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Feasibility of air capture

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Abstract

Capturing CO_2 from air, referred to as air capture, is being proposed as a viable climate change mitigation technology. Technically, air capture is not a new technology; industrial applications can be traced back to the 1930s. This paper explores the feasibility of this technology as a climate change mitigation option. Two different pathways of air capture are assessed: direct air capture, which uses a chemical process to capture CO_2, and biomass coupled with CO_2 capture and storage (CCS), which utilizes the biological process of photosynthesis to remove CO_2 from the air. We find that direct air capture has prohibitively high mitigation costs compared to the costs of climate change mitigation options being considered today. The pathway of biomass coupled with CCS has much more reasonable costs and could be used to offset certain emissions. However, the large land requirement may limit the amount of offsets available. We conclude that relying on air capture technology to play a major role in mitigating carbon emissions is a very risky policy decision.

Keywords: Carbon dioxide capture; air capture; sequestration; climate change; biomass; switchgrass

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1. Introduction

The emissions of Greenhouse Gases (GHG) have gone up by 70% between 1970 and 2004 and carbon dioxide (CO_2) is the most important anthropogenic GHG, as reported by IPCC in their Fourth Assessment Report on Climate Change [1]. The emissions of CO_2 have grown by 80% between 1980 and 2004 [1]. It is also reported with very high confidence that the global atmospheric concentrations of GHGs have gone up significantly since 1750 as a result of human activities and that the net effect of all this has been that of warming [1]. This report predicts that the global GHG emissions, measured in CO_2-eq, would rise by 25-90% between 2000 and 2030, with fossil fuels maintaining its dominance in the energy mix [1]. Based on the findings in the report, pressure is being imposed on major emitter countries to reduce their emissions of GHGs. This is not an easy task given the huge dependence of the world on fuels rich in carbon, which are the major sources of carbon dioxide emissions. The extremely low cost of these carbon-rich fuels will make this dependence a difficult thing to overcome. As shown in the chart below, 87% of the world's energy needs are met by these relatively cheap carbonaceous fuels. As the low carbon and carbon-free fuels will take some time in getting competitive on price with the carbon-rich fuels, this change can be assumed to be a slow, long process.

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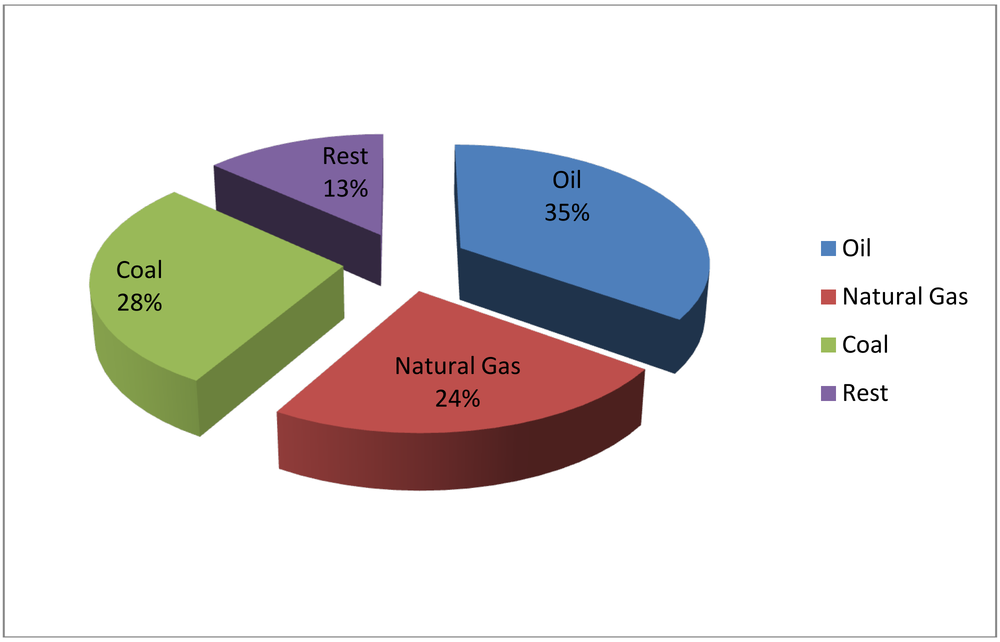

Figure 1 The different sources of worldwide primary energy consumed. [2]

There is not a well defined path towards that low carbon emissions goal and strong fears exist that we might overshoot the emission target. In that case, there could be a need of a technology that “sucks” carbon out of the atmosphere and brings us back to the emission goal. There are also certain papers that conclude that there is a need for some solutions that can reduce the stock of CO_2 already present in the atmosphere. This stock of CO_2 would take a very long time to get dissipated if we depended only on the natural processes [3]. Therefore, processes that reduce the concentration of CO_2 in the atmosphere faster than the natural rate of removal through natural sinks such as the oceans and the trees could be important. Removing CO_2 from the atmosphere (termed “air capture”) is definitely an interesting concept and its exact role in climate change mitigation deserves investigation.

