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Negative Emissions Technologies

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Executive summary

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 the 450 ppm CO_2e target, widely seen as the upper limit of concentrations consistent with limiting the increase in global mean temperature from pre-industrial levels to around 2°C[1]. Limiting cumulative CO_2 emissions is therefore key to limiting the scale of human-induced climate change, and its impact on human wellbeing and the natural world. Hence, in the future, it may become necessary to remove CO_2 from the atmosphere. By capturing CO_2 from the air (directly or indirectly), historical CO_2 emissions can be sequestered and the aggregate amount of CO_2 in the atmosphere reduced, and if necessary, any modest overshoot can be rectified. The technologies that remove CO_2 emissions from the atmosphere are called negative emissions technologies (also known as carbon dioxide removal or CDR technologies).

A number of recent studies have emphasised that cumulative CO_2 emissions (i.e. total emissions over an extended period of time) are more significant than the particular emissions' pathway (i.e. when emissions peak and the rate at which they rise or fall) in determining how the global climate will change[2,3]. This suggests that effective measures to mitigate the risk of dangerous climate change will need to limit *cumulative* emissions of CO_2, which is another significant reason to explore and possibly deploy this family of technologies. Also, the importance in determining the magnitude of climate change impacts of the floor level to which CO_2 emissions tend after their peak in the first part of this century has been a topic of increasing discussion[4]. Technologies that involve 'negative emissions' could be used to offset additional anthropogenic emissions from sectors where greenhouse gas emissions are difficult or impossible to reduce beyond certain limits, such as certain agricultural processes or aviation.

In other analyses, the execution of a variety of least cost energy system optimisation models – i.e. models that seek to deliver the future energy system in the most economically efficient manner – have also demonstrated that as emissions limits start to bite, negative emissions technologies (usually

Contents

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bioenergy combined with carbon capture and storage) become important to "make room" in the economy for emissions which are difficult to mitigate[5].

Negative emissions technologies can be divided into those that directly remove CO_2 from the atmosphere (so-called "air capture" technologies) and those that remove emissions indirectly. The technologies can be further divided into those that store CO_2 as a fluid in geological formations and those that store it in a different stable form. We have chosen five exemplar technologies that are representative of the different options.

The five technologies selected for analysis are:

Direct Air Capture as exemplified by "*Artificial Trees*" is a technology that mimics the processes used by biological plant life to withdraw CO_2 from the atmosphere. In practice, each 'tree' absorbs CO_2 from the air using a special resin. Once saturated, the resin is transferred to a vacuum chamber close to the tree, where hydration results in the resin releasing the absorbed CO_2. A gas compressor is then used to compress the CO_2 from the low pressure of the vacuum chamber, to a high pressure suitable for distribution and storage via a Carbon transport network. An essential feature of the technology is that the main energy input for capture is the electrical power required to drive the CO_2 compressors.

The Lime-Soda process is similar to artificial trees, but uses a chemical scrubbing method to enhance CO_2 capture. Here an alkali absorbent – aqueous sodium hydroxide is brought into contact with the atmosphere using a conventional scrubbing tower arrangement. The resulting sodium carbonate solution is then converted back to sodium hydroxide by reaction with calcium hydroxide (lime) in the so-called soda/lime reaction. The lime can be generated in kilns similar to those used in the cement industry. Calcium carbonate precipitates in the reaction, leaving a liquor of sodium hydroxide solution, which can be reused for absorption in the scrubbing towers. This cyclical process requires energy input in the limekilns and to compress the CO_2 ready for pipeline transportation.

Augmented ocean disposal ("ocean liming") uses lime in oceans to trap CO_2 in a stable, dissolved inorganic form. Lime is generated using lime kilns and is then transported to mid-ocean using ships. The lime is then hydrated (otherwise known as slaking) and then released into the surface layers of the ocean where it reacts with CO_2 dissolved in the water. This has the effect of lowering the pH of the surface waters, helping to tackle surface ocean acidification, while also leading to the rapid absorption of an equivalent quantity of CO_2 from the atmosphere. As with the lime/soda process there is a major energy input into the lime kilns, but there is no need to compress the CO_2 as sequestration occurs in the ocean directly.

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 that 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 also produces a liquid and gaseous energy resource which can be used to substitute fossil fuel sources. Biochar can be used as a soil enhancer and therefore is a potential substitute for fossil fuel derived fertilisers.

Bioenergy with Carbon Capture and Storage (BECCS) is the combination of two mitigation options: biomass combustion to generate energy and Carbon Capture and Storage (CCS). Biomass can be used as the single fuel source for power generation (dedicated use) or in combination with conventional coal sources (co-fired generation). CCS refers to the suit of technologies developed to capture CO_2 gas from the exhausts of power stations and from other industrial sources, the infrastructure for handling and transporting CO_2, and the technologies for injecting and storing the CO_2 in deep geological formations. The fusing of these technologies can generate "negative emissions" by taking atmospheric CO_2 temporarily locked in plants and storing them permanently in geological formations; here energy is the main product and the negative emissions a by-product.

These technologies have been subjected to quantitative and qualitative analyses with a view to identifying their potential performance as well as barriers to their adoption. This Briefing Paper compares the technologies by benchmarking on the basis of their potential to deliver a 0.1 ppm CO_2 reduction per annum and an estimate of the life cycle capture cost (in $\$/tCO_2$) based on the most recent peer reviewed data in the literature. It should be noted that the literature on these emerging technologies is sparse and our analyses should be taken as indicative rather than definitive.

Our key findings include:

- That a wide variety of potential technologies exist for removing CO_2 from the atmosphere. Some of these have other, possibly primary, functions as well (for example, power generation or soil remediation) and could therefore be considered nearer to market deployment.
- That expected future mitigation costs are potentially in the range where deployment of negative emission technologies is feasible given projected future carbon costs. As a result, the cost of the cheapest, broadly applicable negative emissions technology could potentially establish a ceiling price (within supply constraint limits) for all carbon abatement technologies.
- That the technologies are at widely varying levels of development (for example, biochar is an ancient technology while artificial trees are at a very early stage of demonstration).

- There are substantial research needs for all the technologies reviewed with the need to confirm negative emissions potentials at larger scales on a full life cycle basis.
- Bioenergy with CCS appears to be the technology with the most immediate potential and pilot scale demonstrations to explore different system configurations are to be encouraged. Furthermore, two of the other four options we investigated (air capture and lime soda) are heavily dependent on the availability of a substantial capacity for carbon compression and storage which would be dependent on CCS infrastructure development. This underlies the importance of successfully commercializing and deploying CCS at scale for some negative emissions technologies to be a viable technological option.
- The degree of scale-up required for negative emissions technologies to have a material impact on atmospheric emissions (i.e. at a parts per million level) is substantial and probably unrealistic in a short period of time (less than 20 years). Therefore, mitigation efforts remain vital in limiting the risks of climate change. The likely role for negative emissions technologies will be in augmenting a suite of mitigation measures targeting economically or practically difficult emissions.

A number of concerns have been aired by some groups regarding the consideration of negative emissions technologies within the present climate change agenda – the most salient of these include:

- The potential for unintended environmental or even climate consequences in the large scale deployment of these technologies;
- That present costs are based on projections from non-commercial market price estimates – see Annex 1 – meaning that there is a substantial risk that negative emissions may not be cost competitive within a suite of mitigation options thereby negating their role on a least cost basis; and
- The issue of ‘moral hazard’. By giving policy makers the excuse for not developing effective mitigation programmes and low carbon technologies, less will be done to mitigate against climate change.

