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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 \$/tCO_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

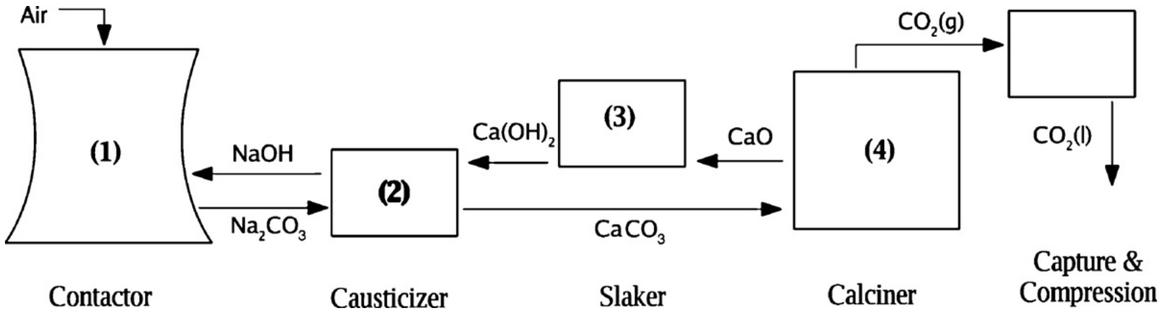

Fig. 1 – Proposed arrangement of equipment to implement lime–soda cycle (Keith et al., 2006).

the surface waters, which in turn leads to the rapid absorption of an almost equivalent quantity of CO_2 from the atmosphere. As with the lime/soda process there is a major energy input into the limekilns, but there is no need to compress the CO_2 as sequestration occurs in the ocean directly.

The overall effect of this process is two-fold: first a CO_2 absorbing agent is added to seawater which stabilises the CO_2 in a different chemical form, and second the pH of the seawater is raised – this allows the seawater to absorb more atmospheric CO_2 per unit volume and could help to tackle ocean acidification. Absorption of atmospheric CO_2 occurs rapidly, with predicted half-lives for the hydroxide ions of a few months (Candy et al., 2007). Critically for the economics of the process, due to the chemistry of bicarbonate formation, for each molecule of oxide released into the ocean, an estimated 1.7 molecules of CO_2 is absorbed from the atmosphere (Kheshgi, 1995). Another important factor is the grain size of the particles in the slurry; the grain size must be such that the residence time of each particle in the surface layers of the ocean is maximised.

The technology involves two industrial activities that require significant energy inputs. Firstly, the production of calcined oxide in a process akin to, but at lower temperature than modern day cement production. This involves the heating of mineral carbonates to high temperature in kilns. If this heat is generated by burning fossil fuels, CCS equipment must be installed to ensure the overall process has the maximum negative emission impact. Work input is also required for rock crushing and post kiln grinding operations, but this is relatively small part of the energy balance when compared to the calcinations. Traditionally, low grade, high ash fuels have been applicable in cement production, but to avoid the potential hazard associated with heavy metal contamination of the oceans, clean fuels (i.e. low ash and sulphur content) such as natural gas, some fuel oils and biomass would be optimal for this process.

The second large-scale activity is the transport of the raw minerals prior to calcination on land and, more problematic, the transport and dispersion of an unprecedented amount of material on the sea. If conducted at scale to reduce atmospheric levels of CO_2 of the order of ppm, logistically the transport, slaking and dispersion step will require a fleet of vessels similar in size to the aggregate world shipping fleet, the building of which represents a major hurdle to technology rollout.

2.4. *Biochar*

Biochar involves the production of enriched carbon biomaterial by combusting biomass in a low oxygen environment in a process called slow pyrolysis. Due to the fact biomass fixes CO_2 which was once in the atmosphere as stable, solid carbon in the biochar it is a form of negative emissions technology. The slow pyrolysis process generates a carbon rich char and a small amount of two by-products – one gaseous and the other liquid. The char can be land filled or used to enrich agricultural land – effectively fixing carbon previously absorbed from the air (Lehmann et al., 2006; Brownsort, 2009; Downie et al., 2007).

