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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$12.7per 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 $CO_2$ absorbing 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 1.9ºC 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 $CO_2$ 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 $CO_2$ gas. The fundamental equations for the reaction between primary or secondary amines and $CO_2$ are shown below;

$$CO_{2(g)} + 2\,RNH_{2(aq)} \leftrightarrow RNHCOO^{-} + RNH_3^{+} \quad (1)$$

$$RNHCOO^{-} + H_2O_{(l)} \leftrightarrow RNH_{2(l)} + HCO_3^{-} \quad (2)$$

Since both primary and secondary amines follow equations (1) and (2) in reactions involving $CO_2$, 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 $CO_2$ capture is approximately equivalent to an average of US$43-54 per ton-$CO_2$ (Naims, 2016). In some countries like Canada, they have enacted a nationwide tax on oil, coal, and gas that starts at US $15 per ton-$CO_2$ and is expected to be at US$38 per ton-$CO_2$ 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$39 per ton-$CO_2$ currently (World Bank, 2019). Clearly, this is lower than the current cost of $CO_2$ 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 $CO_2$ 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$45 per ton-$CO_2$ 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 Protocal.

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 $CO_2$ SEQUESTRATION

Sequestration of $CO_2$ 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 $CO_2$ 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 $CO_2$ and the potential infrastructure cost of building $CO_2$ pipelines to connect CCS power plants with $CO_2$ 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 $CO_2$.

Alternatives to flue gas carbon capture and utilisation (CCU)

Currently, no flue gas $CO_2$ recovery process can presently compete with by-product $CO_2$ (like in the fermentation process for the production of ethanol) (Möllersten et al., 2003) where it is available in sufficient quantity. Moreover, this produced $CO_2$ is already of high quality in comparison to flue gas. We can suggest, therefore, that more of this by-product $CO_2$ is used and the captured flue gas $CO_2$ 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 $CO_2$ sources especially for those that are far away from oil fields so that the captured $CO_2$ can geologically dumped. This is what we are calling CAGD, a better alternative to CCU since for the latter all the utilized $CO_2$ 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).

$$Na_2CO_{3(s)} + CO_{2(g)} + H_2O_{(l)} \leftrightarrow 2NaHCO_{3(s)} \tag{3}$$

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;

$$CO_{2(g)} + (Ca/Mg)SiO_{3(s)} \rightarrow (Ca/Mg)CO_{3(s)} + SiO_{2(s)}$$

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

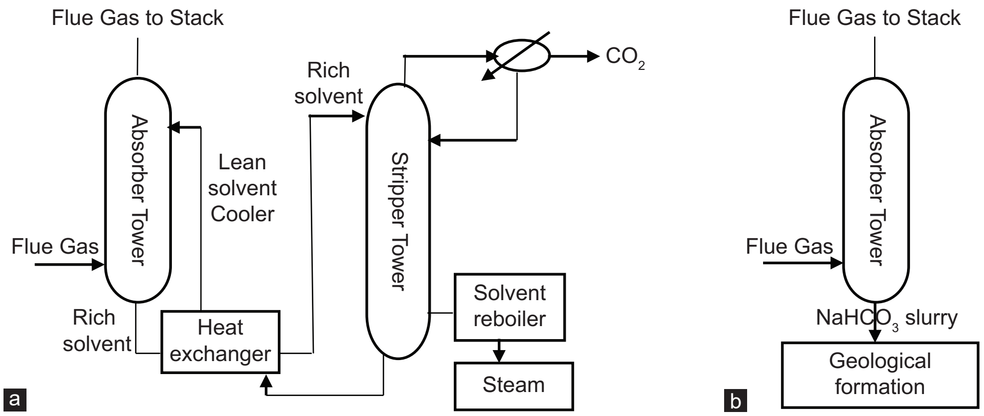

**Table 2: A comparison of materials that can be used as $CO_2$ absorbents**

| 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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