The final section of this paper takes into account these issues while discussing the scalability and limitations in roll out potential for each exemplar, policy and international context for negative emissions technologies, the importance of the development of CCS to realise or optimise many of the technologies and the research agenda for each type of technology. The culminating point being that it is highly recommended that there is governance framework for the future development and possible deployment of these technologies whilst engaging the public on the potential role that these they may play in the future climate change agenda.

Introduction

It seems increasingly likely that concentrations of CO_2 and other greenhouse gases (GHGs) in the atmosphere will overshoot the 450 ppm CO_2e target, widely seen as the upper limit of concentrations consistent with limiting the increase in global mean temperature from pre-industrial levels to around 2°C. Therefore, in the future, in order to correct for the overshoot it may become necessary to remove CO_2 from the atmosphere. This would be achieved by capturing CO_2 from the air; historical CO_2 emissions can then be sequestered and the aggregate amount of CO_2 in the atmosphere reduced – so-called negative emissions. From a UK perspective, a robust strategic plan is needed to achieve the UK target of an 80% reduction in GHG emissions on 1990 levels by 2050. Negative emission technologies ought to be considered as part of the technology mix needed to achieve these reductions at least cost.

This Briefing 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; 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 these strategies are nonetheless important and should be considered within a suite of mitigation measures. Furthermore, Solar Radiation Management (SRM) technologies, which aim to reduce the incident energy on the earth, are not included and raise significant additional issues and concerns.

The Paper is primarily based on a literature survey; thermodynamic and related calculations have been made and, in addition, an assessment of the robustness of claims made in the literature has been completed. In this way, the performance and cost of different technologies have been compared using a consistent methodology. Our analyses are based on sparse data, however, and should be taken as indicative rather than definitive. 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[6]. 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. As many questions remain unanswered in the literature, there remain key uncertainties and 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. The overall objective of this Briefing Paper is to familiarise readers with negative emissions technologies and their associated key performance measures.

Why Negative Emissions?

Removal of CO_2 from the atmosphere can be achieved using a number of technologies. Critically, when compared to traditional carbon abatement technologies most of these involve only a minor increase in the fraction of energy that must be dedicated to the negative emissions process for a fixed quantity of work output – otherwise known as energy penalty. This is a key point, as it may make the potential economics of deploying negative emissions technologies more attractive than some mitigation technologies, particularly when the flexibility that negative emissions technologies give are factored in. For example, there are a number of scenarios in which capturing CO_2 via negative emissions technologies might be the best or the only option, either locally or globally. These include:

- If, at some point in the future, atmospheric concentration of CO_2 has risen to such an extent that removing it from the atmosphere is the only way to avoid potential or actual catastrophic climate change then negative emissions technologies may allow the accumulated level of atmospheric CO_2 to be reduced at an enhanced rate, over and above natural processes or other mitigation technologies.
- Negative emissions technologies provide a potential way to capture short-term ‘excess’ emissions and reduce the amount of CO_2 in the atmosphere to achieve a particular target CO_2 concentration.
- Negative emissions technologies can be used where more established CCS methodologies are impractical or uneconomic to apply and yet some emissions reductions are nonetheless deemed imperative i.e. high emissions complexes that are not economic to tie into a CO_2 pipe network and storage system due to their remote disposition. Additionally, and more generally where decoupling emission sources from capture makes economic and geographic sense (e.g. where access to easy CO_2 storage or cheap or low carbon energy is available). This applies to many transport applications and especially air travel, but also for small to medium scale industrial processes that require the oxidation of fossil carbon inherently – e.g. the reduction of the ‘minor’ metals, where capture at the site is impractical.

Negative emissions technologies may therefore provide advantage in certain countries, isolated geographic locations, or when technological advances occur and one or more of these technologies becomes the cheapest option.

Negative emissions technology therefore has significant potential to collect CO_2 released from any source, at any time, using a device or devices that can be located anywhere. The cost of the cheapest, broadly applicable negative emissions technology could potentially establish a ceiling price for all carbon abatement technologies[7]. It is conceivable that negative emissions technologies could even represent an environmentally preferred option as they capture additional emissions compared to conventional mitigation technologies, and might be able to do so more cheaply than in some ‘difficult’ sectors where conventional mitigation might be more expensive. This was the case with SOx emissions permits whose cost was limited by the cost of flue gas desulphurisation technology[8].

Technology Overview

Negative emissions technologies all involve the absorption of CO_2 at low concentration from the rest of the atmosphere. This absorption takes place naturally during photosynthesis and biomass conversion, while negative emissions technologies employ an ‘industrial’ process of some kind to achieve the absorption. Absorption of gases on an industrial scale can be conducted using one of only a few methodologies. These include: membrane separation, selective condensation, and physical or chemical scrubbing.

Membrane separation and selective condensation are unlikely to be economic for air capture, due to the low concentration of CO_2 in the atmosphere and the small-scale nature of these technologies. However, CO_2 is an acidic gas and therefore it reacts readily with alkali chemical bases of all kinds. There are already a number of alkali scrubbing agents used in industry to remove CO_2 from gas streams. Hence, alkali scrubbing is potentially a viable air capture methodology and all the proposed industrial negative emissions technologies rely on scrubbing in some way. This may be by using simple scrubbing agents such as sodium hydroxide in a scrubbing tower, or calcium hydroxide dissolved in sea water.

Biomass based systems fix CO_2 from the atmosphere by the process of photosynthesis and then require a conversion process, which involves capture and storage or locking of the CO_2 via the combustion of the plant matter. This ensures that a material proportion of the CO_2 is not returned later in the process life cycle.

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.

Box 1: Taxonomy of CCS and Negative Emissions Technologies

Chalmers and Gibbins[9] categorised carbon capture systems into three distinct classes, of which Class 3 was further subdivided by McGlashan et al[6] to describe specific negative emission technologies, thus:

Class 1 systems are those that are carbon positive, despite the addition of CCS technology.

Class 2 systems are those that are near carbon neutral i.e. utilise regular CCS to capture high proportions (more than 90%) of CO_2.

Class 3 systems are those that are (potentially) carbon negative which can be further subdivided thus:

- **Class 3A systems** are those that capture CO_2 directly from the air.
  - Class 3AA systems **where CO_2 is compressed for geological storage**. These methods can be viewed as a subset of traditional post-combustion CCS technology as they all use some form of chemical scrubbing system. The apparatus performing the scrubbing can be either passive, relying principally on wind to effect mass transport of air across an absorbent; or use a more traditional scrubbing/spray tower where air is entrained by a falling liquid or slurry based sorbent. The key costs of these technologies relate to the desorption, compression, transportation and injection into a geological sink of the CO_2 collected initially in the sorbent. A number of suggested configurations have been proposed but, in all cases, three principle steps are enacted:

    a) **The absorption of CO_2 by a chemical sorbent exposed to the atmosphere.** Many potential sorbents exist and by careful selection this process can be made spontaneous – i.e. without energy addition.

    b) **The stripping of CO_2 from the sorbent.** Energy is required to achieve this, either as heat or work input required to produce a pressure swing. The outputs from the stripping section are a stream of CO_2 at low pressure and a regenerated sorbent capable of absorbing a further CO_2 from the atmosphere.

    c) **The compression of pure CO_2 to a high pressure suitable for sequestration.** The compression can be effected using conventional gas compressor technology.

