reducing CO_2 emissions in the power and industry sectors: post-combustion capture, pre-combustion capture, oxyfuel combustion, and industrial processes (IPCC, 2006; Kuramochi et al., 2012; Spigarelli and Komar Kawatra, 2013).

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Recently, carbon capture and utilization (CCU) and carbon capture and storage (CCS), have been seen as the technological options for the power sector that could help to mitigate the climate change (Cooney et al., 2015) when CO_2 is used as a feedstock for the industry, and therefore, reducing anthropogenic CO_2 emissions into the atmosphere (Aresta et al., 2013; Dimitriou et al., 2015; Armstrong and Styring, 2015; Xiaozhi L, 2015). Nevertheless, EPRI (2013) discusses that the above mentioned technologies can give products that would sequester the CO_2 for a lengthy or short time. Armstrong and Styring (2015) analyzed that CCU technology can sequester 6.5 times more CO_2 than immiscible enhanced oil recovery (EOR)-CCS. Meylan et al. (2015) found in CCS significant disadvantages as high cost, low public acceptance, and long-term uncertainty. Although CO_2 can replace petrochemical feedstocks in the production of chemicals and fuels (Aresta et al., 2013; Styring et al., 2014), the energy intensive (200–350 °C) conversion presents a disadvantage, as well as that it requires high-selectivity catalysts due to its highly thermodynamic stability (Rojas et al., 2011; Cuellar-Franca et al., 2015; Dimitriou et al., 2015).

On the other hand, the unexpected decline in fossil fuel prices generates challenges and opportunities for decarbonising the energy system, particularly in the oil and gas industry. According to IEA (2015b), the oil prices in the current scenario will remain close to $50/bbl until the end of this decade before rising gradually back to $85/bbl in 2040. Thus, the relatively high cost of current CCS systems remains a major challenge in power plants and other industrial facilities (IPCC, 2014). For instance, according to Rubin et al. (2015) the current value cost of post-combustion (2013) is between 44 and 111 USD/tCO_2 captured for Natural Gas Combined Cycle Plants (NGCC). Leung et al. (2014) reported estimates of the total cost associated with CCS for electricity production in the range of 60–100 USD/ton CO_2. Given this scenario, the British government has decided to cancel the CCS scheme in the Peterhead Project of 10 MtCO_2/year. Also, the White Rose Project with 2 MtCO_2/year was cancelled (Enerdata, 2015). Hence, this fact and the climate response to five trillion tons of carbon as total cumulative emissions in the atmosphere (Tokarska et al., 2016), require further innovative alternatives or new technological developments. In this regard, the IEA (2015c) has modeled CO_2 reductions scenarios, involving a 13% carbon capture and storage (CCS), as well as other technological options to give the desired outcome of a less than 2 °C rise in temperature to avoid the consequent catastrophic effects on the boundary of the nine planetary systems (Rockström et al., 2009).

Hence, the evaluation of post-combustion CO_2 capture (PCC), mainly by chemical absorption in power plants (Wang et al., 2011, 2015; Spigarelli and Komar Kawatra, 2013) and the use of life cycle assessment (LCA) have been applied to evaluate the environmental impacts of the CCU systems considering different fossil fuel and technologies from electricity production (Marx et al., 2011; Zapp et al., 2012; Corsten et al., 2013; Hussain et al., 2013; von der Assen N. et al., 2014; Cuellar-Franca and Azapagic, 2015). Consequently, an increment has been observed in the use of computer tools for the design of PCC (González Díaz et al., 2010; Chikukwa et al., 2012; Sipocz and Tobiesen, 2012; Carpentieri et al., 2012; Fadeyi et al., 2013; Gaspar et al., 2014; Joel et al., 2014; Kangkang et al., 2014; Tock and Maréchal, 2015; Dimitriou et al., 2015; Yakub, 2015). However, the role of the industrial application in the downstream processes (natural gas processing, ethylene oxide, ammonia and hydrogen production) to CCUS has received little attention or there is insufficient information elsewhere (IEA-UNIDO, 2011). In the particular case of ammonia process, that already has a section shift and CO_2 removal with 98% purity, is used to produce urea (NTEL, 2013; Luis, 2015). For instance, in 2015, CO_2 utilized to produce urea was 132.8 MtCO_2 worldwide and 0.97 MtCO_2 in Mexico; although, 1.275 MtCO_2 are required to meet the demand of urea. On the other hand, the demand of methanol in the world to be used as fuel is growing (see Supporting Information (SI) Table SI-1) and, consequently methanol capacity has been set to reach 184.4 Mt/y by 2020 (Hydrocarbon Processing, 2016), since methanol can be used as an alternative fuel to gasoline. In contrast, Armstrong and Styring (2015) analyzed that the CCS in operations uses only 26.6 Mt/year. Therefore, the increasing demand for urea or methanol from CO_2 (Asinger, 2014), will certainly need profitable processes and contribute to reduce CO_2 concentration in the atmosphere.

