Economics of Carbon Sequestration using Algae

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Abstract—**This research examines the various carbon sequestration options and the impact of these on the economic viability of various carbon capture solutions when measured against algal based options. The base case of a coal fed Fischer - Tropsch facility is used to quantify the impact of these options.**

***Index Terms*—Algae, Carbon, Economics, Fischer-Tropsch, Sequestration.**

I. Introduction

It is clear that internationally, petrochemical and energy companies are faced with a significant social responsibility in respect of their current carbon emissions and the reduction thereof. Carbon footprint is a major focus for the global community currently [1]. South Africa, like most other nations, is creating and implementing government policies in this regard. Good business practices, along with these regulations, are forcing corporates to proactively investigate various carbon mitigation options.

One of the systems that has shown clear promise is that of algal carbon capture and storage of the carbon dioxide. This paper seeks to examine the potential of these systems and identify the key technical elements and issues that impact on the costs and indeed the viability of the technology when compared to the alternative penalties that would be levied in the event of non-compliance.

In examining these parameters, we report on some laboratory testing that has been carried out to explore the relative importance of these factors and some of the optimization options that exist. To contextualize the issues, the carbon emissions from a medium scale Fischer Tropsch (FT) plant are used as the feed quantum for the discussion.

II. Coal to Liquid Fischer-Tropsch Emissions

Fischer-Tropsch is a technology that is used in the conversion of coal (CTL) and natural gas (GTL) into hydrocarbon liquid fuels. The major sources of carbon dioxide in a CTL facility are gasification, which is the first step in producing the carbon monoxide and hydrogen from coal. When the CTL process includes a co-generation capacity, the combustion of the syngas will generate additional carbon footprint for the plant.

Based on the SASOL Investor Insight Paper [2], a typical SASOL CTL facility would produce of the order of 9.47 tonnes of CO_2/tonne of liquid hydrocarbons. This would mean that the deployment of a 30,000 bpd facility would generate upwards of 12.4 M tonnes of CO_2 per annum. What makes CTL a particularly interesting case for this consideration of the carbon sequestration is the fact that in addition to the production of liquid hydrocarbons, a process stream of so called reaction water is also produced.

This reaction water contains up to 10% of oxygenated hydrocarbons which require remediation before the water can either be recycled for use in the plant, or released to the environment.

In investigating algal solutions it is technologically viable to utilize the algal culture to perform the dual task of water remediation and simultaneous carbon capture.

III. Available Techniques for CO2 Mitigation

A. Unchanged direct release into the atmosphere

In many parts of the world, the unmitigated release of carbon remains an option for industries, and the recession and general economic situation have permitted a number of companies worldwide, and especially in third world, to continue with their emissions unchecked. However, the consequence of globalization and the dependency on first world funding for project is creating pressure on developing countries which trickles down to the local companies to act to reduce their carbon footprints.

To achieve the low levels of emissions that are set out both internationally under treaties such as Kyoto, and locally under country specific commitments, many governments have opted to make use of the mechanism of carbon taxes as an incentive to drive the desired change in behavior.

As in many other ways, the South African government has proactively engaged with the challenge of climate change and is, according the a recent KPMG report, the thirteenth most active nation in respect of its attempts to reduce carbon emissions [3]. This ranking was based on the implementation of not only carbon penalties but also proactive grants and development funding to support emission reduction initiatives. In the interests of simplicity for the sake of this paper we will only consider the cost benefit of the carbon emission penalties being implemented.

The proposed tax was proposed to come into operation from January 2015, but implementation has been pushed out after engagement and lobbying from government and industry till 2016 [3]. The tax is proposed to be introduced at a statutory level of 120 ZAR/tonne CO_2 equivalent (~10 USD/tonne CO_2) with an annual increment of 10% per annum till 2021. The tax free threshold and other allowances result in an

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actual cost of between 12-46 ZAR/tonne CO_2 equivalent (~1-4 USD/tonne CO_2 equivalent).
This extremely low cost of continuing to emit carbon creates a challenging economic case for any sequestration options.