    Two potential exemplar arrangements that embody the three steps above are examined in this review, namely: Artificial Trees and the Soda/Lime Process.

    These processes generally involve the industrial scale production of some kind of chemical scrubbing agent that is then added to the environment directly. As a consequence, if fossil fuel is used to fuel this large scale process, traditional CCS technology is still required.

  - An advantage of class 3AB systems is that the CO_2 extracted from the atmosphere does not require compression to high pressure (nor access to geological storage sites), and therefore, fundamentally, the energy required is lower than for comparable 3AA processes. The costs associated with transportation and injection of the much larger quantities of CO_2 associated with 3AA systems can also be reduced or even avoided altogether.

    Specific technologies that fall into this class and which are considered as illustrative examples for this review are augmented ocean disposal process and biochar.

- **Class 3B systems** are those that use biomass in a conventional CCS power plant of some kind – i.e. Biomass energy + CCS (BECCS).

Negative Emissions Technologies

Box 1 explains the taxonomy for CCS and negative emissions technologies. Within this classification system, this report considers only Class 3 systems, namely those capable of negative emissions. In the sections given below, exemplar technologies falling within each of the classes: 3AA, 3AB and 3B are discussed in detail. The five exemplar technologies described cover the three classes. For each technology, energy, equipment costs and environmental consequences 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.

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 – and water resource. Hence, life cycle costs must be included in the analysis of the efficacy of each technology.

For the purposes of this report, in the technology reviews below, 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 per annum[10]. A summary table is included for each technology that gives the energy, material and capital equipment requirement to achieve the 0.1ppm per annum benchmark, based on an instantaneous cost calculated for continuous deployment over a year, and also gives an estimate of the life cycle capture cost in $/$tCO_2$ based on the most recent peer reviewed data in the literature. The total cost of extracting sufficient CO_2 to reduce atmospheric concentrations by 0.1 ppm relative to nominal global GDP in 2010 is also quoted.

Where these estimates have been possible they are based on the assumption that natural gas is used 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. For consistency across technologies, 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/tCO_2, and possibly for below \$100/tCO_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.

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 – by 2030 at least 10% of the UK's current CO_2 emissions could be abated utilising domestically sourced biomass. Because the primary purpose is power generation and negative emissions 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 – including food production – and soil organic carbon emissions from direct and indirect land use changes. Full lifecycle analyses such as this remains challenging, but are essential prior to full scale roll-out – see Box 2. However, in terms of the technology itself, there are no significant technological challenges for BECCS, beyond those facing CCS, and demonstration and commercial plants could be developed in the short to medium term. It is worth noting that in the near term, the use of biomass to displace fossil fuels will have a similar mitigation potential as BECCS because there is much scope for displacement. However once CCS becomes widespread and mitigation targets tight BECCS is likely to be required to achieve these targets. Furthermore, as described earlier, we may need such technologies to deal with overshoots. This indicates that CCS technologies should be developed with co-firing of biomass (in solid, liquid or gaseous forms) in mind.

Apart from BECCS, the initial cost estimates for other direct negative emissions technologies included in the study, such as artificial trees, also appear to be favourable but have yet to be validated on scale up. Estimates of energy costs also appear reasonable, a reduction of 1ppm 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 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 taken in the location of these since access to low carbon power and a CO_2 transport system or sink, as well as water, will be needed.

Direct Air Capture – Artificial Trees

There are multiple direct air capture technologies in development at present. The artificial tree concept was one of the early exemplars of the concept and is used for this review. Though representative of direct air capture technology it may not necessarily be the optimal system for this class of negative emissions technology.

An "artificial tree" is a device that mimics the processes used by biological plant life to absorb CO_2 from the atmosphere. In nature, plants combine CO_2 from the atmosphere with water from their sap chemically, 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[11]. Lackner's trees are essentially passive devices (i.e. no energy input required for the capture of CO_2) that present a large surface area of CO_2 absorbing material to the atmosphere – akin to the leaves of natural trees. Wind is used to drive 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[12] 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 (but not quantifiable based on the present literature) amount of water, which may limit the application of artificial trees to non-arid regions.

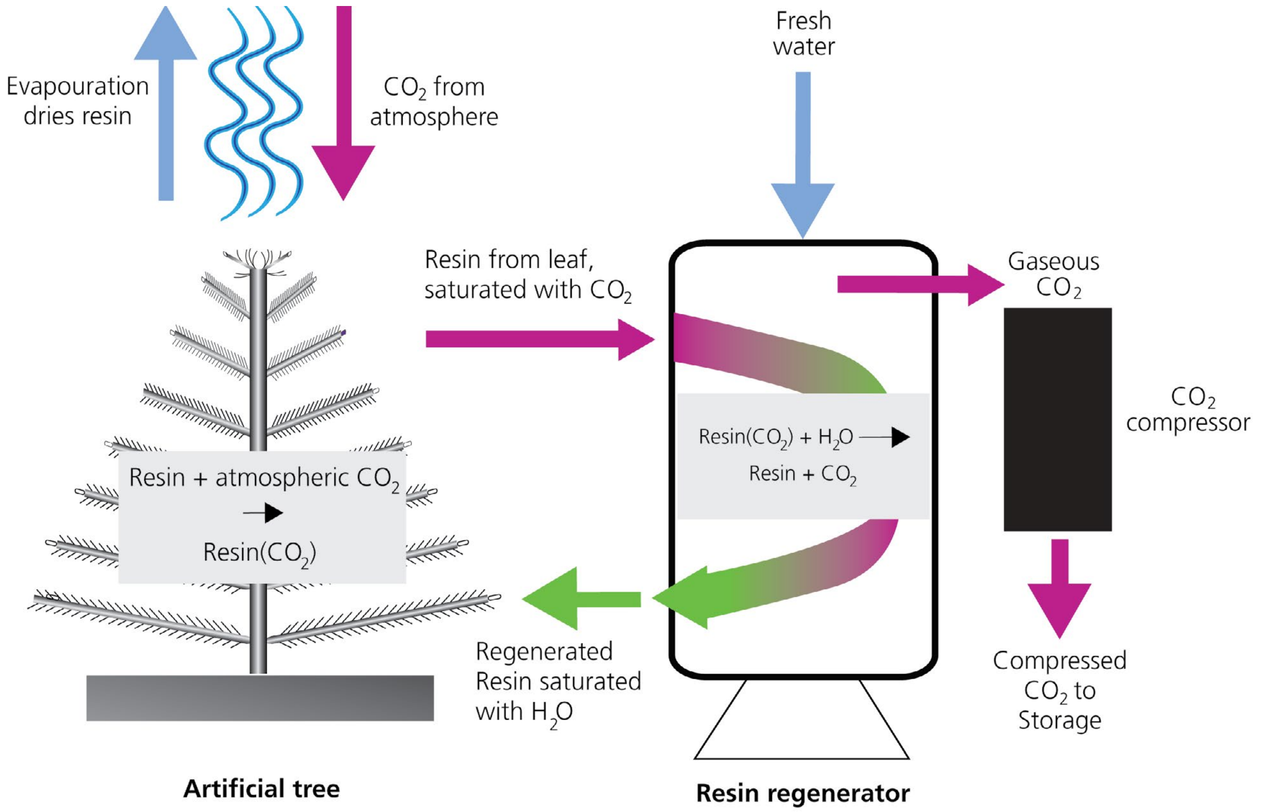

Figure 1. Proposed arrangement of artificial trees[11].