Another suggested role for air capture is its ability to offset emissions from distributed sources, which are more than half of the total current emissions. Essentially, for certain applications especially in transportation, fossil fuels could continue to be used as an energy source as long as air capture could offset their emissions [4].

Currently, there are three major approaches to air capture that are under serious consideration:

- Direct Air Capture: This methodology uses chemical processes to capture CO_2 from air
- Biomass Coupled with CO_2 Capture and Storage (CCS): The CO_2 is captured from the air by trees that produce biomass in a sustainable manner. The biomass is then fed to a power plant to produce energy and the CO_2 is captured using conventional CCS.
- Enhancing Natural Sinks: This process is executed by enhancing the natural sinks artificially to capture more CO_2 from air. The natural sinks could be the oceans, soil or vegetation (e.g., trees). This topic is beyond the scope of this paper but more information can be found in the IPCC Special Report on Land Use, Land Use Change and Forestry, 2000 [5].

2. Motivation

The concentration of CO_2 in air is about 390 parts per million (ppm), which is about 300 times more dilute than the concentration of CO_2 in a flue gas stream, about 12% by volume. In general, separation costs for a specific compound depend on how dilute this compound is in the starting mixture, as illustrated by the Sherwood plot (see Figure 2 below).

Originally, the Sherwood plot was an empirical relationship between the price of a metal and the concentration of the metal in the ore from which it was extracted, plotted on a log-log scale. Since its publication in 1959, the Sherwood plot has been extended to several other substances which are extracted from mixtures. The plot is shown with the approximate concentration of CO_2 in power plant exhaust gas (CCS) and CO_2 in air (Air Capture) marked on it.

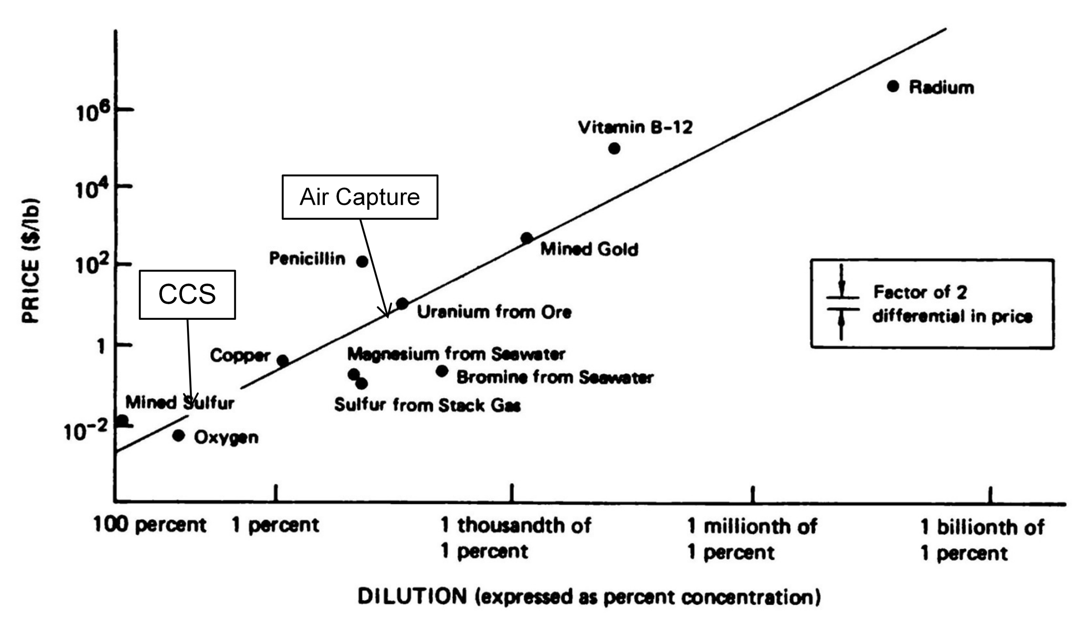

Figure 2 The Sherwood Plot [6]

The x-axis has the level of dilution of the mixture and the y-axis has the market price. The y-axis can be used to see a ratio of costs of two processes. As can be seen from the plot above, the ratio of costs of Air Capture and CCS is expected to be about 100. The cost of CCS is accepted to be in the range of $(200-300)/tC ($55-82/tCO$_2$) [7]. Therefore, the Sherwood plot suggests that the cost of air capture will easily run into thousands of dollars per ton of carbon. However, proponents of direct air capture put its cost of mitigation in the range of $100/tC ($27/tCO$_2$) [8] to $500/tC ($136/tCO$_2$) [9]. This is in the ball park range of CCS mitigation cost listed above. Given the empirical relationship shown in the Sherwood plot, these numbers seem highly optimistic at best and very well could be unrealistic. This discrepancy provided motivation to look more closely at the technology and costs of air capture. Since air capture is a “seductive” technology [10], it is very important to objectively evaluate its technical and economic feasibility.

