

Direct Air Capture: Economy and Technical Cost of Low-Purity CO₂ on Post-Capture Operating Cost

¹Luqman K. Abidoye

¹Department of Chemical Engineering, Osun State University, Osogbo, Nigeria
abidoye.luqman@uniosun.edu.ng

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ORIGINAL RESEARCH

Abstract— Direct air capture has the potential to capture from innumerable random, mobile and immobile small-scale carbon-emission sources. In this study, simulations result of Direct Air Capture (DAC) reveal the isentropic compression work increases as the mole fraction of CO₂ decreases in the stream. At the same depth of sequestration, compression power requirement increases by 20% to sequester 10% CO₂ stream compared to pure CO₂. Also, sequestration at deeper geological layer further raises the power cost of the compression by approximately 14% from 1000 to 1500m and by almost 32% from 1500m to 2500m depth, for pure CO₂. This increases to around 34% for storage at 2500m with 50% CO₂ mole fraction and 36% for 20% CO₂ fraction at the same depth. Similarly, the cost of cooling compressed CO₂ increases in proportion to the reduction in CO₂ mole fraction in the gas stream. It was shown that the solution density increase with impurities as a result of falling pH in the presence of N₂ and O₂.

Keywords— compression, dissolution, direct air capture, economy

1 INTRODUCTION

The continuous emission of greenhouse gases into the atmosphere is setting a pathway to difficult climate conditions with consequences on ecological displacement and shift. This trend is already aggravating the state of the global warming. Fossil fuel consumption and transformation generates 13 gigatonnes of CO₂ annually (IAEA, 2013). Substantial reduction of emission is needed to keep within and below the 2°C. This requires emissions reduction of about 37Gt/yr till 2050 or removal of the atmospheric incremental of 1 Gt CO₂ per year (Haszeldine et al., 2018). This shows the enormity of the tasks required to remediate the climate and safeguard the planet.

Among the existing emission reduction technologies, Direct Air Capture is a promising option, owing to the possibility to tackle innumerable random, mobile and immobile small-scale carbon-emission sources that account for half of the global GHG emissions, which are simply impossible to neutralize by conventional CO₂ capture applications (Seipp et al., 2017). The other options are simply expensive and restricted in scope. For example, bio-sequestration by microbes, plants, oceans, rock weathering and so on, have been on for ages but at rate not in step with emission rate since industrial revolutions (Goepfert et al., 2012).

Even the popular carbon capture and sequestration (CCS), carbon capture and utilization (CCUS), cryogenic carbon capture (CCC) and so on are far too expensive and technically costly to operate.

DAC is advantageous in that it can be engineered to consume less space, avoid toxic solvent for capture while continuously loop to sense and scrub the atmosphere of carbon (Haszeldine et al., 2018). Thus, Direct Air Capture (DAC) provides the lifeline to deal comprehensively with the menace of unceasing emission from these innumerable sources.

Thus, the use of DAC is pivotal to attain the target CO₂ concentration in the atmosphere. But, the presence of impurities in the CO₂ captured by DAC system has been a source of concern over time, because of the dilute nature of gases in the atmosphere (Broehm et al., 2015; Goepfert et al., 2012; Lackner, 2009). To be completely satisfactory, effective and sustainable DAC technology must be of lower cost and promotes environmental safety, among others. Also, the technology must be all-pervasive to cover many distributed outlets of emissions in different localities with a view to meeting the target of limiting global warming below 2 °C by the end of this century (Brethomé et al., 2018). But, the challenge of purity in the CO₂ stream emanating from DAC system is difficult to overcome. Therefore, emphasis has to be placed on the effects of these impurities on the performance of the DAC systems owing to the unique compositions of gases available for this system, vis-a-vis its effects on the economy of the technology and the mineralization or permanent storage of the stored carbon.