Table 1 shows the energy, equipment and materials requirement to achieve a 0.1 ppm annual reduction in atmospheric CO$_2$ using artificial trees. The table is based on Lackner's estimate that the long term cost of a 500m^2 tree will be around $20,000 and that each tree could absorb 10 tCO$_2$/day – 15 days of annual maintenance are assumed. It is worth emphasising that availability of comprehensive dis-aggregated costs for components of the system are lacking making these cost estimates indicative – further caveats to the cost calculations can be found in Annex 1.

Item	Amount/0.1 ppm CO$_2$	Cost
Energy		
Work	**28.2 GWe**	**22.1 $/tCO$_2$e**
Heat	**N/A**	**N/A**
Material		
Water	**Not known**	**Location dependant**
Equipment		
Tree units	**0.21 Million**	**72.4 $/tCO$_2$e**
	Total	**~95 $/tCO$_2$e**

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

The total cost of generating 0.1 ppm change in atmospheric GHG concentrations per annum would be US$ 78.3 Billion[#] the equivalent of approximately 0.1 – 0.12% of global nominal GDP in 2010.

As Table 1 shows, at ~95 $/tCO$_2$e, artificial trees (at least if the proponent's cost claims are accepted) are economically competitive with many other carbon abatement methodologies[7]. Hence, assuming a water source is available, the trees can be located in any geographic location where there is a source of (low carbon) electricity. Indeed, the trees are ideal consumers of electricity generated by 'intermittent energy sources' such as wind turbines. The only other requirement when choosing a suitable site for the trees is that some means must be available for transporting and storing the pure CO$_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 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 (Table 8).

[#] This is based on the logistics of rolling out each technology to the scale sufficient to extract sufficient CO$_2$ (0.781 Gt) to reduce atmospheric concentrations by 0.1ppm from the most recent peer reviewed data in the literature.

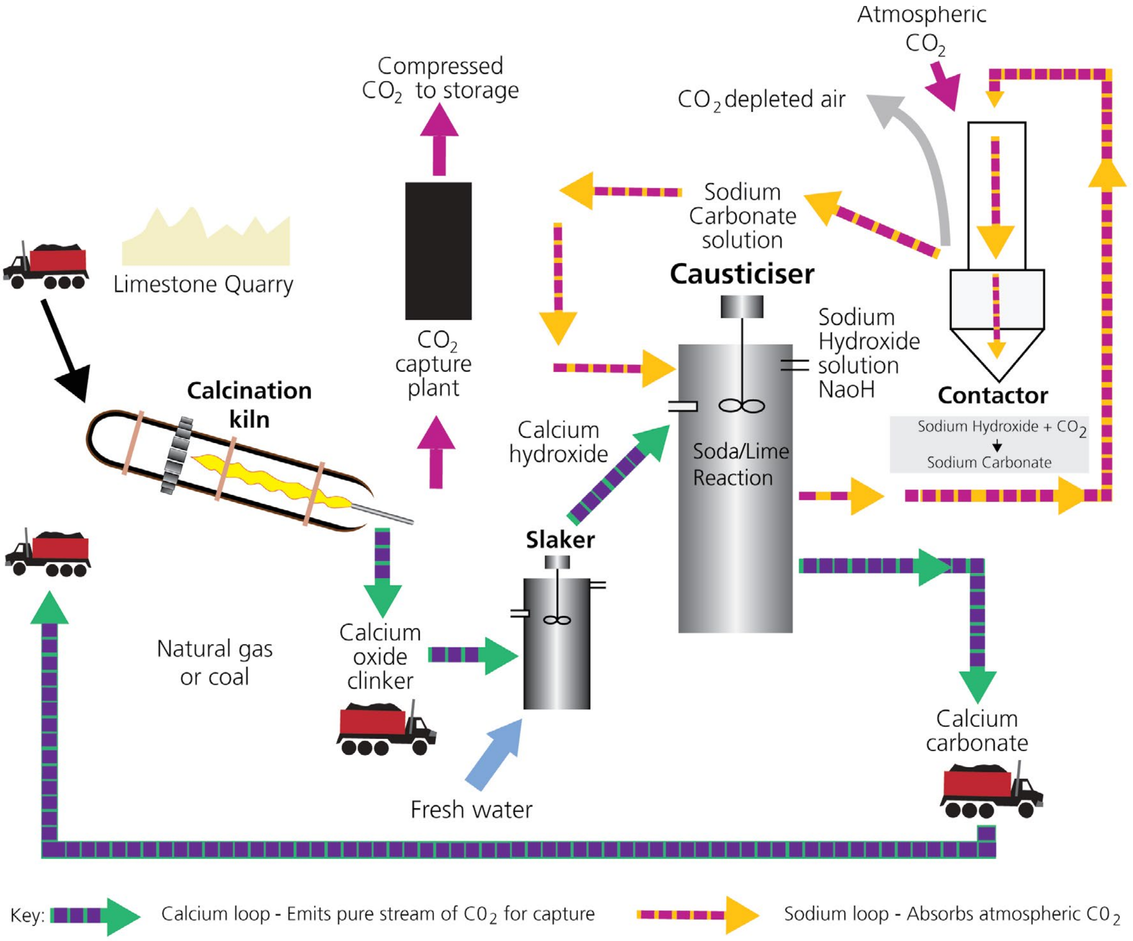

Figure 2. Proposed arrangement of equipment to implement the Lime-Soda cycle[18] which involves taking quarried limestone (Calcium Carbonate) and converting to lime.

Soda/Lime Process

The Soda/Lime process is similar to artificial trees but uses active (i.e. energy input required for the capture of CO_2) rather than passive CO_2 capture. Here an alkali absorbent – aqueous sodium hydroxide is brought into contact with the atmosphere using a conventional scrubbing tower arrangement[13,14,15,16,17]. The resulting sodium carbonate solution is then regenerated by reaction with lime (calcium oxide) in the so-called soda/lime reaction. The lime can be produced in kilns similar to those used in the cement industry. Calcium carbonate precipitates in the reaction, leaving a liquor of sodium hydroxide solution, which can be reused for absorption in the scrubbing towers. This cyclic process requires energy input, principally in the limekilns, to compress the CO_2 ready for pipeline transportation – see Figure 2. In the design shown, the downward flow of alkali solution 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 this case in a two-step process. Two chemical loops are embodied in the process and this offers thermodynamic advantages as each 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 internal reagents are continuously circulated within the process.

The underlying chemistry of the process consists of four reactions in two interlinked parts – one of which absorbs atmospheric CO_2 and the other emits pure stream for capture. The waste product from this process is calcium carbonate, which precipitates as a fine powder of chalk, and can 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 (but operating at lower temperature). 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. 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.

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 around 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 2 shows the energy, equipment and materials requirement to achieve the benchmark 0.1 ppm/yr reduction in atmospheric CO_2. The energy figures are the best case estimates of Baciocchi[19], whereas the capital cost estimates are based on the work of Keith[18]. More recent work by American Physical Society[13] appears to have excessive capital equipment prices and has been discounted in this work. Caveats to the cost calculations can be found in Annex 1.

Item	Amount/0.1ppm CO_2	Cost
Energy		
Work	**39.6 GWe**	**31.1 \$/tCO_2e**
Heat	**148.6 GW**	**24.0 \$/tCO_2e**
Material		
Limestone/Soda	**Minimal**	**Minimal**
Equipment		
Absorbtion units	**200 Units**	**99.0 \$/tCO_2e**
	Total	**~155 \$/tCO_2e**

Table 2. Summary table of energy, raw material and capital costs for lime/soda process – 0.1 ppm per annum target.