3. History of air capture

The technology of removing CO_2 from air has been in use for over 70 years now, although on a much smaller scale than envisioned for air capture [10]. The first industrial use of capturing carbon dioxide from air was reported in cryogenic oxygen plants to prevent condensed carbon dioxide in air from clogging the heat exchangers [10]. Today, the major applications of CO_2 removal technology are air separation (i.e., oxygen) plants, space craft, and submarines.

Carbon dioxide removal from air has been an integral part of the space program. As human beings emit CO_2 at the rate of 1 kg/person/day, the concentration of CO_2 can go up pretty quickly in the air in a space shuttle, especially one which has more than one astronaut [10]. Thus, a lot of research has gone into finding out more efficient ways to capture carbon dioxide from the air in such systems. Today, the space shuttle uses a molecular sieve system regenerated by the vacuum of space to remove CO_2 from the air.

While the technology of capturing CO_2 from air has been used industrially for decades now, this process was always a small part of an overall process where the cost of achieving this was never a priority; in fact it was absolutely necessary to get this step done at any cost. The only objective was to get “clean air” for the process and no thought was given to the waste CO_2 captured by the process, which was mostly vented to the atmosphere or outer space. Air capture is not only about getting “rid” of CO_2 in air but also about isolating and storing the captured CO_2. This adds the requirement to regenerate pure CO_2 and, in turn, increases overall cost of the process. Thus, air capture has the burden to cost-effectively “clean” the air as well as store the CO_2.

4. Estimating cost of direct air capture based on minimum work

The minimum work can be used to estimate the cost of air capture. The minimum work required for air capture is calculated to be 20 kJ/mol CO_2 (462 kWh/tC) [11]. This assumes the process is ideal with 100% thermodynamic and thermal efficiencies. However, we know operating at the thermodynamic minimum requires infinite capital costs, so we must assume some efficiency. Thermodynamic efficiency calculated in literature for air capture processes are in the 2-3% range [9, 12].

Air capture, to be feasible, requires a carbon free electricity source for capturing carbon. The use of any fossil fuel generated electricity will only end up releasing more CO_2 to the atmosphere than capture [12]. Here, we assume that the cost of carbon-free electricity is 10¢/kWh (though there are many indications it may be much higher [13]). Assuming a thermodynamic efficiency in the range of 1-5%, the energy cost for air capture can then be estimated as \$900-\$4600/tC (\$250-\$1200/tCO_2). This is just the energy cost, without factoring even a single dollar for the capital cost. Adding in the capital cost will increase this estimate significantly. This calculation shows that many of the total cost numbers reported in the literature (\$100-500/tC (\$27-136/tCO_2)) are not very believable.

5. Absorber comparison between air capture and flue gas capture

In absorber design for gas absorption, the cross sectional area of the column can be expressed as

$$A = \frac{\Delta CO_2}{C_{CO2} \times f \times v} \tag{1}$$

Where A is the cross sectional area of the column (m^2), • CO_2 is the rate of CO_2 captured (mol/s), C_{CO2} is the inlet concentration of CO_2 (mol/m^3), f is the fraction of inlet CO_2 captured, and v is the linear velocity of vapor in the column (m/s). As a rule of thumb in absorber design, the linear velocity of gas in a column varies between 2-3 m/s for the optimum performance of the column. Hence, the term v is the equation above could be taken as a constant. Using this in equation 1 for a fixed rate of CO_2 captured, we get the following relationship:

$$A = \frac{C_1}{C_{CO2} \times f} \tag{2}$$

where C_1 is a constant.

Equation 2 shows that the cross sectional area of an absorber is inversely proportional to the inlet CO_2 concentration and the fraction of CO_2 captured. Thus, as the inlet concentration of CO_2, or the fraction captured, goes down, the cross sectional area required goes up. The inlet concentration of CO_2 is 300 times smaller in air capture compared to flue gas capture. Using the formula above, the cross sectional area of the absorber required for air capture would be 300 times the value for flue gas capture (as would the amount of gas processed).