Advocates of biochar state that the process could generate a potential carbon sink of 1 $GtCO_2$/year by 2030 UKBRC (UKBRC, 2008/2009) rising to 5.5–9.5 $GtCO_2$/year by 2100 (Gaunt and Lehmann, 2008). For the UK, upper bound estimates suggest that between 5.7 and 8.0 $MtCO_2$/year could be sequestered (Wallage et al., 2009).

Biochar contains a carbon content of between 60% and 90% (Guar and Reed, 1995). The carbon is fixed though a fraction is relatively mobile (termed the labile and super-labile fractions) which for the sake of calculations is considered instantaneously released. Most of the remainder will mineralise eventually (over a period of 100–1000 years) and a very small proportion is inorganic (ash – i.e. permanently fixed). Char can be used as a source of fuel or for soil amendment. It is claimed that adding biochar to the soil has the added benefit of increasing crop yields due to improvements in soil quality and water retention and also can act as a substitute for man-made nitrate fertilisers. Pyrolytic liquids (bio-oils) and synthesis gas or syngas is the gas product of pyrolysis can both be used for generating heat, power or chemicals – the extent of these uses is at various stages of development.

Phases in the biochar life cycle where CO_2 may be sequestered/avoided are:

- Avoided emissions from substitution of bio-oil/syngas for fossil fuels;
- Stabilisation and storage of carbon in biochar; and
- The reduction in agricultural emissions due to reduced fertiliser usage.

2.5. *Biomass energy with carbon capture and storage (BECCS)*

BECCS involves the direct or co-combustion of biomass fuels in a conventional power plant fitted with CCS. By growing biomass such as trees and plants, CO_2 is drawn from the atmosphere by the photosynthesis process in plants. This biomass is then harvested, stored, dried, and normally processed into to pellets, bales or chips. This raw fuel is then transported to the biomass power plant, where it can be used to generate power. The power plant may be completely or partly fired with biomass as the source of fuel. Assuming CCS is installed at those plants which capture the carbon released

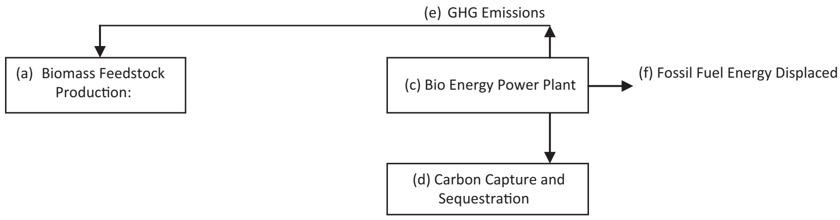

Fig. 2 – Concept diagram for BECCS.

during the burning of the biomass, a significant proportion (approximately 90% – though dependent on the economics of carbon sequestration) of the CO_2 released in combustion can be captured and sequestered. BECCS plants therefore have the potential to generate negative emissions of CO_2 through net removal of carbon from the atmosphere. Without CCS, the technology becomes a low carbon process rather than a carbon negative one. The potential of this technology is becoming recognised by many agencies such as the UK Energy Technology Institute who are undertaking related research projects. Fig. 2 is a simple schematic showing the main carbon and energy flows in the process.

Of the case study technologies considered in this report, BECCS has the greatest technology maturity and could be introduced relatively easily in today's energy system. The presence of a main saleable product (e.g. electricity from a biomass fired power plant) also contributes to making this an attractive option for removing CO_2 from the air. It is also important, however, that BECCS will require appropriate policy support and integration with general CCS deployment strategies for significant commercial-scale deployment to occur. The availability of substantial accessible supplies of sustainable biomass without impacting on eco-system services and food production is also important (Slade et al., 2011) – see below.

3. Energy and capital cost

As with most carbon abatement technologies, there are both financial and energy costs associated with the implementation of negative emissions technologies. In addition, the operation of some of the technologies requires a significant amount of material – both fuel and mineral inputs. Hence, life cycle costs must be included in the analysis of the efficacy of each technology.

For the purposes of this report, a standard benchmark has been used to enable comparisons to be made between the very different methods and also other carbon abatement systems. In this case, the logistics of rolling out each technology to the extent that a reduction of the concentration of CO_2 in the atmosphere by 0.1 ppm (per annum) is achieved is used. This is equivalent to withdrawing 0.781 Gt of CO_2 from the atmosphere. Table 1 shows the energy, equipment and materials requirement to achieve this reduction, and also gives an estimate of the life cycle capture cost in $/t$CO_2$ based on the most recent peer reviewed data in the literature.