The total cost of generating 0.1ppm change in atmospheric GHG concentrations per annum would be US\$ 120 Billion[#] the equivalent of approximately 0.17 – 0.19% of global nominal GDP in 2010.

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 operated globally on large a scale by either the chemical or cement industries. Hence, there is minimal technological risk and the cost estimates are likely to be 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 from the scrubbing towers due to humidification of the air flowing through them and this may restrict the locations where the towers can be sited.

Augmented ocean disposal

Augmented ocean disposal ("ocean liming") uses lime (calcium oxide) in oceans to trap CO_2 in a stable mineral form. Lime is generated using lime kilns and is then transported to mid-ocean using ships. The lime is slaked (hydrated) and then released into the surface layers of the ocean where it reacts with CO_2 dissolved in the water. This has the effect of lowering the pH of the surface waters, which in turn leads to the rapid absorption of an equivalent quantity of CO_2 from the atmosphere. As with the lime/soda process there is a major energy input into the lime kilns, 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.

This process 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. This oxide mixture is then shipped to the 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 raising the pH of the ocean's surface waters, thereby increasing its capacity to absorb atmospheric CO_2. Absorption of atmospheric CO_2 occurs rapidly, with predicted half-lives for the hydroxide ions of a few months[20]. 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[21]. 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 sufficient to allow dissolution in the top 50 m of ocean. Figure 3 shows a schematic diagram of the process.

The technology involves two industrial activities. Firstly, the production of calcined oxide in a process akin to, but at a 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 – which can also capture emissions from the production of calcined oxide – 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 a 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. 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*. Note that the figures in Table 3 represent an instantaneous cost assuming year round deployment of the technology – hence the use of the units ship and lime kiln.

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*Though recent work by Rau suggests that this could be reduced by the deployment of an alternative technology using wet limestone scrubbing in seawater for flue gases with high concentrations of CO_2. The work by **Rau, G.H.**, 2010, *CO_2 mitigation via Capture and Chemical Conversion in Seawater. Environmental Science & Technology*, 45 (3), 1088-1092 suggests that this could be developed for point-source CO_2 capture and storage scheme at coastal locations.

[#] Same as for previous tables, see page 7.

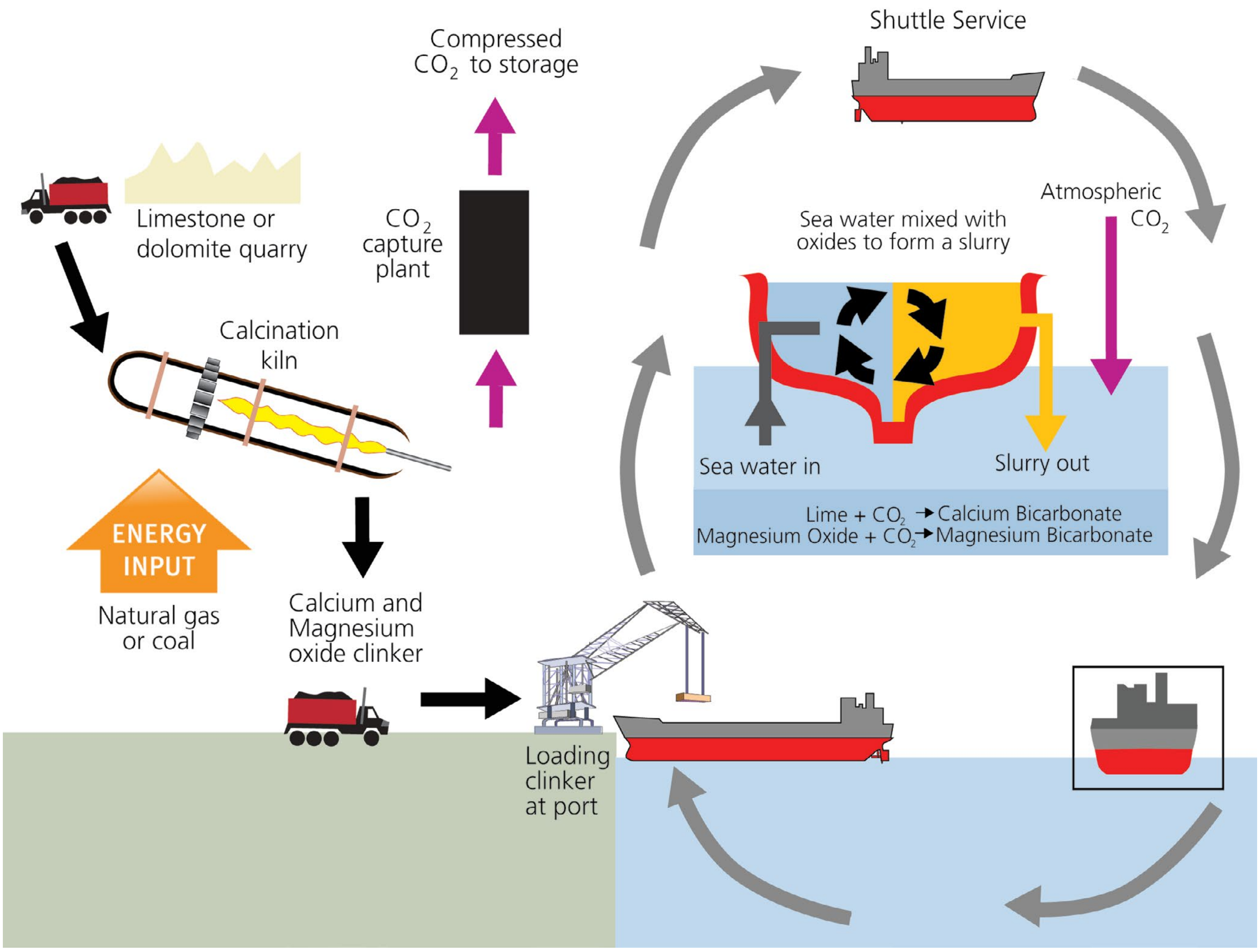

Figure 3. Proposed arrangement of augmented ocean disposal[16].

Table 3 shows the energy, equipment and materials requirement to achieve a 0.1 ppm/yr reduction in atmospheric CO_2 using Augmented Ocean Disposal. These figures are based on the analysis conducted by McGlashan et al.,[6] and were rechecked for this work.

Item	Amount/0.1 ppm CO_2	Cost
Energy		
Work	9.4 GWe	7.38 $/tCO_2e$
Heat	123 GW	19.9 $/tCO_2e$
Material		
Limestone/ Dolomite	0.76 Mte	Minimal
Equipment		
Lime kilns	1 Units	61.6 $/tCO_2e$
Bulk carriers	1 Ship	2.2 $/tCO_2e$
	Total	~90 $/tCO_2e$

Table 3. Summary table of energy, raw material and capital costs for Augmented Ocean Disposal process (0.1 ppm per annum reduction target).

The total cost of generating 0.1ppm change in atmospheric GHG concentrations per annum would be US$ 71.1 Billion[#] the equivalent of approximately 0.1 – 0.11% of global nominal GDP in 2010.

At ~90 $/tCO$_2$e, this technology is potentially cost effective as a negative emissions process 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 is currently at odds with a number of extant international protocols regarding ocean disposal. These protocols, specifically the London Convention[22], 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, and amendments are being proposed to allow small scale experiments.