It is often stated by air capture proponents that since the supply of air is essentially limitless, the capture percentage for air capture could be freely varied and need not be about 90% as in flue gas capture. The formula above makes it clear that the lower the capture percentage, higher is the required cross sectional area of the column. Thus, if the capture percentage is lowered from 90% to 25%, for the same rate of capture of CO_2, the cross sectional area required (as well as the amount of air processed) for air capture goes up by a factor of 3.6 (the amount of air processed would be over 1000 times that of flue gas capture for an equivalent amount of CO_2!). Such high cross-sectional areas of the absorber for air capture will result in significantly larger capital costs compared to flue gas capture. The increased gas flow will almost surely result in significantly higher energy requirements for the blowers and fans.

The two options for solvent considered in literature are amines and hydroxides. Because amines are impractical for air capture [11], literature studies commonly use hydroxides as the air capture solvent. However, the chemical reaction between CO_2 and the hydroxide binds the gas to the solvent in an irreversible fashion, meaning the solvent cannot be regenerated by a simple temperature swing. This makes the task of solvent regeneration more complex and energy intensive, resulting in much greater costs. This illustrates an inconvenient truth in designing many chemical engineering processes – everything is a trade-off. Using a stronger base as a solvent helps overcome the small concentration driving forces present in air capture but requires a much more complex and expensive regeneration process [11].

6. Air capture via biomass with carbon capture and sequestration

There is an alternate way in which atmospheric stock of carbon can be reduced, through the use of biomass energy. CO_2 could also be captured in power plants fuelled with biomass, or fossil-fuel plants with biomass co-firing. This combination of biomass energy used with CO_2 capture and storage (BECS) can yield net removal of CO_2 from the atmosphere. The CO_2 put into storage comes from biomass which has absorbed the CO_2 from the atmosphere as it grew. Provided that the biomass is not harvested at an unsustainable rate, the overall effect can result in ‘negative net emissions’.

The system basically consists of a few simple building blocks: a fixed tract of land, a power plant driven by biomass energy and a conventional CCS setup. The process consists of harvesting the piece of land sustainably to produce a steady stream of biomass, which feeds into the power plant that produces electric power. The emissions resulting from the plant operations are then captured and sequestered using the conventional CCS equipment. The energy required to drive the plant's capture equipment is derived from the electrical energy output of the plant and any excess electricity is sold for credit. The schematic of the model is shown below.

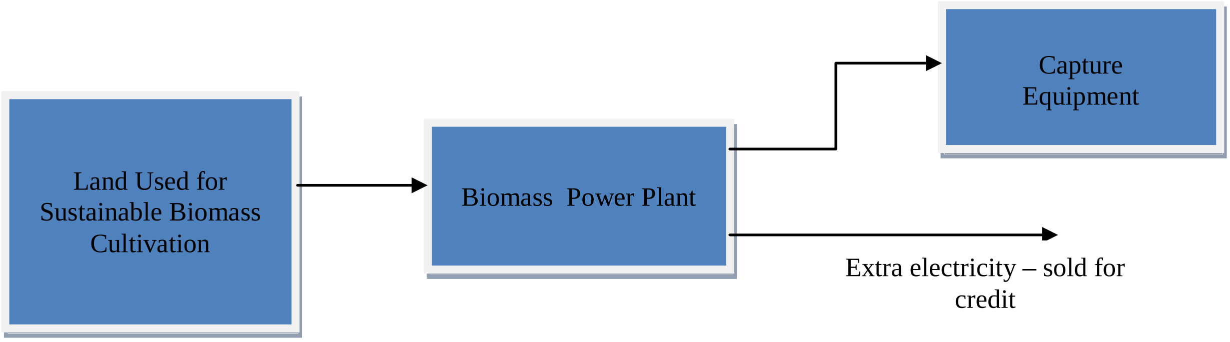

Figure 3 The schematic showing the BECS process description

Melillo et al. [14] worked on fugitive emissions associated with land use changes, both direct and indirect, in the production of biofuels from bioenergy. Direct fugitive emissions are those that are linked to the production, such as emissions due to the use of fertilizer, equipments etc. on the land. These are the emissions that are considered in the work here. Indirect emissions are linked to changing land practices, for example change of a wetland to a crop land. Such land use changes could result in significant carbon emissions. However, indirect emissions are excluded from the scope of this work, but would need to be considered in any actual project.