Where these estimates have been possible they are based on the assumption of using natural gas to generate both the electricity and the heat required by each process. It was assumed that an amine (chemical absorbent) based post-combustion scrubbing system with 90% capture efficiency was used to capture CO_2 emitted either in electricity or heat production. The resulting price for electricity (work) input is $0.0194/MJ and the price for heat is $0.004/MJ (2010 basis).

The capital cost of plant is more difficult to determine. In this work, the estimates of capital cost made by the advocates of the technologies have been adopted or the most recent estimates in the literature. These prices have been amortised assuming a discount rate of 5% with a 10-year payback period.

From our initial analyses of the cost estimates (based primarily on peer reviewed resources), negative emissions technologies appear to be broadly competitive with other CCS technologies. These emerging findings indicate there is the technical potential for CO_2 abatement at prices below $200/t$CO_2$, and the potential is there for below $100/t$CO_2$. However, these numbers carry a strong warning – some of these technologies are at the very early stages of development and more research is needed on barriers and costs from development to implementation. See Annex 1 for the caveats to the cost calculations.

3.1. *Artificial trees*

The figures in Table 1 for artificial trees are based on Lackner's estimate that the long term cost of a 500 m^2 tree will be around $20,000 and that each tree could absorb 10 tCO_2/day – 15 days of annual maintenance are assumed. As Table 1 shows artificial trees, at least if the proponent's cost claims are accepted, are competitive economically with many other carbon abatement methodologies. Hence, assuming a water source is available, the trees can be located in any geographic location where there is a source of (low carbon) electricity. Indeed, the trees are ideal consumers of electricity generated by 'intermittent energy sources' such as wind turbines.

The only other requirement when choosing a suitable site for the trees is that some means must be available for transporting the pure CO_2 stream generated by them. A disadvantage of artificial trees is that a relatively large exposed area is required. As a result a typical artificial tree installation (many 100s) will cover a large land area and there is an associated planning risk. The scope to scale up the size of the units to reduce the land area impact is not known and could be considered a specific area for future research once many other more fundamental issues have been assessed – see above.

3.2. *Soda lime*

As for artificial trees, compression of the CO_2 generated in the calcination process represents a major energy input along with the heat necessary in calcination itself – typically conducted at ca 900 °C. However, an advantage of the process is that the calcination can be completed on an industrial scale. Nonetheless, the energy requirements for this technology are significant. Table 1 shows the energy, equipment and materials requirement to achieve the benchmark 0.1 ppm/year reduction in atmospheric CO_2. The energy figures are the best case estimates of Baciocchi et al. (2006), whereas the capital cost estimates are based on the work of Keith et al. (2006).

Table 1 – Summary table of energy, raw material and capital costs for technologies reviewed – 0.1 ppm per annum target.

Item	Artificial trees			Soda lime			Augmented ocean disposal			Biochar			BECCS		
		0.1 ppm	$/tCO_2$		0.1 ppm	$/tCO_2$		0.1 ppm	$/tCO_2$		0.1 ppm	$/tCO_2$		0.1 ppm	$/tCO_2$
Energy															
Heat (GWe)		28.2	22.1		39.6	31.1		9.4	7.38		360.2	282.8[a]		102.2	80.2[a]
Work (GW)		N/A	N/A		148.6	24.0		123	19.9		–	–		–	–
Material	Water	NK[b]	Minimal	Limestone	Minimal	Minimal	Limestone/dolomite	0.76 Mt	Minimal	Biomass[c]	2.6 Bt	301.4	Biomass[c]	0.64 Bt	86.9
Equipment	Trees	0.21 M	72.4	Absorption units	200	99.0	Limekilns	1	61.6	Pyrolysis 200 t/day	37,000	115.5	1 GW plant	~125	52.1–104.2
							Bulk carriers	1	2.2						
Total cost		~95			~155			~90			~135		~59–111		

Notes:
[a] Revenue from electricity is based on price input for electricity at $0.0194/MJ.
[b] Not known.
[c] Biomass including transport costs.