[#] Same as for previous tables, see page 7.

Biochar

Biochar involves the production of enriched carbon bio-material by partially combusting biomass in a low oxygen environment in a process called slow pyrolysis. The slow pyrolysis process generates a carbon rich char and a small amount of by-product – 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. Due to the fact that 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. A concept diagram is shown in Figure 4.

Advocates of biochar state that the process could generate a potential carbon sink of 1 Gt_C/yr by 2030[26] rising to 5.5 to 9.5 Gt_C/yr by 2100[27]. For the UK, upper bound estimates suggest that between 5.7 and 8.0 Mt_C/yr could be sequestered[28]; though these are heavily dependent on Mean Residence Times of biochar which is highly uncertain.

Biochar contains a carbon content of between 60 to 90%[29]. 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 to 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[27] 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 fertilizers. 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 are 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 – called the Mean Residence Time – the effectiveness of which is poorly understood (see Table 8); and
- The reduction in agricultural emissions due to reduced fertilizer usage.

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

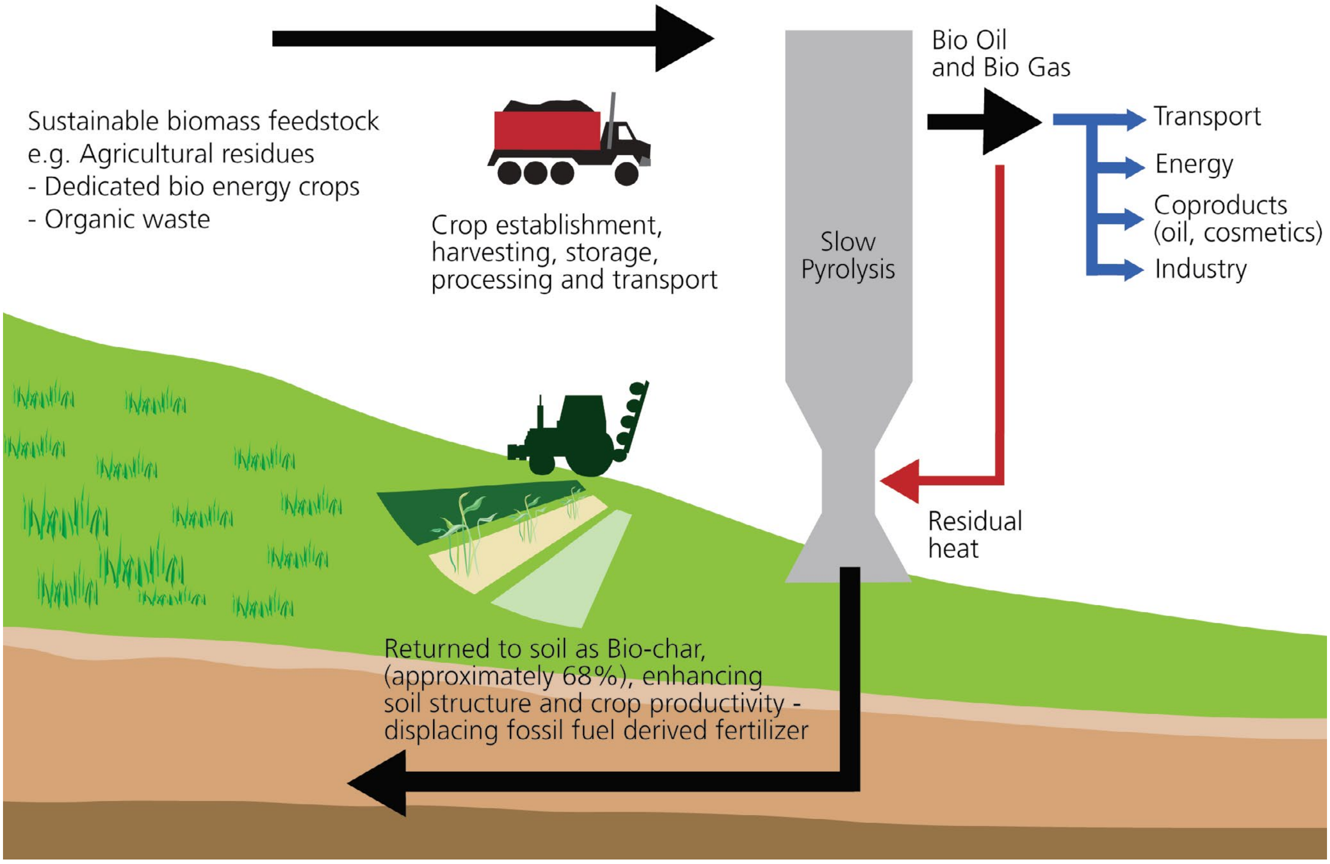

Figure 4. Concept diagram of biochar sequestration process from feedstock production to low-temperature (slow) pyrolysis and biochar application to enhance soil fertility[23,24,25].

Item	Amount/0.1 ppm CO_2	Cost
Energy		
Heat	360.2 GW	(282.8) $/t$CO_2$e
Material		
Biomass incl. transport	2.6 Bt	301.4 $/t$CO_2$e
Equipment		
Large Scale Slow Pyrolysis Plant (200 t/day)	~ 37,000 Units	115.5 $/t$CO_2$e
	Total	~135 $/t$CO_2$e

Table 4. Summary table of energy, raw material and capital costs for Biochar process (0.1 ppm per annum reduction target).

The total cost of generating 0.1ppm change in atmospheric GHG concentrations per annum would be US$ 104.7 Billion# the equivalent of approximately 0.15 – 0.17% of global nominal GDP in 2010. 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 would be substantially lower than conventional fertilisers to the point of having no sale value. However, the benefits to ecosystem services – if these were priced – could be substantial.

The above costs for producing biochar is based on a centralised, large scale biochar value chain. Biochar can also be deployed on a small scale, using a large number of small scale pyrolysis stoves. Costs based on this value chain work out at approximately 11.54 $/t$CO_2$e 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 to 0.015 ppm per annum. The availability, concerns and issues surrounding the large scale utilisation of biomass are addressed in Box 2.

Biomass Energy with Carbon Capture and Storage (BECCS)

BECCS involves the direct or co-combustion of biomass fuels (which could be in solid, liquid or gaseous form) 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 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 these plants which captures the carbon released 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 processes technology becomes a low carbon process rather than a carbon negative one – see Box 2. The potential of this technology is becoming recognised by many agencies such as the UK Energy Technology Institute who are undertaking related research projects. Figure 5 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 cost calculations below were based on the most recent estimates of costs within a potential BECCS value chain.

Item	Amount/0.1 ppm CO_2	Cost
Energy		
Heat	102.2 GWe	(80.2) $/t$CO_2$e
Material		
Biomass incl. transport	0.64 Bt	86.9 $/t$CO_2$e
Equipment		
1 GW Dedicated biomass plant w CCS	~ 125 Units	52.1-104.2 $/t$CO_2$e
	Total	~59-111 $/t$CO_2$e

Table 5. Summary table of energy, raw material and capital costs for BECCS process (0.1 ppm per annum reduction target).

The total cost of generating 0.1ppm change in atmospheric GHG concentrations per annum would be US$ 46 to 86.6 Billion# the equivalent of approximately 0.07 – 0.14% of global nominal GDP in 2010. The availability, concerns and issues surrounding the large scale utilisation of biomass is addressed in Box 2.