Switchgrass has been used as the biomass in this work and the plant considered is an IGCC biomass fired power plant. The details of the calculation can be found in Ranjan, 2010 [11]. Avoided cost of the process is calculated by the equation below:

$$Avoided\ Cost\left(\frac{\$}{tCO2}\right)$$

$$= \frac{Cost\ of\ Electricity\ for\ a\ capture\ plant - Cost\ of\ carbon\ free\ electricity}{(CO2\ emitted\ by\ the\ plant - CO2\ emitted\ in\ the\ life\ cycle\ of\ capture\ plant)} \tag{3}$$

Figure 4 shows the calculated avoided cost for a range of fugitive emissions. The graph for the avoided cost shows the exponential increase in cost numbers as the fugitive emissions rises, as a percentage of the total plant emissions.

The calculated land area required for the case of a 500 MW biomass capture plant, with a thermal efficiency of 22%, is roughly 1016 square miles. This land is calculated for the case of 90% capture of the plant's CO_2 emissions. The land area required to capture and store 1 Gt of CO_2 through this route is 203,125 square miles, which is a third more than the land area of California.

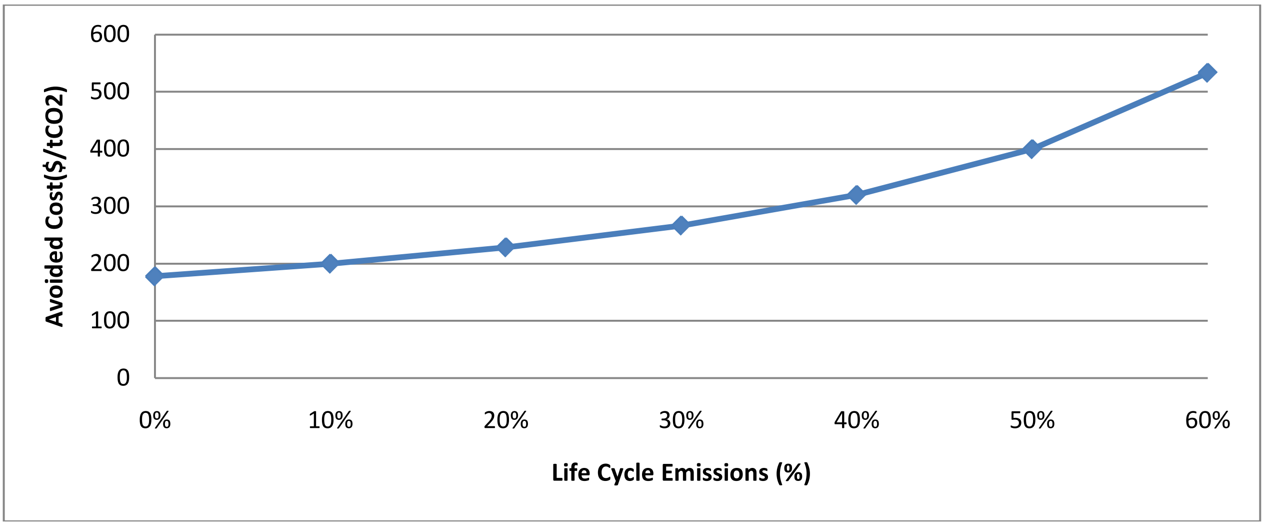

Figure 3 Avoided Cost curve for the BECS process as a function of fugitive emissions

Though at the high end, the cost of the BECS process is in the range where it can compete with climate change mitigation technologies under consideration today. However, the major issue comes in the land requirement, especially for widespread application of this technology.

Variance in the input values to the model built here can challenge the results shown above. Hence, sensitivity analyses were performed to account for the spread in values in literature. These are shown in Figures 5-8.