More recent work by American Physical Society (Socolow et al., 2011) appears to have excessive capital equipment prices and has been discounted in this work.

This technology is more expensive than other air capture options, but it benefits from the fact that all of the processes are well understood; the processes have been enacted on a large scale by either the chemical or cement industries. Hence, there is minimal technological risk and the cost estimates are likely to be more accurate. In addition, unlike artificial trees, the specific size of each unit is low, but the process can also be conducted on large scale. Hence, relatively few, large capacity scrubbing systems are needed. To minimise transport cost of process streams, these units could be located usefully adjacent to the calcination works. Raw material costs are also low as the process steps merely circulate sodium and calcium compounds. One potential problem is that water is lost form the scrubbing towers due to humidification of the air flowing through them and this may restrict the locations where the towers can be sited.

3.3. *Augmented ocean disposal*

These figures for Augmented Ocean Disposal are based on the analysis conducted by McGlashan et al. (2010). This technology is cost effective and has the advantage of employing existing technology. However, a clear issue is the risk to the environment caused by such a major intervention into the natural balance of the ocean ecosystem. This issue requires further research. Further, the process breaks a number of extant international protocols prohibiting 'ocean dumping'. These protocols, specifically the London Convention, would need to be reviewed substantially, before the process could be enacted at anything other than a pilot scale. This is, however, not without precedent as conventions have been amended for CO_2 storage in the oceans.

3.4. *Biochar and BECCS*

The cost calculations for Biochar and BECCS were based on the most recent estimates of costs within a potential large-scale pyrolysis/biochar and BECCS value chain.

The costs for large-scale production should in theory be offset by the possible sale of biochar as a fertiliser substitute. Whether it would be sufficiently effective to act as a substitute for nitrate based fertilisers on a tonne for tonne basis is not presently known. What is evident is that if biochar is even moderately effective as a substitute, produced on this scale, the fertiliser market would be saturated to the point that the price of biochar would be substantially lower than conventional fertilizers. However, the benefits to ecosystem services – if these were priced – could be substantial.

The costs of producing biochar using the large number of small scale pyrolysis stoves works out at approximately 11.54 $/tCO_2$ and is more efficient relative to the large scale system on a negative emissions produced per unit biomass basis. This is due to the GHG impact of the supply chain being removed from the value chain, however, the ability to capture syngas for its energy potential is lost. Furthermore, even if the 2.6 billion portion of the world population who use traditional biomass were to be issued with a slow pyrolysis stove the ppm impact would be limited at between 0.15 and 0.015 ppm per annum.

From our initial comparison of the current technologies under consideration, the deployment of Biomass enhanced

CCS (BECCS) in the UK has the most immediate 'negative emissions' potential – with a negative emissions capacity equivalent to at least 10% of current UK CO_2 emissions by 2030 utilising domestically sourced biomass. Because the primary purpose is power generation and negative emission is a by-product, BECCS does not need the same level of policy support as technologies purely for negative emissions. However, there are limits in scope given the finite amount of biomass that can be economically and sustainably generated in the UK (or imported with low lifecycle GHG emissions), and a full life cycle analysis is needed to understand the impact of large scale biomass plantation development on wider ecosystem services and soil organic carbon emissions from direct and indirect land use changes. Full lifecycle analyses such as this

Table 2 – Rollout potential and limitations of each of the exemplar technologies.