A summary of the costs on a $/t$CO_2$e basis for the different technologies reviewed is shown in Table 6.

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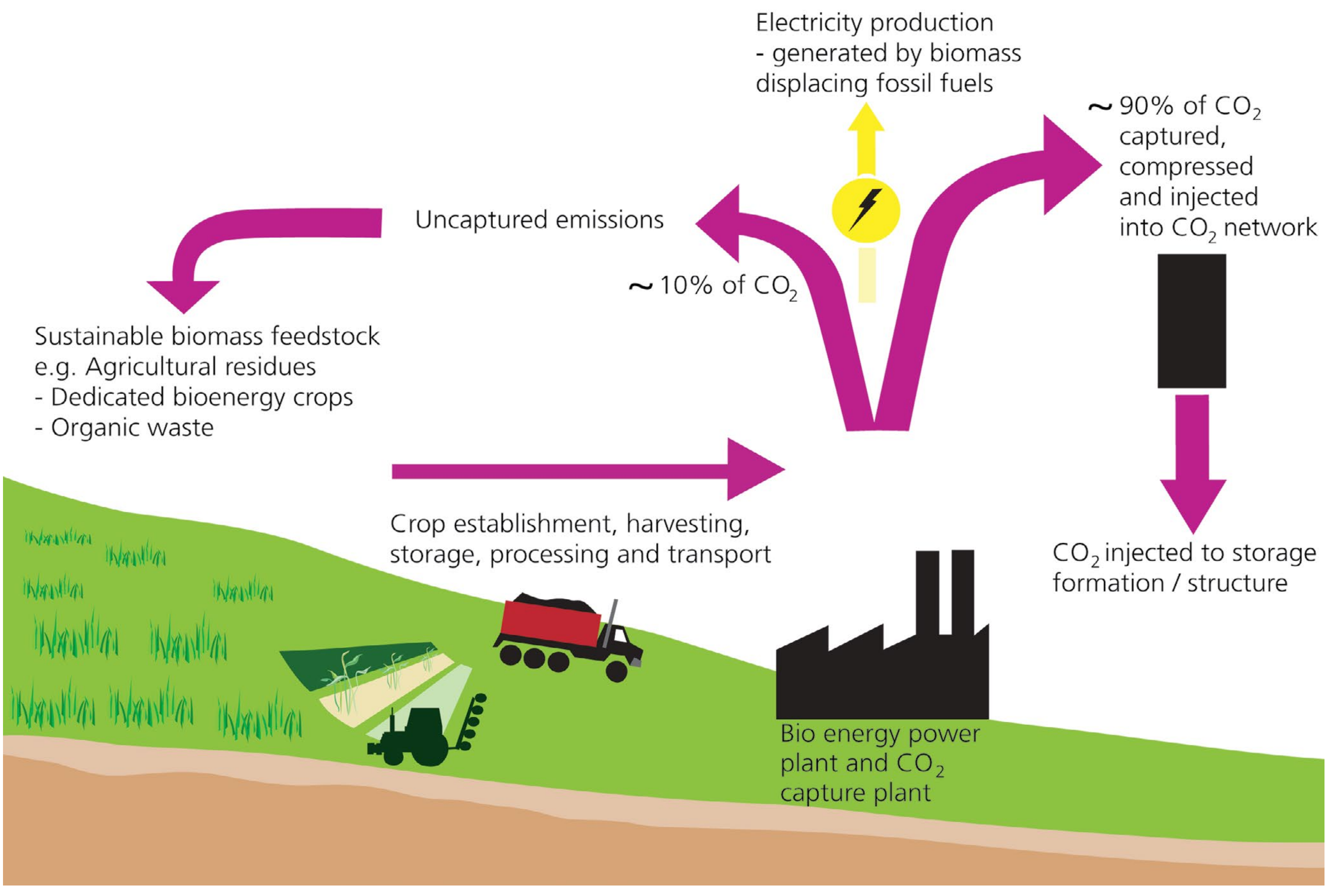

Figure 5. Concept diagram of the BECCS process from feedstock production to combustion to generate electricity and the sequestration of CO$_2$.

	Item	Energy		Material	Equipment		Total Costs
		Heat (GWe)	*Work (GW)*				
Artificial Trees				**Water**	**Trees**		
	0.1 ppm	28.2	N/A	NK[#]	0.21 M		
	$\$/\mathrm{tCO_2e}$	22.1	N/A	NK[#]	72.4		~95 $\$/\mathrm{tCO_2e}$
Soda Lime				**Limestone**	**Absorption Units**		
	0.1 ppm	39.6	148.6	minimal	200 units		
	$\$/\mathrm{tCO_2e}$	31.1	24	minimal	99		~155 $\$/\mathrm{tCO_2e}$
Augmented Ocean Disposal				**Limestone/ Dolomite**	**Lime Kilns**	**Bulk Carriers**	
	0.1 ppm	9.4	123	0.76 Mt	1 unit	1 ship	
	$\$/\mathrm{tCO_2e}$	7.38	19.9	minimal	61.6	2.2	~90 $\$/\mathrm{tCO_2e}$
Biochar				**Biomass***	**Pyrolysis 200 t/day**		
	0.1 ppm	360.2	–	2.6 Bt	37000 units		
	$\$/\mathrm{tCO_2e}$	–282.8	–	301.4	115.5		~135 $\$/\mathrm{tCO_2e}$
BECCS				**Biomass***	**1GW Plant**		
	0.1 ppm	102.2	–	0.64 Bt	~125 units		
	$\$/\mathrm{tCO_2e}$	–80.2	–	86.9	52.1 – 104.2		~59 – 111 $\$/\mathrm{tCO_2e}$

Table 6. Summary table of energy, raw material and capital costs for technologies reviewed – 0.1 ppm per annum target.

[#] Not Known

*Biomass including Transport costs

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 – see Box 2, section on biomass potential.

For type ‘3AA’ systems, i.e. those that place CO_2 emissions in geological storage, practically this would mean that a large number of small, distributed absorption units are needed. An advantage of this is that the production, installation and operation of many similar units will have clear economies of mass production although operating costs may be an issue. Nonetheless, the incremental cost of each unit is low allowing the gradual rollout of the technology operated by perhaps many different ‘negative emissions companies’. Installing many small units also has the advantages that they can be located adjacent to remote CO_2 sinks and use low carbon energy from sources that would otherwise be considered stranded or that generate primary energy in a manner unsuitable for other uses – e.g. fluctuating wind power.

However, in countries with strict planning systems, a system consisting of a small number of large capacity units has clear benefits. There are different economies of scale here, principally operating cost. Type 3B and 3AB systems fall into this bracket. 3A systems (BECCS) are likely to employ existing power plant (or at least new plant built on existing sites) and is therefore centralised inherently. Similarly, type ‘3AB’ systems lend themselves to centralised equipment as there is a requirement to generate very large quantities of processed minerals. In both cases, due to the large size of the plants involved in either power generation or mineral processing, respectively, these processes can be conducted on an industrial scale, leading to reduced marginal operating cost.

In Table 7 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.

	Rollout and Limitations on Potential
Artificial trees **Type: 3AA**	• 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 or solar cells. • 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 though the extent of the CO_2 transport network needs to be considered. • 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. • The main limitation on the potential of the technology is validation of its costs.
Soda/Lime process **Type: 3AA**	• 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. • Given 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 around 2 hectares per 28 $M.tCO_2$/yr unit, based on the unit size stated in Stolaroff et al. (2008)[17]. Hence land usage is not a major restriction.
Augmented Ocean Disposal **Type: 3AB**	• Ecological impacts allowing – see Table 8 – roll out limitation is principally determined by the rate at which both lime kilns 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[30]. • 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/yr. 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 could be 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, and a fleet of vessels similar in size to the aggregate world shipping fleet would be required.