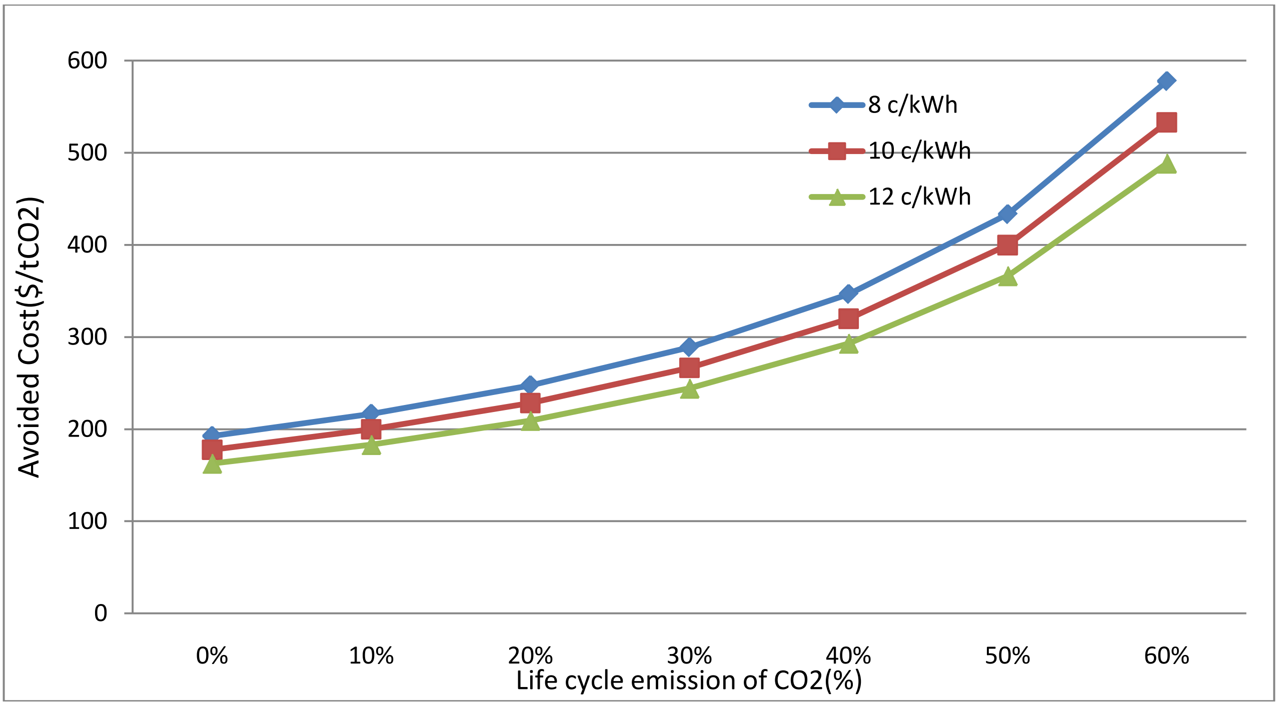

Figure 5 Sensitivity of avoided cost to the cost of carbon-free electricity (base case = 10¢/kWh)

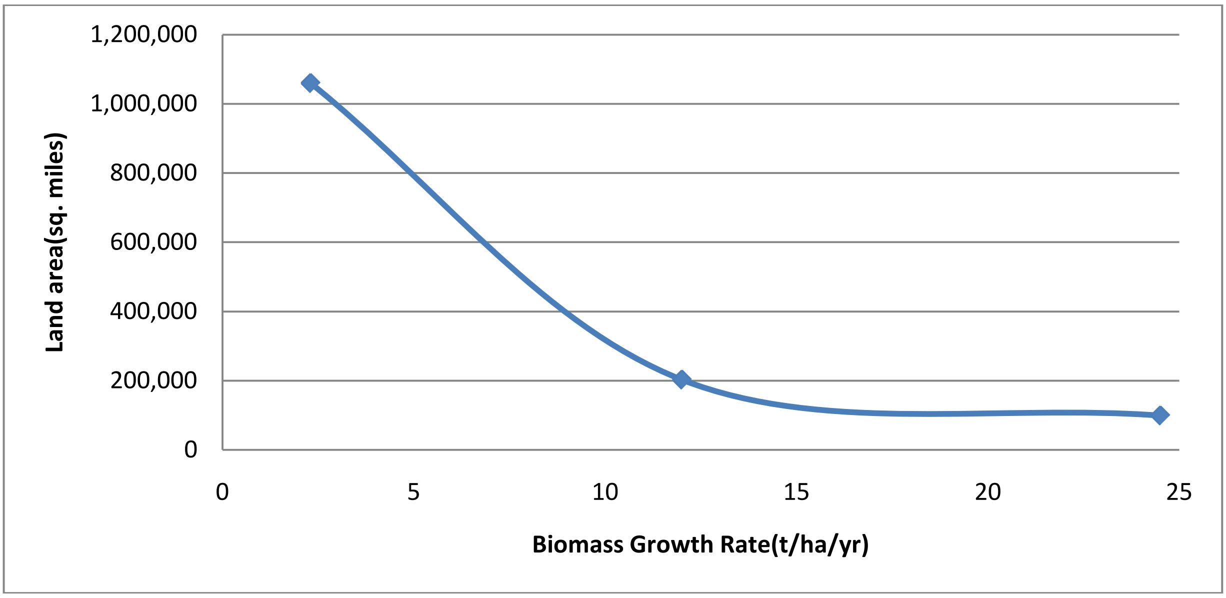

Figure 6 Sensitivity of the land area required to capture 1 Gt CO_2/yr to the biomass growth rate (base case = 12t/ha/yr)