	Rollout and limitations on potential
Artificial trees	• Electricity demand of the trees represents the biggest obstacle to rollout closely followed by the need for abundant supplies of water. Although the trees can consume electricity 'off-peak' it is likely that new generating capacity would be required for a substantial rollout of the technology. Nonetheless, building dedicated additional generation capacity is achievable in principle, especially if the trees are built adjacent to dedicated wind turbines. • Land usage is not a restriction even in a populated country such as the UK. Each 500 m^2 tree and associated equipment occupies a relatively small area and the number of units is not large. • As with all other CCS techniques the pure CO_2, generated must be disposed of in geological sinks. However, as this technology is comparable in energy input to existing CCS, the storage requirements will be similar. • For these reasons, the only major limitation on the potential of the technology is financial.
Soda/lime process	• The energy requirement is substantial for this technology, as both electricity and heat demand (at 900 °C) are high. In particular, the calcination step requires the use of high heating value fuels. • The high heat requirement of the technology, unlike artificial trees it is necessary to burn fuel (and probably fossil fuels) in the limekilns. As a result, additional CO_2 sink capacity, and this may limit the technology's long-term potential. However, the contactors can be placed in close proximity and the estimated footprint is ca. 2 hectares per 28 $MtCO_2$/year unit. Hence land usage is not a major restriction.
Augmented ocean disposal	• Roll out limitation principally determined by the rate at which both limekilns and the bulk carriers required to ship CaO/MgO at sea can be built. There appear to be no limitations due to the availability of source mineral – i.e. limestone/dolomite (USGS, 2009). • The only benchmark for the rate of escalation of lime production is the comparable build up in recent years in China where from 2000 to 2006 production increased at a rate of 0.25 Gt/year. Given that this rate of increase could be enhanced by international collaboration, it is likely that rollout of this technology can be achieved within a sensible timescale. • Transport at sea is the main bottleneck. The principle limitation is the rate at which large ships can be built this is limited by available yard capacity, which is not readily increased. This problem is acute if the technology is adopted internationally as countries will then compete for limited shipbuilding resource.
Bio-based technologies – general	• The scalability of bio-based negative emissions technologies is dependent on global biomass potential (and its allocation to other competing sectors) and logistical considerations for large-scale biomass supply chains. Issues of global potential and logistical considerations for large-scale biomass feedstock supply chains are discussed below. • The availability, allocation, efficiency and sustainability of biomass production have a strong bearing on the scale and efficiency of biochar and BECCS as a negative emissions technology. The lower the emissions in biomass development and processing the more efficient the process. • The scales of development to have a material impact on global levels of emissions are substantial. For examples, the amounts of biomass needed supply BECCS and biochar to attain 1 ppm reduction in CO_2 are of the order of 6–7 and 26–27 Bt, respectively. This compares to the coal industry which presently extracts around 6–7 Bt pa.
Biochar	• The process technology can be rolled out rapidly on a small, non-capital intensive scale which suggests that the process lends itself to farmers, small landowners and local authorities in developed nations and in developing nations will assist in rural diversification and poverty alleviation (UKBRC, 2008/2009). • Should a more centralised approach be taken the scalability of the slow pyrolysis process technology is at present is only at the development stage with a capacity of 2628 t per annum. • Such is the nascent state of pyrolysis technological development there is no precedent available for the build rates of pyrolysis plants though the size of the charcoal industry which is the closest similar industry is approximately 41 Mt per annum (FAO Stat, 2009) meaning that to attain 0.1 ppm would require a scale up of over 63 times present charcoal production capacity. • The interaction of the char with different soils (i.e. the capacity to utilise biochar for soil remediation/enhancement and the impact on mean residence times (MRT)), i.e. carbon sequestration – needs to be better understood in order to better quantify the extent of negative emissions generated.
BECCS	• After biomass availability (see above), the scalability of BECCS as a negative emissions process technology is heavily dependent on the development and roll out of carbon capture and storage technology, availability of a CO_2 piping network and storage capacity for CO_2 though the ability to retro-fit power stations alleviates the need to write off plant before the end of their useful lives. • In terms of precedent for the roll out of dedicated BECCS plant build rates, in 2007 the Chinese – a rapidly developing economy – installed over 90 GW of coal capacity and in the UK – a liberalised energy market – between 1991 and 2004, during the so called 'dash for gas' period of power generation expansion over 20 GW of gas power plant capacity was added in the UK; this translates into a rate of approximately 1.5–2 GW/year. This suggests that it will take a roll out over a period of 14 and 600 years to attain the capacity to remove 1 ppm from the atmosphere in respective situations.

remains challenging, but are essential prior to full scale roll-out. However, in terms of the technology itself, there are no significant technological challenges for BECCS and demonstration and commercial plants could be developed in the short to medium term.