Currently and in the near future, DAC economy will be reckoned by factors such as Cost/tCO₂, Energy/tCO₂, space/unit DAC, Capture capacity and so on. Right now, DAC technology is reckoned with significant cost reduction potential (Keith et al. 2018; Fasihi et al. 2019) while overall efficiency in extracting CO₂ is comparably high (Fuss et al. 2018). Company like Carbfix (Iceland) had embarked on open air installation of this technology and started to capture carbon, creating large-scale Direct Air Carbon Capture and Storage (DACCS) or CO₂ utilization (Direct Air Carbon Capture and Utilization-DACCU). Application of the captured carbon can be

*Corresponding Author

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found in transport fuels, including in marine, aviation and chemical industries (Haegel et al. 2019).

Keith et al. (2018) reported process of CO₂ capture from air using an aqueous KOH sorbent coupled to a calcium caustic recovery with levelized cost from 94 to 232 USD/tCO₂. Combining temperature and vacuum swing adsorption (TVSA), the authors successfully deployed DAC to achieve 95-100% vol CO₂ with energy consumption around 10kWh/kg. Economic improvement can be seen in the demonstration and proposition of High Hopes Lab in Israel, resulting \$100-\$250 per ton, for the first stage and \$40-\$50 at the second stage.

Sustainable DAC requires sorbents with high CO₂ capacity, easily regenerable, favorable kinetics, ready availability and environmental compatibility. The solvent/sorbent cost should be ordinarily cheap or lowered through continuous improvement and innovation. These cheap and efficient sorbents and solvents will make DAC, not only reduce the cost of operation, but also overcome the lower net contribution of DAC to CDR. Choice of solvent is another major factor that hampers efficiency of DAC. Many solvents suffer from the problems of volatility, toxicity, costs and separation difficulty. There are cases of solvent hampering the successful conversion of captured carbon from DAC into methanol, owing to volatility issues, oxidative degradation, and notable toxicity, making them less suitable for DAC in a scaled-up process. Using waste minerals or industrial wastes as adsorbents may eliminate the recovery stage, saving energy, project cost while also providing raw materials for other uses.

In addition, the DAC performance under different weather conditions and integration of DAC to systems with abundant waste heat needs to be demonstrated for overall sustainable energy performance, which will also bear down on cost. The flexibility of the sorbents and solvents under varying and extreme weather conditions are required to be checked for maintaining consistent performance (Kong et al. 2022).

In this work, cost-implications of impurities contained in CO₂ captured through DAC were investigated using ASPEN software. Questions answered include how the quality or compositions of captured carbon influence the DAC economy? What effects do the post-capture processes have on the cost of operations? How does the stream impurity affect storage space in the aquifer?

2. METHODS

This study simulates the compression characteristics of CO₂ and its impurities, captured from DAC system.

The study utilized simulation software- ASPEN (version 10), to investigate the effects of post-capture processes on the economy of DAC and storage parameter.

The study further simulates the effects of these impurities on the solution density in the formation using PHREEQC. This is further related to the influence of depth and associated conditions.

Parameters utilized in the simulations were listed in tables 1 and 2.

Table 1: Geological depths for gas storage in Anorthite- and Goethite-rich rock together with the associated

conditions. Tsuji et al. (2017)		
Geological Depth (km)	Temperature (oC)	Pressure (Mpa)
1.0	38	10
1.5	52.5	15
2.5	80	25

Probable mole fractions of N₂-O₂-CO₂ stream in DAC process are listed in Table 2.

Table 2: Mole fractions N₂-O₂-CO₂ stream in DAC process Tsuji et al. [17]

CO ₂	N ₂	O ₂
1	0	0
0.8	0.16	0.04
0.7	0.24	0.06
0.5	0.4	0.1
0.3	0.56	0.14
0.2	0.64	0.16
0.1	0.72	0.18
0.05	0.76	0.19
0	0.8	0.2