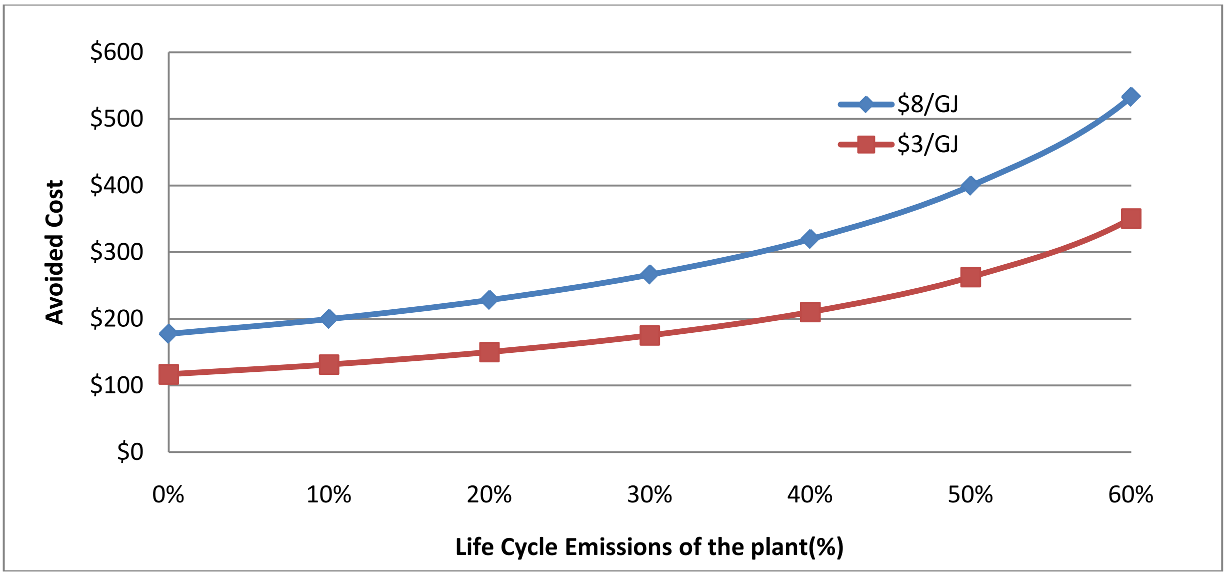

Figure 7 Sensitivity of avoided cost to the cost of biomass (base case = $8/GJ)

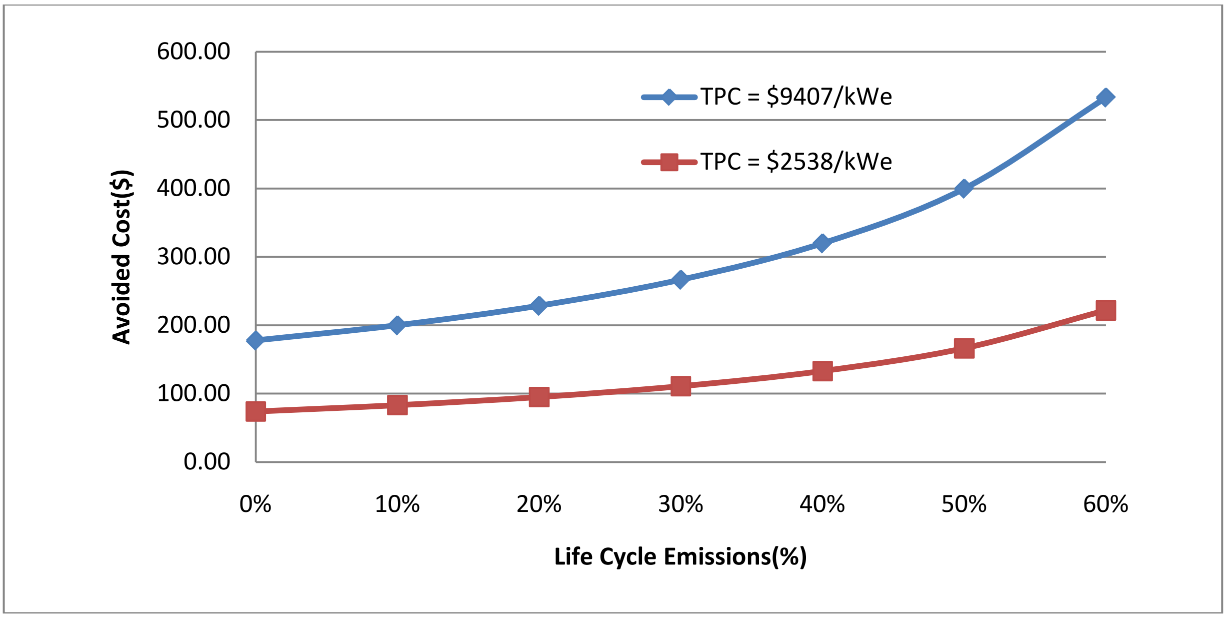

Figure 8 Sensitivity of avoided cost to the capital cost of the BECS plant (base case = $9407/kW$_e$). A capital cost as low as $2538 was found in the literature [15].