B. Geological sequestration

One of the most demonstrated and established forms of carbon capture and sequestration involves the compression and underground storage of the fugitive carbon emissions.
This form of sequestration captures and stores CO_2 in stable porous geological formations that lie far below the earth's surface. This storage takes place at such pressures and temperatures that ensure that the CO_2 is in a liquid or supercritical phase.
Examples of suitable formations include depleted oil or gas reservoirs, deep saline formations or unminable coal resources. When used with depleted oil and gas wells this sequestration also provides the possibility of enhancing the recovery of hydrocarbons from the reservoir though what is termed enhanced hydrocarbon recovery.
The most promising reservoirs as reported by ANSOLABEHERE, et al. [4] are porous and permeable geological bodies found at depths of in excess of 1 km below the surface of the earth. These formations have the potential of storing 100's of gigatonnes of CO_2.
This study reviewed the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project. This was a pioneering demonstration project to assess the viability of CCS and ran from 2000 till 2011. The project over this time captured an estimated 18 M tonnes of CO_2 by 2010. The establishment and operation of the project cost an approximate 85 Million USD. This would provide a cost of 4.72 USD (2010 value) per tonne of CO_2 sequestered [5].
A report by Mason and Veld [6] described an analysis of the best achievable gain from the injection of CO_2 into the Wyoming's Powder River Basin (PRB) and Green River Basin and the resulting recovery of methane and oil. This form of geological sequestration uses Enhanced Coal Bed Methane Recovery (ECBM) and Enhanced Oil Recovery (EOR). For ECBM the authors report a cost of \$4/ton CO_2 for a maximum CO_2 Sequestration of 200 $MtCO_2$/year which corresponds with the EIAGHG study. For EOR they reported for the PRB a cost of \$130/ton CO_2 at a maximum of 5 $MtCO_2$/year and for the Green River Basin (GRB) a cost of \$170/ton CO_2 for a maximum of 1.8 Mt CO_2/year.

C. Carbon recycling

There are several different technology options that could be used to convert CO_2 to any one of a number of useful products. These include:

Methanol production

In this process, the CO_2 is reacted with H_2 to produce methanol and derivative products such as di-methyl ether and other energy products. This requires the availability of H_2 to convert the material. This is possible to produce in a number of ways, however the costs for these processes greatly exceed the taxation charges, and as such will not be included in this study.

Thermolysis

In this option, CO_2 is converted to CO and O_2 through thermolysis at approximately 2400 ^oC [7]. The CO is then converted to any one of a number of products via standard chemical reaction routes. There is some experimental work looking at solar options to operate this via CSP options, but none of these are yet commercial and as such will be excluded from this assessment.

Forestation

The effectiveness of this route has been hotly debated in academic circles, especially given the offset of the captured carbon against the methane produced in the rotting of leaf fall. The Pew Study by Stavins and Richards [8] showed a cost range for large scale capture of between 7.50 and 22.50 USD/ tonne CO_2 captured.

Algae

Utilizing algae has been shown to have several benefits over the other CO_2 recycling routes. In addition, a diversity of products can be produced from Algae. These include food for fish in aquaculture to provide an alternative protein source, fuel source for drying, feedstock for bio-oil extraction and conversion thereof to biodiesel, pharma chemicals, etc.
The specific application of the algae is species specific, and the balance of this paper will address the development of an economic model to evaluate this opportunity. The nature of algae and its flexibility create several options that can improve or detract from the economic viability of this solution.

IV. FACTORS IMPACTING THE CAPITAL AND OPERATIONAL COSTS OF CO2 SEQUESTRATION USING ALGAE

A. Light

One can easily assume that the dependence of light for photosynthesis would be the same for all autotrophs, and that a general rule of optimization would be to expose all autotrophs to maximum possible light radiation.
When dealing with algae this is complicated by the consideration of how deep the culture is. In very deep cultures and high algal concentrations the initial surface incident light intensity must be high, as it needs to penetrate the water and the algae [9].
In contrast when using small containers to cultivate the algae, high light intensities can actually lead to photo inhibition. By definition, photo inhibition is a state of physiological stress that occurs in all oxygen evolving photosynthetic organisms exposed to high intensity light [10] for extended periods of time.
This trade-off presents a good basis for optimization. Using a deep pond means less land area is needed but, as mentioned earlier, there is a limit due to the maximum depth that light can penetrate into the culture mass. If the culture is too shallow, this can lead to overexposure to light and thus photo inhibition. A proper investigation will lead to the most feasible type of reactor, open versus closed for a given situation, and consequentially the most feasible dimensions.

