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High-level techno-economic assessment of negative emissions technologies

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ABSTRACT

This paper presents results from research conducted to provide a high level techno-economic and performance assessments of various emerging technologies for capturing CO_2 from the air, directly and indirectly, on a life-cycle basis. The technologies assessed include 'artificial trees', the soda lime process, augmented ocean disposal, biochar and bio-energy with carbon capture and storage.

These technologies are subjected to quantitative and qualitative analyses, based on the most recent peer reviewed data in the literature, to identify their potential performance as well as the technical and non-technical barriers to their adoption and scale up. Key findings for each technology are presented which seek to highlight the state of technological development and research needs, the anticipated life cycle capture cost in $/t$CO_2$ based on their potential to deliver a 0.1 ppm CO_2 reduction per annum, policy requirements for scale up and, in light of these findings, the likely role that they will play in addressing climate change and broader environmental issues in the medium to long term.

The key finding from the work is that the degree of scale-up required for negative emissions technologies to have a material impact on atmospheric emissions (i.e. at a ppm level) is probably unrealistic in less than 20 years. Therefore, emissions prevention efforts should remain the main focus in addressing climate change and the likely role for negative emissions technologies will be in augmenting a suite of mitigation measures targeting economically or practically difficult emissions.

Keywords: Techno-economic; Artificial trees; Soda lime; Augmented ocean disposal; Biochar; Bio-energy with carbon capture and storage

1. Introduction

Carbon dioxide (CO_2) is a persistent atmospheric gas, and it seems increasingly likely that concentrations of CO_2 and other greenhouse gases in the atmosphere will overshoot targets of "safe" levels (e.g. the 450 ppm target set as the tolerable level of atmospheric concentration (IPCC, 2007)). Limiting cumulative CO_2 emissions, therefore, is key if global temperature rises are to be kept below the 2 °C above pre-industrial levels target (Allen et al., 2009). Hence, in the future, it may become necessary to remove CO_2 from the atmosphere.

This paper deals with the practicalities of certain classes of negative emissions technologies and addresses the likely energy, economic, environmental and policy implications of the use of specific technologies. The main objectives of the paper are to introduce the concept and its relevance to climate change mitigation, to describe and evaluate alternative technologies, and to estimate likely costs and other performance measures. A range of options have been identified, which are at various stages of development. The paper presents the output from an initial scoping study, which aims to provide consistent performance and cost estimates on feasible options for capturing CO_2 from the air, as well as identify the scale at which these technologies could eventually remove CO_2. The study is based around case studies of five different technologies, which have been chosen because they exemplify alternative strategies for achieving negative emissions: artificial trees; the soda/lime process; augmented ocean disposal;

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biochar; and biomass energy with carbon capture and storage (BECCS). The review does not consider reduced emissions from deforestation and forest degradation plus enhanced forest carbon stocks (REDD+), but this is nonetheless important and should be considered within a suite of mitigation measures.

The analysis is not based on original research, but rather is based on data available from a literature survey combined with judgement and engineering calculations of the over-arching costs and technical feasibility. In this way, the performance and cost of different technologies have been compared using a consistent methodology. Furthermore, the technologies' negative emissions credentials have been tested based on a full life cycle assessment without benchmarking to a reference fuel. Additional details of data sources, coefficients and calculations are available in a more detailed version of this report (McGlashan et al., 2010). Though an assessment of the robustness of claims made in the literature has been undertaken, as many questions remain unanswered in the literature, there remain key uncertainties, gaps and considerable further work is required in certain areas. The conclusions should therefore be regarded as preliminary and subject to revision in the light of further research.

Our particular choice of exemplar technologies is not intended to be an endorsement of any one approach or for that matter of the principal architects of the technology. However, when selecting the methodologies, those areas and techniques supported by peer reviewed articles and other sources of data were favoured. For each technology, energy and equipment costs are assessed and in later sections of the report, the rollout potential for each method is examined. In addition the research and development work deemed necessary before each technology can be considered viable is also discussed.

