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An Analysis of the Possible Financial Savings of a Carbon Capture Process through Carbon Dioxide Absorption and Geological Dumping

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ABSTRACT

Herein, we discuss possible ways to reduce the cost of carbon dioxide (CO_2) sequestration with a special focus on the process and the solvent used. Modifications to the process to eliminate the stripper section and focus on just the CO_2 adsorbing and geological dumping (CAGD) can lead to significant reductions in the sequestration cost per tonne of CO_2 compared with ordinary CO_2 capture and geological storage (CCS) processes. In the case of CAGD, savings of steam used in the ordinary CO_2 capture process can go up to US\$12.7 per ton of CO_2 captured and additional savings on the waste disposal cost of US\$175/tonne of waste can be made. More savings on the energy costs for compression and cooling of the captured CO_2 gas can be realized if the absorbent and flue gas/ CO_2 slurry is directly dumped in a geological formation. A change of the capture solvent can also make this process better economically by using the proposed substitute. Many commercially available alternatives to monoethanolamine (MEA) have been presented in this research by mainly focusing on how their loading capacity and cost compare. Aqueous Sodium carbonate (Na_2CO_3) has been proposed as the best material for use in the CAGD CO_2 adsorbing process based on the economic advantages it presents.

Keywords: Cost of Carbon Dioxide, Geological Dumping, Financial Saving

JEL Classifications: Q, Q5, Q54

1. INTRODUCTION

Concerns for global warming caused by the effects of green house gases (GHGs), particularly CO_2 , are on the rise. Going by the prediction of IPCC, by year 2100, the atmosphere may contain up to 570 ppm of CO_2 , causing a rise of mean global temperature of around 1.9°C and an increase in mean sea level of 3.8 m (Stewart and Hessami, 2005). Fossil fuels are now widely accepted as a major source of carbon dioxide (CO_2) emissions which is contributing to global warming inducing climate change. It would make sense, therefore, to do away with these fossil fuels and focus on renewable energy, however, the cost has been evaluated to be almost similar to retrofitting coal power plants with carbon capture utilization and storage (CCUS) units (Zitelman et al.,

2018). Coal to power as a CO_2 emitting source is responsible for 9.03 Gt CO_2 /year (IEA, 2018). It is therefore important to capture and geologically store or use the CO_2 captured.

The current approach is to capture the flue gases and separate them while also regenerating the capture material used. The bulk of the costs associated with this are due to separation and capture as opposed to transportation and injection into saline aquifers and depleted oil and gas reservoirs (Herzog, 2000). Removal of CO_2 from flue gases is more challenging because of its relatively higher quantities in the gas stream (typically 5-15% v/v of net steam generating power depends on the fuel being used), low partial pressure of CO_2 in the flue gas, and relatively high temperature of flue gases (Olajire, 2010) (Rackley, n.d.). One of the biggest

reasons for the regeneration is to strip the adsorbent of the CO₂ captured from flue gas in a short time to use it in the next cycle. Conventionally, the absorbent is usually a primary amine like monoethylamine (MEA) which requires a certain energy to be stripped of the absorbed CO₂ gas. The fundamental equations for the reaction between primary or secondary amines and CO₂ are shown below;



Since both primary and secondary amines follow equations (1) and (2) in reactions involving CO₂, it would be better to use the cheaper secondary amines. For the case of tertiary amines, the reaction can proceed as shown in equation (2) only and any carbamate formed will be highly unstable.

2. CARBON PRICE

The cost of CO₂ capture is approximately equivalent to an average of US\$43-54 per ton-CO₂ (Naims, 2016). In some countries like Canada, they have enacted a nationwide tax on oil, coal, and gas that starts at US \$15 per ton-CO₂ and is expected to be at US\$38 per ton-CO₂ by 2022. Places like British Columbia already have a higher carbon tax in place at about US\$30 per ton and expected to grow still. For the whole of Iceland, however, this figure is at US\$39 per ton-CO₂ currently (World Bank, 2019). Clearly, this is lower than the current cost of CO₂ capture per ton as per World Bank statistics. Increasing the carbon price/tax might be one way to ensure the flue gas is captured by emitters. However, we believe that if we can lower the current cost associated with sequestration then the effect would be more profound. The total cost of CO₂ capture per ton is backed up by an extensive study done by Dan Chapel (Ernest, 1999) which gives the total cost as US \$29 as in 1999. This is about US\$45 per ton-CO₂ currently. If the carbon price is higher than the capture cost, the belief is that many nations will pay attention to meeting their commitments to the Kyoto Protocol.