Apart from BECCS, the initial cost estimates for other direct negative emissions technologies included in the study, such as artificial trees, are not prohibitive, but have yet to be shown to be achievable. Estimates of energy costs also appear reasonable – 1 ppm global contribution per annum would require less than 2% of current global electricity demand. However, negative emissions technologies require a large surface area of absorbent to be exposed to the atmosphere or large areas of biomass production. Thus if the methodology involves a

Table 3 – Summary of the technological challenges faced for each of the exemplar technologies.

	Feature/technical challenges
Negative emissions – general	Though the authors have attempted to assess costs for all the technologies reviewed with the most up to date material this is an area where further work needs to be undertaken as it has a bearing on the economic role of the technologies within a portfolio of mitigation technologies (IMechE, 2011). There is also the general need for research on negative emissions technologies in the following key areas: • How to engage the public (Corner and Pidgeon, 2010; Orr et al., 2011; IAGP[a]). • How best to establish governance (Royal Society, 2009). • Development of policy for scale up and assessment of their role in the interaction with existing laws and conventions (Bracmort et al., 2011). • Their impact on existing and role in future international agreements (Barrett, 2008) and agree a set of standards on how to measure, monitor, report and verify (MRV) the effectiveness of different negative emissions technologies.
Artificial trees	• *Sorbent technology to improve thermodynamic efficiency*. Reducing the heat of reaction between CO_2 and sorbent simultaneously reduces the energy loss during absorption and the energy input required to regenerate the absorbent. To achieve this, novel sorbent technologies need to be developed in future. • *Mechanical design to cope with intermittent operation*. A particular area of concern may well be the development of liquefaction systems suitable for intermittent operation as artificial trees are likely to be low rank users of primary energy.
Soda/lime process	• *Sorbent technology to reduce energy input for regeneration process*. Significant thermodynamic improvements can be achieved by the development of novel sorbent types. Sorbent regeneration processes and systems would further enhance process energy needs. • *Scrubbing tower design*. Enhancing the tower configuration to balance process needs whilst reducing the size and hence cost and footprint of the towers.
Augmented ocean disposal	• *CaO/MgO production optimised for process*. Present assessments are based on cement technology but cement requires much higher temperatures than is strictly necessary to calcine limestone or dolomite. There is scope to optimise the process. • *Limekiln CCS technology*. Implementing CCS on limekilns is already an active area of research due, principally, to the interest of the cement industry. This would improve the CO_2 balance of the process. • *Transportation*. Building a suitable transport infrastructure to ship the calcined product to mid ocean remains a major hurdle before this technology can be implemented in practice. • *Biological effects*. This technology involves a major intervention in the chemistry of surface ocean waters, and on a global scale. Before this technology can be implanted, therefore, detailed studies including local pilot studies would need to be carried out.
Bio-based technologies – general	For process technologies that utilise biomass there is an over-arching need to assess the sustainable biomass potential, economics, best allocation and logistical value chain optimisation of biomass within a whole system assessment of the role of bio-energy within the wider energy system. Within this framework the allocation of biomass to negative emissions technologies can be identified. Research in the ability to avoid the negative impacts of biomass production on water availability, soil quality, biodiversity and ecosystem services, soil organic carbon emissions from indirect land use change (ILUC) is also needed. Indeed, this work may be extended to the effective production of biomass to enhance the negative emissions profile for all biomass production chains. There is work being undertaken suggesting that where best practice biomass production practices are employed land may be used as a carbon sink whilst producing biomass (Lal, 2009).
Biochar	• *Pyrolysis and scale up of slow pyrolysis process*. Influence of slow pyrolysis process (in terms of temperature and duration at each temperature) on biochar yield and stability is poorly understood. There is a lack of dominant design for slow pyrolysis. • *Mean residence time of char*. Mean Residence Time (MRT) of the carbon in char is fundamental (>1000 years) to its sequestration and negative emissions potential yet its behaviour is poorly understood and the impact of different soil conditions on its behaviour even less so. • *Effects of char on soil*. Effects on soil properties and productivity are poorly understood. • *Most efficient use of char*. The economics of utilising Char has value as a fuel or as a soil enhancement product is highly contextual.
BECCS	• *Roll out of CCS technology, infrastructure and storage capacity for CO_2*. The realisation of CCS at scale, the establishment of an infrastructure for CO_2 transport and storage capacity for CO_2 are technical factors that are relevant to CCS as a whole as much as they are to BECCS. • *Integration of biomass combustion with CCS technology*. Research to assess the impacts of the combustion of coal, co-firing of coal with biomass and dedicated biomass on the flue gas produced and therefore the efficiency of the CCS technology needs to be undertaken to understand if there are any serious issues in this area.