3. RESULTS AND DISCUSSIONS

The results of the simulation performed in this work shows the increasing cost of compression based on the mole fractions of CO₂ in the stream. This is shown in Figure 1. Just like in the work of Tsuji et al. (2021), the ratio of N₂ to O₂ in the mix was assumed consistent with atmospheric conditions (4:1). The isentropic compression work increases as the mole fraction of CO₂ decreases in the stream. At the same depth of sequestration, compression power requirement increases by 20% to sequester 10% CO₂ stream compared to pure CO₂. Also, sequestration at deeper geological layer further raises the power cost of the compression by approximately 14% from 1000 to 1500m and by almost 32% from 1500m to 2500m depth, for pure CO₂. This increases to around 34% for storage at 2500m with 50% CO₂ mole fraction and 36% for 20% CO₂ fraction at the same depth. Thus, purity poses the net cost on the carbon compression and eventual total capture and storage cost. Furthermore, the cost of cooling compressed CO₂ imposes addition burden on the total storage cost. This is because the compression is an exothermic process, which makes the system requires heat reduction before further processing. Figure 2 shows the heat duty requires to cool the compressed, corresponding to various depths. In the figure, the amount of heat needed to be removed increases as the purity of CO₂ reduces while also increases with depth of the storage domain.

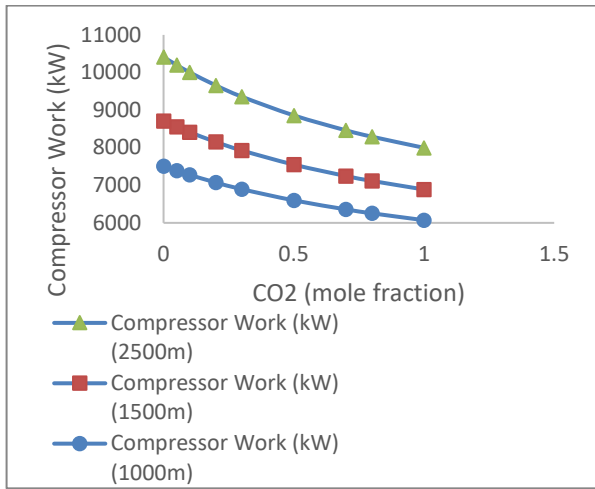


Figure 1: Compressor Work at various CO₂ purity level

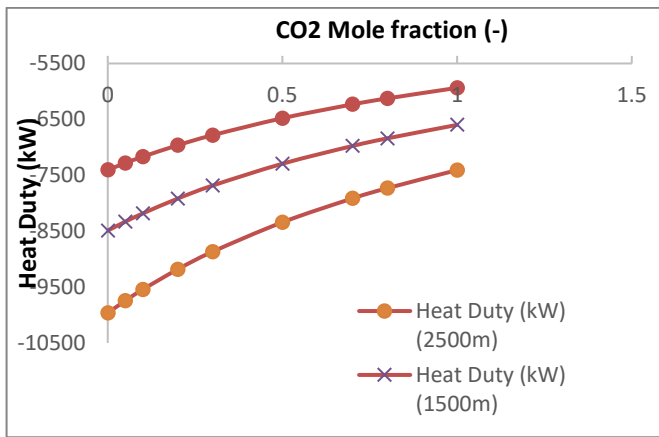


Figure 2: Heat duty at various CO₂ purity level

Apart from compression and cooling power requirement, Tsuji et al. (2021) found that low-purity of CO₂ stream raised the cost of storage disproportionately, owing to density disparity. For example, at 1000m depth, low purity stream was found cost-ineffective owing to reduced CO₂ density of the CO₂ at low purity. At 80% CO₂ purity, storage cost is doubled that of 90% CO₂ stream, barring the costs of drilling and transport, which can be offset by situating the system near the injection site (Tsuji et al., 2021). Comparing the work of these authors with the findings in this work shows that low-purity of CO₂ is generally problematic to DAC cost. But, the cost impacts of density disparity under different conditions can be ameliorated by choosing higher depth to raise the density of the stream and consequently the amount of CO₂ stored. The net increase in the cost of compressional and cooling can be offset by the storage quantity per unit space allocated at higher depth. The impurity or presence of higher proportion of N₂ and O₂ decreases the CO₂ density and affects the effectiveness and cost of the storage (Tsuji et al., 2021). Commonly, CO₂ possesses much higher freezing point (-78oC) than many other components of the gas stream (Font-Palma et al. 2021). So, the presence of impurity will lead to reduced density of CO₂, as other components exist as mainly gas even under high pressure, unlike CO₂ that increases in density under pressure at pure condition. Some unclear deleterious and possibly advantageous effect of low purity CO₂ and high concentrations of N₂ may be complex to decipher. Ordinarily, owing to its high