A summary of the possible process cost savings on a low sulphur coal fired power plant with a capture capacity of 1000 tons/day that can be made with the CAGD practice is shown in the Table 1 (Ernest, 1999)

3. CURRENT TREND OF CO₂ SEQUESTRATION

Sequestration of CO₂ into geological sinks, such as depleted oil and gas reservoirs, is currently being done for the benefit of enhanced oil recovery (EOR) in declining oil fields for financial gain. However, the use of CO₂ for EOR is limited to areas accessible to oil fields. More common are saline aquifers that can be found in many regions of the United States and other countries. Other costs involved in carbon capture and storage (CCS) include transportation of CO₂ and the potential infrastructure cost of building CO₂ pipelines to connect CCS power plants with CO₂ sinks. In order to minimize such transportation infrastructure for first of a kind (FOAK) CCS power plants, siting of power plants will probably be as close as possible to storage locations. Doing away with the regeneration completely and the flue gas desulphurization unit (FGD), nitrogen removal unit, and the selective catalytic reducer altogether would significantly lower the cost of sequestration of CO₂.

Alternatives to flue gas carbon capture and utilisation (CCU)

Currently, no flue gas CO₂ recovery process can presently compete with by-product CO₂ (like in the fermentation process for the production of ethanol) (Möllersten et al., 2003) where it is available in sufficient quantity. Moreover, this produced CO₂ is already of high quality in comparison to flue gas. We can suggest, therefore, that more of this by-product CO₂ is used and the captured flue gas CO₂ sequestered without need for purification thus saving on both the capital costs and operation costs. This is even more economical in times when the oil prices are really low hence making EOR obsolete due to high costs of the gas. It is therefore imperative to try and reduce the overall cost of capture at coal power plants and other CO₂ sources especially for those that are far away from oil fields so that the captured CO₂ can geologically dumped. This is what we are calling CAGD, a better alternative to CCU since for the latter all the utilized CO₂ is eventually released to the atmosphere.

Figure 1a shows the conventional carbon capture process. At lower operational and capital costs, our proposal involves using only the absorber tower, as shown in figure 1b for CAGD.

3.1. Alternatives to the Capture Solvent (MEA)

Use of materials like methyldiethylamine (MDEA) with a higher absorptive capacity and much cheaper than the MEA is ideal

Table 1: Comparison of the costs for CAGD to conventional carbon capture

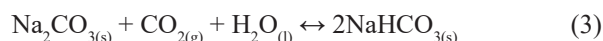
Item	Cost US \$/tonne	Proposed CAGD
	Conventional carbon capture	
Steam, 345KPag sat.	7.90 (Ernest, 1999)	0
Electric power	2.77 (Ernest, 1999)	1.801 (about 35% less (Rubin, 2002))
Cooling water	0.34 (Ernest, 1999)	0
Make-up solvent	2.40 (Ernest, 1999)	Not applicable
Caustic	0.07 (Ernest, 1999)	0.07
Activated carbon	0.19 (Ernest, 1999)	0.19
Operations and maintenance	3.31 (Ernest, 1999)	2.317 (about 30% less)
SO ₂ removal at 250 ppmv SO ₂	1.72 (Ernest, 1999)	0
Capital cost recovery	10.8 (Ernest, 1999)	7.56 (about 30% less)
Total	29.5 (45.43 currently)	11.938 (18.39 currently)

(Singh, Rao, and Chandel, 2017). There are however many other materials that can be used. A comparison of the alternatives to MEA is shown in Table 2.