[a] Integrated assessment of geo-engineering proposals: http://www.iagp.ac.uk/.

machine of some kind, the combined area of the devices must be very large. Practically this would mean that a large number of small, distributed units would have to be installed. The actual number of individual units depends on technology approach chosen, but for artificial trees, we could need around 1.5 million units to capture 10% of annual UK CO_2 emissions. Care will need to be take in the location of these since access to low carbon power and a CO_2 transport system or sink, as well as possibly water, will be needed.

4. Scalability and rollout potential

Looking at negative emissions technologies in general, regardless of the mix of technologies adopted, to capture a significant amount of CO_2 requires a large surface area of 'absorbent' to be exposed to the atmosphere. This in turn means that either a great deal of plant/machinery must be erected; or, in the case of BECSS or biochar, a great deal of land used to generate the required biomass.

In Table 2 the scalability and rollout potential of each technology is summarised. In addition limitations on the potential, both in the short and long term are examined.

There are also a number of non-technical issues which need to be assessed regarding the general deployment of negative emissions technologies. These are described in areas for further research below. Furthermore, with regards the bio-based technologies there are a number of additional issues which are worth being aware of. The issues include the global biomass potential (Slade et al., 2011; Berndes et al., 2003; Dornburg et al., 2008; Smeets et al., 2007; IEA, 2009) the development of supply chains (Heinimö and Junginger, 2009) and international trade, benefits of large scale biomass for energy/negative emissions production (Doornbosch and Steenblik, 2007; Murphy et al., 2010; Lynd and Woods, 2011) and land use change impacts (Searchinger et al., 2008; Fargione et al., 2008; Oladosu et al., 2011; Kim and Dale, 2011; Kim et al., 2009; Galbraith, 2005; Foley et al., 2011; Lynd and Woods, 2011) – these are substantial topics in themselves and further detail can be found in the references cited.

4.1. *Role of the development of carbon capture and storage and negative emissions technologies*

Though the development of CCS has been discussed with regards to its role in BECCS the need for the ability to develop and adopt the technology for three of the other four options we investigated (air capture, lime soda, augmented ocean disposal) is also equally important. This is due to the fact that they are heavily dependent on the availability of a substantial capacity for carbon compression and storage which would be dependent on CCS infrastructure development. It is, therefore, critical for CCS to be successfully commercialised and deployed at scale for other negative emission technologies.

5. Research agenda

The research agenda of the negative emissions technologies discussed in this report are summarised in Table 3. The general needs for negative emissions technologies and bio-based technologies are also reviewed.

6. Conclusions

The findings from this work indicate that a mix of options to remove CO_2 from the atmosphere could be viable at a reasonable scale and a reasonable cost relative to mitigation technologies. These are based on exemplar technologies and there is still room for innovation in this sector. In the longer term this may allow a cap or series of caps on CO_2 emission trading/tax costs and support a rational carbon price by the technology setting a ceiling price for CO_2.

Some options, BECCS in particular, have the technological potential to make a significant contribution to emissions reductions by 2030, and are supported by an underlying economic rationale through the production of a useful product (electricity) and by energy security considerations. In general, we feel that technologies that offer a product in addition to carbon sequestration are more likely to be deployed early on. Other studies (e.g. undertaken by the Climate Change Committee (2011) and the Energy Technologies Institute (2011) also indicate the promise of this particular family of technologies and indicate that the important first step is to establish demonstration facilities for CCS upon which this technology can build. Nevertheless all the technologies could have a useful role to play as GHG reduction targets bite.

Overall, we found that the practical domestic potential exists for negative emissions amounting to about 10% of UK current emissions; this may provide significant flexibility in delivering long-term GHG reduction targets by offsetting emissions that are difficult to capture (e.g. from agriculture and transportation point sources).