7. Conclusion: Role for air capture

While air capture looks “seductive” on paper, this paper raises issues about its practicality, especially its cost. Estimates of $100/tC ($27/tCO_2) to $500/tC ($136/tCO_2) found in the literature for direct air capture are just not believable. Absent a technological breakthrough that departs from humankind’s accumulated experience with dilute gas separation, direct air capture is unlikely to be a serious mitigation option until the price on CO_2 is measured in thousands of dollars per tonne of CO_2.

It would be a stretch to believe that the climate policy of the future should be favorable towards such a costly technology. We cannot agree on climate policies today that involve much cheaper mitigation options. The way direct air capture is being promoted, it also runs the risk of creating a moral hazard. It is reported in literature, both scientific and mass media, that air capture can mitigate all the carbon emissions seamlessly. This deludes us into thinking we don’t have to face the climate change issue because we always will have air capture as a way out. This enables us to continue business as usual and not make the investments required to move to a lower carbon energy system.

Air capture technology via the BECS approach may be useful as an offsetting option. It could be used to offset emissions from a particular sector, which would be very costly to mitigate otherwise. The transport sector is usually highlighted as a key target. The automobile sector is not the best target because there are other potential ways to reduce emissions from this sector, through the use of biofuels, hybrid vehicles etc. Also, the magnitude of the offsets would be too large for BECS due to the land requirements. However, the aviation sector may be a good fit. Switching fuels in the aviation sector may not be a technically or economically feasible option and air capture can be useful here as an offset.

8. Acknowledgements

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References

[1] "Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change" (2007) Intergovernmental Panel on Climate Change, Fourth Assessment Report.

[2] US Energy Information Administration (2009) "International Energy Outlook 2009". Available at http://www.eia.doe.gov/oiaf/ieo/index.html

[3] Keith, David (2009) "Why Capture CO_2 from the atmosphere?" Science 325, 1654-1655, 25 September, 2009.

[4] Lackner, K.S. (2009) "Capture of Carbon Dioxide from ambient air" The European Physical Journal Special Topics 176, 93-106.

[5] IPCC special report (2000) "Land Use, Land Use Change and Forestry", Cambridge University Press.

[6] Sherwood, T. K. (1959) "Mass Transfer Between Phases", Phi Lambda Upsilon, Thirty-third annual Priestly Lectures.

[7] Hamilton, M.R., Herzog, H.J., Parsons, J.E. (2008) "Cost and U.S. public policy for new coal power plants with carbon capture and sequestration." Energy Procedia.

[8] Lackner, K.S., Grimes,P., Ziock, Hans-J. (1999) "Capturing Carbon Dioxide from Air" Sourcebook 57(9), 6-20.

[9] Keith, David W., Ha-Duong, Minh (2006) "Climate Strategy with CO_2 Capture from Air." Climatic Change 74, 17-45.

[10] Heinrich, J.J. (2003) "CO_2 capture from Air – Current Practices" Publication No. LFEE 2003- 001 WP, Massachusetts Institute of Technology, Cambridge, MA, USA.

[11] Ranjan, M., (2010), "Feasibility of Air Capture", MIT Masters Thesis. Available at http://sequestration.mit.edu/pdf/ManyaRanjan_Thesis_June2010.pdf

[12] Baciocchi, R., Storti, G., Mazzotti, M. (2006) "Process Design and Energy Requirements for the Capture of Carbon Dioxide from air" Chem. Eng. Process. 45, 1047-1058.

[13] EIA (2009) *Annual Energy Outlook 2009*.

[14] Melillo, J. M., Reilly, J. M., Kicklighter, D. W., Gurgel, A. C., Cronin, T. W., Paltsev, S., Felzer, B. S., Wang, X., Sokolov, A. P., Schlosser, C. A. (2009) "Indirect Emissions from Biofuels: How Important?" Science 326, 1397-1399.

[15] Larson, E.D., Jin, H., Celik, F.E., (2009) "Performance and cost analysis of future, commercially mature gasification-based electric power generation from switchgrass" Biofuels, Bioprod. Bioref. **3**,142 - 173