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Thus the cost of sequestering the associated CO_2 can be clearly coupled to selected reactor design. Once set up, light optimization doesn't present any day to day operational cost. This component of the overall reactor cost will be denoted $C_{L.}$

B. Nutrients

Light alone, even with its great abundance, cannot maintain algal growth. The main nutrients requirements for growth are phosphorous, nitrogen, hydrogen and oxygen. Being aquatic organisms, algae have an ample supply of hydrogen and oxygen in the water. The other three nutrient requirements can offer a limitation. This comes about as the bigger the algal culture the greater the demand and the requirement to provide sufficient circulation to provide the nutrients to all parts of the culture. One advantage lies in the fact that most seawater, brackish water and waste water contain these nutrients already to some lesser or greater extent. Also, in the case of integration of wastewater into the system, the algae then provides an additional water treatment advantage [11].

Nutrients taken up by algae are nitrogen in the form of a nitrate and phosphorus in the form of ortho-phosphate. These nutrients can be added in the form of fertilizers or straight from a waste water streams. Using fertilizer presents a problem in that the production of fertilizers is in itself a major energy consumer and pollution creating industry. To produce 1 tonne of ammonia, a core component in fertilizer production, 37 to 40 GJ of low heating value natural gas is used. To add to this 1.2 kg of CO_2 is produced for every 1 kg ammonia produced [11].

Therefore, in the overall CO_2 balance, when evaluating the efficiency of the sequestration process, the fertilizer addition step increases the CO_2 produced. It has also been shown that algae production consumes more fertilizer than terrestrial autotrophs [11].

As mentioned before, when using waste water, algae can also act as a reagent to purify the waste water extracting not only the aforementioned nutrients, but also other organic materials including oygenates and aromatic compounds [11].

In this case not only does one get readily available nutrients at a lower cost in terms of price and CO_2 emissions, there is a reduction in the energy required for the waste water treatment. According to a survey done in the U.S in 2008, 32.345 million gallons per day of waste water is produced. In this production there is enough N and P in each litre to produce 0.6 g of algae for a total of 77.6 million kg/day [12].

This clearly demonstrates a large economic potential in the use of waste water. As mentioned earlier, waste water treatment is energy intensive and costly as well. The U.S. has wastewater infrastructure investment requirements of $13 billion to $21 billion annually with an additional $21.4 billion to $25.2 billion required for annual operation and maintenance [12]. The operating costs will be the labour required in maintaining the nutrients at optimum concentrations.

The cost of nutrients and savings due to usage of waste water from the facility will be evaluated using:

C_N = Cost of Nutrients + Operating Costs – Cost equivalent of treatment of Chemicals Present in Waste Water.

C. Temperature

Most commonly cultured species of microalgae tolerate temperatures between 16°C and 27°C [9]. In the base case study, due to the typical emission conditions, it is relatively easy to ensure that the algae culture is maintained above 16°C. In this case it must then be evaluated which is more cost effective: cooling the CO_2 stream to suitable temperatures or cultivating only the strains of algae which can tolerate high temperatures. South African temperatures range at average of 8°C and 28°C; this means that cooling would be required in hot seasons and heating during winter. This then presents an energy cost which has to be added to the overall costing, to be represented as C_T.

D. pH

The pH range for most cultured algal species is between 7 and 9, with the optimum range being 8.2-8.7 [9]. The flue gas may contain some SO_X which can, subject to the dilution ratio, drop the pH to as low as 2.6. It has been shown that pH values this low can inhibit algal growth [12]. Dissolved CO_2 can also in high enough concentration bring the pH down to 5.7. Due to the competing enhanced growth from great carbon availability it does not have a huge effect on the algal growth [12].

A study was done for *Chlorella* sp. and *Spirulina plantesis* [14]. Both organisms were subjected to a pH range of 7–13 at constant input CO_2 concentration of 10%. A pH of 10.0 was found to be the optimum for both organisms with the highest growth rate of 0.14 g/L/day and 0.08 g/L/day observed for *S. Plantesis* and *Chlorella* sp., respectively. The media pH was found to play a vital role in growth of the organism with slightly acidic pH of 6.0 showing the least growth rates for both organisms [14].