Some other options may be viable in the longer term but will take longer to scale up – at least 20 years. The key advantage of some direct negative emissions devices is flexibility in location, which will be helpful to offset large CO_2 positive systems and will benefit from deployment in the most physically and geographically suitable areas (e.g. those enjoying CO_2 storage and/or a surplus of solar energy). Some of the options have potential significant environmental and related impacts (potentially both positive and negative) and these would need to be investigated in detail as an integrated part of the evaluation of these options.

A top priority going forward is more detailed research and analysis on the costs, systems engineering and other key performance measures (e.g. energy and water requirements) of the more forward looking technologies, to include R&D pilot and scale-up support, and proper life cycle analyses. This is essential if these technologies are going to be available in the timescales needed. If BECCS is to be considered part of the mix, appropriate policy support and integration with the general CCS strategy should be deliberated urgently. This should include some form of support for active CO_2 removal from the atmosphere, for which no formal credit systems operate (although there are voluntary offsets that support this).

The scale of development for these technologies required for them to have material impacts on atmospheric levels of CO_2 to be significant would, in many cases, result in the need for the development of supply chains in less than 20 years from an extremely low level or from scratch to the scale of many of the largest industries in existence today which have developed over centuries. This strongly implies that emission avoidance must still remain the main near term effort in terms of addressing climate change. Negative emissions technologies can be seen as an economically rational tool to augment mitigation efforts and prevent emissions trajectories overshoot within a portfolio of mitigation measures.

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Annex 1. Caveats on the cost calculations for the technologies reviewed in this paper

Artificial trees and the lime–soda process

- The capital cost of both artificial trees and the lime soda process, as quoted in this work, are those proposed in papers written in each case by one group. For a more accurate assessment of the technology to be made, independent, full and accurate costings are required.
- In published works on these technologies, no considerations have been made of the cost of purification of the collected CO_2. Although the CO_2 collected by these systems should be of high purity, removal of water and perhaps other contaminants will be required to avoid problems within the distribution network. Such purification will add significantly to the cost of each system.
- The cost of transport of high pressure CO_2 collected from a distributed network of collectors is likely to exceed the expected cost of transport from centralised collection points. Additional costs include the purchase for each at each site of: safety systems and insurance.
- The operating cost of both technologies will be highly dependent on the local cost of energy – principally electricity for artificial trees and fuel for the soda lime process.

Augmented ocean disposal

- Estimates for the cost of the two principle capital items for this process: the calcination plant and bulk carriers are based on existing best practice. At the scales required for the [process to be practical these may well turn out to be overestimates.
- No consideration has been made in this work of the potential cost savings due to the integration lime and power production in a calcium looping system. This would offer potential cost savings due to the incorporation of necessary carbon capture step into the process.

Biochar

- Costs for large scale slow pyrolysis plants are presently at the high end of the development curve, i.e. first of a kind and likely to fall so the figures here may be at the upper end of the scale – no attempt has been made to assess *N*th of a kind costs of large scale slow pyrolysis plants. The lack of accurate costs for feedstock is also an issue due to there being no existing on full-scale commercial development of this industry at present.
- The opportunity to produce energy from slow pyrolysis may be integral to the economics of large-scale value chain development. The relatively high levels of energy produced as a function of tCO_2 removed from the atmosphere is a function of the relatively low proportion of CO_2 stored as a function of energy produced and biomass input. For example, it takes nearly four times as much biomass to sequester a unit of CO_2 compared to BECCS.

BECCS

- The cost of CCS components, infrastructure and operations may be underestimated due to the lack of full scale commercial experience, knowledge with CCS systems and availability of accurately estimated data hence the range of costs for plant costs. The figures here are based on a new build of dedicated plant with CCS option rather than a retrofit to an existing plant option.
- With transport being the most reliable cost value and feedstock and CO_2 piping/storage costs being >50% of total costs and least reliable due to neither industries existing on full scale commercial development the figures are subject to substantial uncertainty.
- Costs of sequestering CO_2 from BECCS will be highly sensitive to the price of electricity which can fluctuate considerably, e.g. in the UK between 2007 and 2008 the base-load price for electricity varied between £29 MWh and £71 MWh.

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