4. DISCUSSION

Clearly, the absorbent of choice for our CAGD process is Na_2CO_3 which is also non-volatile and non-hazardous, has lower fouling and corrosion issues than amine compounds and most importantly is a cheap multipollutant capture material. (Vega et al., 2018) The slow absorption rate associated with its reaction with CO_2 to form sodium bicarbonate and the solid and slurry management problem can be solved by injecting the mixture in the depleted reservoir while taking care about the proper reaction ratios needed for complete reaction (Vega et al., 2018).

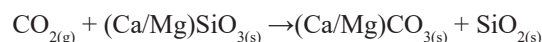
The reaction between Na_2CO_3 and CO_2 is as shown in the following equation (3).



For purposes of comparison the sorption capacity of MEA the traditional sorbent was reported as 111 mg/g versus 282 mg/g for the Na_2CO_3 and the capacity for pure water was reported as only 0.7 mg/g.(Cai et al., 2018).

The reaction between CO_2 and Na_2CO_3 progresses well in the temperature range of 60-70°C. (Liang et al., 2004) This is almost the same temperature range for most oil and gas reservoirs which means that the heat required for the forward reaction can be supplied naturally and the issue of reaction speed would not be a problem since the two reactants can interact underground without having enough heat for reacting reversibly.

The natural rock weathering process which takes place normally over hundreds to thousands of years upon CO_2 sequestration is really slow. It involves the reaction between CO_2 and the rock;



Therefore, aqueous sodium bicarbonate storage can substantially increase the rate of carbonation and this also helps alleviate concerns about leakage of the stored GHG. The NaHCO_3 formed can be precipitated out in slurry form and any unreacted CO_2 can react in the geological store.

In addition to this, the price of Na_2CO_3 is almost 1/10 of the price of MEA (Abanades et al., 2004) and the price of the sorbent is only 10% of the total annual costs of a capture system. On the other hand, energy requirements and investment costs which include capital costs account for about 75% of the total annual costs. There can also be significant savings on the costs for solid