The use of waste water and addition of CO_2 will have a direct impact on the pH, and thus there will be need to add pH buffering chemicals which adds a cost that is referred to as C_{pH}.

E. CO_2 concentration

CO_2 is clearly the major ingredient in the photosynthetic reaction. The ambient air itself has about 0.03% CO_2 by volume and this is, in natural circumstance, typically the limiting factor to growth [14]. In order to increase algal growth rate the CO_2 concentration must therefore be increased in the reactor medium. In order to increase CO_2 concentrations different bio-reactor setups will be investigated with a focus on how to introduce CO_2 and achieve high dissolving rates.

A CTL facility has various sources of CO_2, including the acid gas removal step after gasification, and in the recycle process after the FT reactors and from the flue gas from power generation. These streams are recovered as relatively pure streams, and as these are required for the FT process, the only costs associated with the sequestration will be any compression costs for optimal injection pressure into the bio-reactor. The rate at which CO_2 will dissolve in water will also be affected by temperature and pressure, thus consideration will have to be given when assessing the cost of maintaining temperature and compression costs. The cost of compressing and supplying the CO_2 will be denoted "C_C".

F. Bio-reactor options

The choice of reactor is situation-dependent with algal species and the final use of algae being the overriding factors. The algal species will dictate the conditions to be maintained in the reactor such as pH, temperature and nutrient levels. In the laboratory work that was done, a local stain of algae harvested from a local dam was used for this purpose. No particular species classification was done.

Positive growth was achieved in a batch bioreactor which simulated the conditions of an open agitated pond. If algae is to be used for human consumption or pharmacological applications, then the standards that need to be adhered to will push the capital and operating costs up. The algae that we tested would not be suitable for this purpose, but having seen positive results with a consortium of algae means a more optimal reactor system can be designed and the algae used as biomass feedstock for biomass to liquid (BTL). Open and closed system options are discussed below.

Open pond system

This system will consist of a pond and pumps used for agitation. Thus the main capital cost will be from pumping power required for agitation. The challenge with an open pond system is the low uptake rate, thus requiring a larger volume which poses a space challenge. Other challenges include reduced control on parameters such as temperature as the temperature of the surrounding will be more determining. Contamination is also a major problem with open systems, and bacterial contamination is inevitable. This then adds to treatment costs such as adding anti-biotic and stricter upfront sterilization techniques. Open system systems need large volumes to produce adequate algae for the sequestration and water treatment. The challenge is that algae will only make up about 2% of the total volume. In the event that algae is to be used as biomass or harvested for its rich lipid content, a substantial processing cost arises [1]. With this, it is clear that for a CTL which produces large amounts of CO_2, using an open pond system would require a lot of space.

Closed systems

A closed system at first glance seems to be the more suitable option for our purposes, but before that, proper consideration has to be done on the higher capital investment required when compared to the open systems. Closed systems have the following advantages over open system: i) they are smaller; ii) they are capable of producing high population densities; iii) they offer greater control on parameters such as temperature, oxygen and pH, iv) greater gas transfer and v) lower chances of contamination. Starting from the results obtained from the previous body of work, also incorporating positive aspects of the reactors shown here, a bio-reactor will be designed which will best assess the parameters needed to construct the economic model.

V. ECONOMIC MODEL AND FUTURE WORK

Having identified the various factors, we can confidently propose an economic model of the costs required for an algal bioreactor. This cost model is summarized as:

$$\text{Total Cost} = C_L + C_N + C_T + C_{pH} + C_C \quad (1)$$

In order to develop this economic model, the next body of research will involve the development of a design of the proposed algal processes. From this design we will be in a position to estimate the operational cost and amortize the capital expenses for the project. From this simple model, scale up calculations will be done to get to representative costs for the processing of the CO_2 outputs from a full scale 30 000 bpd CTL facility.

To properly assess the economic viability and opportunity, this cost model will then be weighed against the revenue streams. These include those saving from the carbon taxation (C_{TA}), possible revenue stream from algae usage (C_A) and savings achieved from the incorporation of the water remediation functionality (C_W).

In investigating the utilization of algae, the possible uses as animal feed and as feedstock to bio-fuels production will be investigated to arrive at a market value.

$$\text{Total Revenue} = C_T + C_W + C_A \quad (2)$$

Offsetting the costs from Equation 1 and the revenue from Equation 2 we will arrive at the Net Gain/Loss for a proposed process using algae for CO_2 Sequestration and water remediation.