2. Technology overview

2.1. *Artificial trees*

An "artificial tree" is a device that mimics the processes used by biological plant life to withdraw CO_2 from the atmosphere. In nature plants combine CO_2 from the atmosphere with water from their sap biochemically forming various hydro and oxy-hydrocarbons. However, in the case of artificial trees, the output from the 'tree' is a stream of essentially pure CO_2 at high pressure, ready for sequestration.

The key proponent of artificial trees to date has been Klaus Lackner (Lackner, 2002, 2009). Lackner's trees are passive devices at the air capture phase (i.e. no energy input is required for the capture of CO_2) that present to the atmosphere a large surface area of CO_2 absorbing material – akin to the leaves of natural trees. Wind drives a current of CO_2 laden air across an absorbent surface so that mass transfer of CO_2 to the absorbent takes place. The sorbent, over time, becomes saturated with CO_2 and must be regenerated. Lackner (2009) developed an absorbent that can be regenerated by simple rehydration; soaking the saturated sorbent with water results in it releasing a portion of the CO_2 chemically bound to it. This process must be done in a sealed chamber held at reduced pressure. After regeneration, the sorbent can be re-exposed to the air where it first dries, and then absorbs another tranche of CO_2 from the atmosphere. It is claimed that this absorption/stripping cycle can be repeated many thousands of times without degradation of the sorbent and experiments have confirmed this on laboratory scale. All that remains is to dehydrate and compress the CO_2 released in the regeneration chamber ready for transport to the sequestration site.

A feature of Lackner's trees, therefore, is that the only significant energy requirement is the electricity needed to drive the gas compressors. Some heat input is required in the regeneration process, but this could be supplied from heat recovery in the CO_2 compression process. However, due to the dehydration step, a process that contributes to the overall energy balance of the system, the devices require a significant amount of water, which may limit the application of artificial trees to non-arid regions.

2.2. *Lime/soda process*

The lime–soda process is similar to artificial trees, but uses active (i.e. energy input required to move the absorbent for the capture of CO_2) rather than passive CO_2 capture. The process has been examined by a number of authors (Pfeffer et al., 2011; Zeeman, 2001; Stolaroff, 2006; Kruger, 2010; Stolaroff et al., 2008). In the process an alkali absorbent – aqueous sodium hydroxide – is brought into contact with the atmosphere using a conventional scrubbing tower arrangement – see Fig. 1. In the design shown, the downward flow of alkali solution in the tower is used to entrain air, which, therefore, is scrubbed in a co-flow arrangement. The output from the tower is an alkali/carbonate solution carrying absorbed CO_2, which can be regenerated in the causticiser, by reaction with lime (calcium containing inorganic material). This last step is the lime–soda reaction, which has been practiced since the 19th Century. Calcium carbonate precipitates in the reaction, leaving a liquor of sodium hydroxide solution, which can be reused for absorption in the scrubbing towers. The calcium carbonate, which precipitates as a fine powder of chalk, can be removed from solution continually by filtration. This powdered chalk is then converted back to lime using the calcination reaction in a rotary kiln similar to those used in the cement industry. The resulting lime clinker is then slaked to form calcium hydroxide and returned to the causticiser to regenerate more sodium carbonate. These process steps are repeated indefinitely and the internal reagents are continuously circulated within the process.

This cyclic process requires energy input in the lime kilns and to compress the CO_2 ready for pipeline transportation. However, because two chemical loops are embodied in the process the process offers thermodynamic advantages as each step in the process can be operated close to equilibrium. Although the process appears complicated, the overall effect is simply to generate a concentrated CO_2 stream from the very dilute CO_2 in the air. The output from the process is a stream of CO_2 generated in the calciner (operating at relatively high temperature), which, if fossil fuel fired, must have an associated CCS system of some kind to maximise the negative emissions of the overall system.

2.3. *Augmented ocean disposal*

Augmented ocean disposal ("ocean liming") works by decomposing (calcining) readily available minerals such as limestone, magnetite or dolomite, generating either calcium or magnesium oxides, or a mixture of the two (Kruger, 2010). This oxide mixture is then shipped to mid ocean and mixed with surface water, forming the respective hydroxide. The resulting slurry of hydroxide particles is then dispersed directly in the ocean on a large scale. This has the effect of lowering the pH of