Figure 1: Carbon capture process

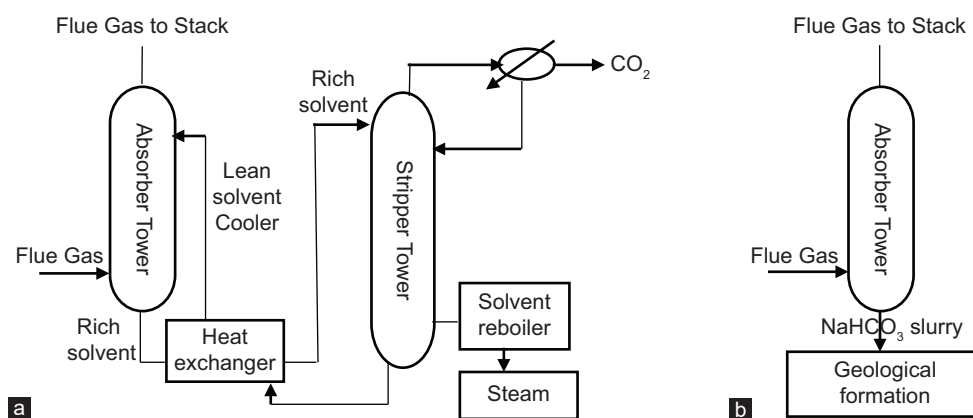


Table 2: A comparison of materials that can be used as CO_2 absorbents

Absorbent	Absorption capacity	Cost per ton	Concentration	Final Product thermal stability
Aqueous NH_3	>1.0 kg CO_2 /kg NH_3 (Bai and Yeh, 1997)	US\$ 450-530 (Department of Agricultural and Consumer Economics, 2018)	5-10% (Bai and Yeh, 1997)	38-60°C (Shale et al., 1971)
MDEA	1.0 mol of CO_2 /mol of amine (Nuchitprasittichai and Chremaschi, 2013)	US\$ 800-1400	50% (Lang et al., 2017)	2493 kJ/kg- CO_2 or about 85°C (Li et al., n.d.)
DEA	0.5 mol of CO_2 /mol of amine (Nuchitprasittichai and Chremaschi, 2013)	US\$ 600-1400	30% (Kim et al., 2013)	100-200°C (Stewart and Hessami, 2005)
MEA	only 0.36 kg CO_2 /kg MEA (Bai and Yeh, 1997)	US\$1550 (Meehan, n.d.)	30% (Li et al., 2013)	100-200°C (Stewart and Hessami, 2005)
Na_2CO_3	0.73 mole CO_2 /mole CO_3^{2-} (Vega et al., 2018), also 228 mg/g CO_3^{2-} (Cai et al., 2018)	US\$162 (Abanades et al., 2004)	70% w/w Na_2CO_3 30% H_2O (Cai et al., 2018)	100-150°C (Green et al., 2004) (Abanades et al., 2004)

waste disposal which is about US\$175/tonne of waste associated with MEA. (Rao and Rubin, 2006) For our proposed process all the slurry is dumped in a geological formation. Na_2CO_3 can also be used for multipollutant control in one unit for sulphurous and nitrogenous acidic gases. (Meuleman et al., 2016) This brings in extra savings for the entire process when combined with the CAGD practice. To highlight, the importance of CAGD, the saving on steam of about US\$ 12.7/ton CO_2 captured is equivalent to US\$ 127M/10 M tonne- CO_2 for storage in a geological formation that has the capacity to sequester 10 M tonnes of CO_2 .

In another study done by (Rubin, 2002) for a low sulphur coal fired power plant, the energy required for regeneration of solvent and compression of CO_2 accounts for about 22.41% of the total cost of the carbon capture plant. If the CAGD process is applied, this would be a significant saving. The figures for the capture of CO_2 usually reported never include the storage and transportation costs (Leeson et al., 2017) and that is why focus is on the process only. In the same study, there is a consideration for a flue gas desulfurization unit for sulfur removal, a low- NO_x burner and selective catalytic reduction for removal of NO_x elements. Addition of the CO_2 capture system increased the total plant capital cost from US\$571M by 23.5%. The cost of one ton of MEA was taken to be 1250\$ but this, of course, has increased by about 24% currently. It was estimated that the costs of a CO_2 capture unit with solvent regeneration increased by about 24% and about 29% of that was taken to be due to energy requirements of which 49% is for the regeneration of a solvent and amounts to about US\$19M. There have been some attempts to show how this particular cost can be brought down using blends of amines (Zhang et al., 2017), however, it is still significantly high even with the modified amines. MEA make-up accounted for about US\$13.4M which is another significant expenditure. Our proposed approach would be much cheaper than this and yet keep the GHG sequestered for a very long time.

5. CONCLUSION

The possible ways to reduce the cost of CO_2 sequestration have been discussed with a special focus on the direct dumping of the absorbent- CO_2 /flue gas mixture into geological formations through CO_2 absorbing and geological dumping (CAGD) by eliminating the stripper section to regenerate CO_2 and the CO_2 compression unit. The total reduction in the cost per tonne of CO_2 has been evaluated as up to US\$12.7/tonne- CO_2 by saving on the steam required for regeneration. This figure has been shown to be equal to US\$127M/10 M tonne- CO_2 captured and stored in the geological formation. This lowers the capture cost to about US\$33/ton- CO_2 and makes it lower than the carbon price already in Iceland and close to that in British Columbia hence prompting the emitting industries to treat their flue gas. There is an additional saving that was reported to be around US\$175/ton waste produced during CO_2 capture.

Additional savings on the energy needed for compression and cooling units by about 67% of the total energy requirements make the CAGD process more economically sound. It has been found that the capture solvent/absorbent can be changed to a

cheaper one, like Na_2CO_3 which makes the process more viable economically. Moreover, it has been proven by several reporters to have a higher capture capacity than the more conventional and more costly MEA. CAGD needs to be demonstrated on a pilot plant for a detailed feasibility study.

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