VI. CONCLUSION

Having laid out the foundation required to build a proper economic analysis for algal sequestration for CO_2 and having other technologies for comparison in terms of cost, Fig 1 shows that, for at least in the South African context, the current cost models clearly favor the direct release of CO_2 into the atmosphere with forestation being the second most favorable.

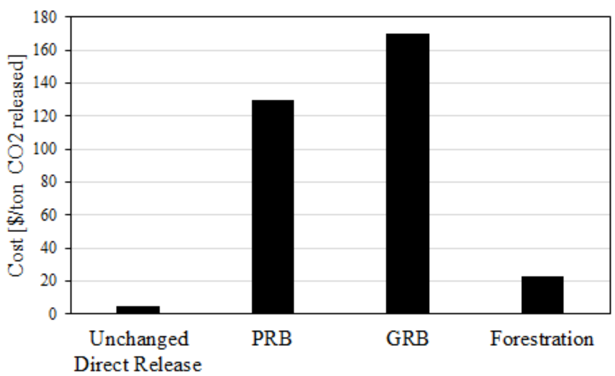

Fig 1: \$/tonne CO_2 cost for direct release of CO_2 vs sequestration techniques

In order for sequestration using algae to be economically viable, it has to at the very least come in at a cost lower than that of forestation, or preferably lower than the cost of direct release penalties.

A very interesting and yet secondary result of this assessment is that if governments are serious about addressing carbon emissions, and promoting the uptake of any technology to make energy production cleaner, the mitigation of CO_2 must be economically favorable for the companies, and that current legislation does not support that behavior.

References

[1] Treasury, Department of. CARBON TAX POLICY PAPER, Reducing greenhouse gas emissions and facilitating the transition to a green economy. s.l. : South African National Treasury, 2013.

[2] Sasol Limited, Investor Insight, Johannesburg, July 27, 2007

[3] G. Wiebe, Y. Boer, The KPMG Green Tax Index 2013, https://www.kpmg.com, 2013

[4] S. Ansolabehere, J. Beer, J. Deutch, The Future of Coal, MIT study on the future of coal, (2007) 43-44

[5] S. Whittater, IEA GHG Weyburn-Midale CO2 Storage & Monitoring Project, Petroleum Technology Research Center, 2010

[6] C.F Mason, K.Veld. Economic Analysis of Geologic Carbon Sequestration Potential for the BSCSP Region using Enhanced Coalbed Methane Recovery and Enhanced Oil Recovery, Big Sky Carbon Sequestration Partnership Phase II (2010) 1, 10-11, 17

[7] A.J. Traynor, R. J. Jensen "Direct solar reduction of CO2 to fuel: First prototype results." Industrial & Engineering Chemistry Research 41(8) (2002) 1935-1939.

[8] J. Carlie, R. Wike, Climate Change Seen as Top Global Threat, PEW Research Center, 2015

[9] P. Coutteau, Manual on the Production and Use of Live Food for Aquaculture, Food and Agriculture Organization of the United Nations, 361 (1996) 8-15

[10] A. Noam, Z. Hagit, S. Susana, O. Itzhak. Photoinhibition - a historical perspective, Kluwer Academic Publishers, 76 (2003) 343-370

[11] K.L Man , T.L Keat, Microalgae biofuels: A critical review of issues, problems and the way forward, Biotechnology Advances, 30 (2012) 673-690

[12] C. Logan, S. Ronald, Production and harvesting of microalgae for wastewater treatment, biofuels and bioproducts, Biotechnology Advances, 29 (2011) 686-702

[13] K. Kanhaiya , N.D. Chitralekha, N. Bikram , L. Preter , D. Debabrata, Development of suitable photobioreactors for CO_2 sequestration addressing global warming using gren algae and cynobacteria, Bioresource Technology, 102 (2011) 4945-4953

[14] R. Rishiram, K. Krishnamurthi , D. Ashok , Y. Raju , C. Tapan , Enhanced algal CO2 sequestration through calcite deposition by Chlorella sp. and Spirulina platensis in a mini-raceway pond, Bioresource Technology, 101 (2010) 2616-2622