In this regard, NTEL (2013) carry out study on cradle-to-gate GHG emissions for CO_2 of the process stream from ammonia production. They found a value of 1.41 kg CO_{2e}/kg CO_2 produced. In turn, Luis (2015) observed that production of CO_2 in the steam/air reforming of natural gas was 1.15–1.40 kgCO_2/kg NH_3 without including CO_2 in combustion gases. Haas and van Dijk, in Europe, (2010) estimated that around 1.5 tons of CO_2/t of NH_3 are emitted to the atmosphere during production of ammonia (NH_3) (Anderson et al., 2008). Makhlouf et al. (2015) calculated from the LCA of an ammonia plant in Algeria, yet the rest (process gas) was not taken into account. Kramer et al. (1999) reported a value of GHG emissions during the production of 1 ton of ammonia of 2.16 tCO_{2e}/t of NH_3, and Williams and Al-Ansari (2007) a value of 2.07 tCO_{2e}/t of NH_3. However, there are no evaluations with CO_2 connected or integrated to flue gases with the process stream together (AP-2CO_2) in the same plant to ammonia production "free of GHG".

1.1. Ammonia process in the Cosoleacaque Petrochemical Complex (CPC)

By design, the ammonia plant has two key sources of CO_2 emissions, one from the reformer unit and the other from the emissions of the stripper unit that removes CO_2 from the ammonia product stream. Ammonia production depends on natural gas (NG) as both as a feedstock and as a fuel. Anhydrous ammonia is synthesized by reacting hydrogen with nitrogen at a molar ratio of 3 to 1, then is compressed and cooled to −33 °C (−27 °F). Nitrogen is taken from the air, while hydrogen is obtained from the catalytic steam reforming of natural gas (EPA, 2015). Six process steps are required to produce synthetic ammonia using the catalytic steam reforming method: 1) natural gas desulfurization, 2) catalytic steam reforming, 3) carbon monoxide shift, 4) carbon dioxide removal, 5) methanation and 6) ammonia synthesis. Four of these steps remove impurities such as sulfur, CO, CO_2 and water from the NG (EPA, 2015; Luis, 2015). The CPC has four ammonia plants (IV to VII) in operation, each with a production of 480,000 tons of ammonia per year (tNH_3/y) and 497,000 tCO_2/y as byproduct with 98% purity. 1783 tCO_2/d are generated in this section, with a relation of 1.4 t CO_2/t of NH_3. Currently, the CO_2 generated is employed for urea production and for the beverage industry; the rest is emitted to the atmosphere.

1.1.1. Shift & CO_2 removal section (potassium carbonate solutions)

In the final shift gas step, CO_2 is removed using potassium carbonate (PC) solutions. The CO_2 gas is sent upward through an adsorption tower countercurrent to a 30% solution of PC in water fortified with effective corrosion inhibitors. After absorbing the CO_2, the PC solution is preheated and regenerated (carbon dioxide regenerator in a reactivating tower). This reacting tower removes CO_2 by steam stripping and then by heating (Fig. 1). The CO_2 gas (98.5 percent pure) is either vented to the atmosphere or used as chemical feedstock. The regenerated PC is pumped back to the absorber tower after being cooled in a heat exchanger and solution cooler. According to T.N.G. Borhani et al. (2015), PC solutions have been applied in more than 700 plants worldwide for CO_2 and