bond energy, N₂ requires high activation energy for reaction to take place. To get the best yield of carbon adsorption for carbon mineralization, it is essential to reduce the level of competing molecules, like unreactive N₂, that can preferentially occupy adsorption sites of the mineral adsorbents. Thus, it is essential to utilize dehumidifier for the entering air to reduce moisture entry. Figure 3 shows that the density of the solution increases with impurities in the CO₂ stream.

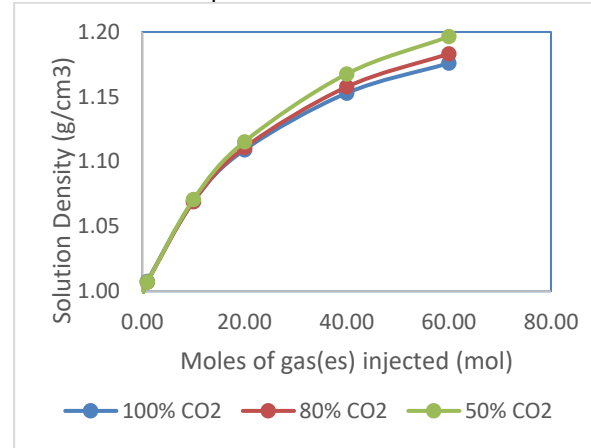


Figure 3: Solution Density at 1km Depth

This is because the pH decreases in the presence of N₂ and O₂, which leads to increased mineral dissolution. The increase in solution density should not be confused with the density reduction of the gas stream, reported by Tsuji et al. (2021). The solution density increases purely as a result pH fall with impurities.

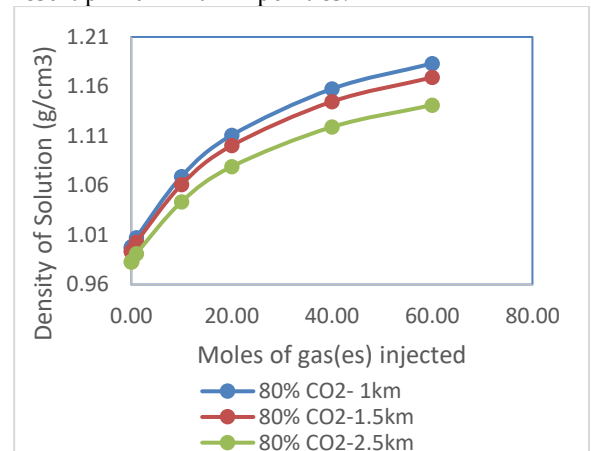


Figure 4: Solution Density at Different Depths

Figure 4 shows that the solution density decreases with depth. This is because, though, pH increases with depth of sequestration, but mineral dissolution decreases, as a result of rising temperature at higher depth.

4. CONCLUSIONS

The potential of Direct Air Capture (DAC) in tackling numerous and distributed small and medium scale mobile and immobile emission sources is affected by the number of impurities present in the gas stream. In this study, simulations results reveal the isentropic compression work and cost increase as the mole fraction of CO₂ decreases in the stream. At the same depth of sequestration, compression power requirement increases by 20% to sequestrate 10% CO₂ stream compared to pure

CO₂. Also, sequestration at deeper geological layer further raises the power cost of the compression by approximately 14% from 1000 to 1500m and by almost 32% from 1500m to 2500m depth, for pure CO₂. This increases to around 34% for storage at 2500m with 50% CO₂ mole fraction and 36% for 20% CO₂ fraction at the same depth. Thus, purity poses the net cost on the carbon compression and eventual total capture and storage costs. Similarly, the cost of cooling compressed CO₂ will impose addition on the total storage cost, as it increases in proportion to the reduction in CO₂ mole fraction in the gas stream. Also, the density of the solution increases with impurities in the CO₂ stream as a result of pH fall in the presence of impurities.

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