	Rollout and Limitations on Potential
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 such as for food, fibre and feed) 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 in Box 2. Note that in the early stages of emissions reductions, biomass is more likely to be used in "low emissions" rather than negative emissions applications. This will build experience and supply chains. • The availability, allocation, efficiency and sustainability of biomass production has a strong bearing on the scale and efficiency of biochar and BECCS as a negative emissions technology (see Box 2). 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 example, the amounts of biomass needed to supply BECCS and biochar to attain 1 ppm reduction in CO_2 are of the order of 6 to 7 and 26 to 27 Billion tonnes, respectively. This compares to the coal industry which presently extracts around 6 – 7 Billion tonnes pa.
Biochar **Type: 3AB**	• 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[26]. • Should a more centralised approach be taken the scalability of the slow pyrolysis process technology is at present only at the development stage with a capacity of 2,628 tonnes per annum – see Table 8. • 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[31] meaning that to attain 0.1ppm 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 – see Table 8.
BECCS **Type: 3B**	• 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 to 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 to 2 GW/yr. 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 if carried out only in a single country.

Table 7. Table showing rollout potential and limitations of each of the exemplar technologies

There are also a number of non-technical issues which need to be assessed regarding the deployment of negative emissions technologies. These are described in areas for further research in Table 8 – in the row 'Negative Emissions General'. Furthermore, with regards the bio-based technologies there are a number of additional issues which are essential to consider. The issues include the global biomass potential, the development of supply chains and international trade, benefits of large scale biomass for energy/negative emissions production and land use change impacts – these are detailed in Box 2 below.

Box 2: Biomass for energy issues – global potential, the need for supply chain and international trade development and potential risks and benefits of the a global biomass for energy and negative emissions industry.

Biomass Potential. There is considerable variability in projections for global bio-mass potential due to how comprehensively the different categories of biomass resources are included, the uncertainties and sensitivities in the parameters used to project the availability underlying resources needed for biomass production, such as land availability, yield improvements, climate and even issues such as demographics and dietary changes impacting on food consumption[32]. A review of the literature highlights that assessments of the global biomass potential range across three orders of magnitude from 50 to 1,500 EJ/year[33,34,35,36] – due mainly to different forecasts of land availability and yield improvement in both the food and bioenergy sector. Further analyses on the UK's ability economically to access a reasonable proportion of this potential would also be useful.

Biomass Supply Chain Development and International Trade. In order to develop the full potential of biomass based negative emissions technologies efficient and large scale biomass supply chains will have to be established. Though the local use of biomass is presently more economically rational at the small scale – subject to a number of logistical barriers, the economics of long distance transport of biomass is becoming increasingly feasible allowing nations with lower costs and surplus biomass potential to export. Indeed the international trade in biomass is developing rapidly, particularly in the form of biomass pellets, albeit comprising a limited proportion of total biomass energy use. Present transnational biomass trade is estimated to be 1 EJ/year[37] this compares to oil at 112 EJ/year[38].

Potential Benefits of Large Scale Biomass Production for Energy and Biomass based Negative Emissions Technologies. The development of large scale biomass supply chains could facilitate establishment of a robust global agricultural sector supporting food, feed, fibre production, bioenergy and biomass based negative emissions supply needs. If introduced within the framework of extension services and amendment of present trade agreements[39] this could have potential environmental (land use, soil restoration, water management, ecosystem and bio-diversity preservation) and social benefits (poverty alleviation)[40,41].

Land Use Change/Indirect Land Use Change Impacts. Expanding the production of biomass has led to substantial controversy with a number of sustainability issues being levelled at biomass production for bioenergy. The most salient of these is the carbon debt created by the conversion of land for bioenergy crop production directly or by crops displaced by bioenergy crop establishment which may result in greater soil organic carbon release than is saved by the displacement of fossil fuels by bioenergy – so called indirect land use change. The extent of carbon debts for bioenergy supply chains is still subject to much debate. However, the studies which suggested long pay-backs[42,43] are now being considered as having used overly simplistic/inappropriate methodologies and assumptions[44,45] and recent studies have suggested substantially lower payback periods[46]. The evidence base also suggests that in some cases biomass for bioenergy production has had positive benefits (see for example Galbraith[47]). Despite this, it is clear that for sustainable bioenergy to be produced the destruction of high above and below ground carbon stocked biomes should be avoided in order to preserve the ecosystem services these provide. This should be undertaken within a framework of more efficient use of land globally and the development of sustainable intensification practices in order to reconcile the need to ensure sufficient land for food and fuel without displacement of the former with the latter. Furthermore, it is increasingly being understood that in order to address sustainability issues associated with biomass for bioenergy – biomass production across all end-uses – for food, fibre and feed – need to be addressed as well[48,41].

Policy and International Context

At the heart of successful climate change mitigation projects that provide revenue streams and are therefore financeable, is the presence of suitable domestic policies and international incentive structures, such as carbon pricing, subsidies and regulation. Investors and entrepreneurs need visibility on the cash flows created by these mechanisms, as well as a route to market, before capital will be deployed at scale.

Fortunately, some progress is being made to deploy such instruments, which have in turn enabled global investment in low carbon and clean technologies to increase from approximately US$ 40 bn in 2004 to US$ 243 bn in 2010[49]. But while mechanisms to support renewables and other low carbon technologies are spreading and even reaching maturity in some markets, the development of similar mechanisms for negative emissions technologies are still in their infancy.

Considering that negative emissions technologies are relatively new concepts for policy makers, researchers and investors this is hardly surprising, as credible mechanisms to support development and deployment have not had the opportunity to emerge. But given the role negative emissions technologies can play in mitigating climate change, this state of affairs needs to change quickly albeit without impacting the investments in other low carbon technologies.

For negative emissions technologies to mature successfully they will need to be developed and demonstrated and a credible route to market for investors created. Policy makers have a fundamental role to play in this process by making projects economic and, therefore, financeable all the way from early stage demonstration to (subject to appropriate governance) large scale deployment and diffusion. There are a number of ways that this can achieved across all the negative emissions technologies explored in this paper, and for specific technologies in particular given their characteristics and how they relate to existing markets and mechanisms.

Public policy can play a vital role in the research, development and deployment of negative emissions technologies, particularly at two key points in their maturation process (see Figure 6). The first is at a very early stage of technology development and the second is the point when technologies are mature, but would be deployed as first-of-a-kind projects or be the first commercial sized demonstrations. These so-called “Valleys of Death” are well documented[50] and are periods where private capital is scarce or unavailable, which holds up development and deployment. When there is a public interest in doing so, such as tackling climate change more quickly and cost-effectively, there can be a strong case for public funds to step in and bridge these “valleys”.

This can be done in a number of ways. To bridge the first valley public funding can be made available to support technology research, testing and refinement at universities and research laboratories. The second “valley” is where investments, say in large scale demonstrations, are too large for traditional venture capital and perceived to be too innovative by project finance or bank lenders. Here a greater number of interventions are available to policy makers.

For negative emissions technologies, support might include carbon credits or equivalent mechanisms that remunerate a project based on the amount per tonne of CO_2 successfully extracted from the atmosphere and sequestered. The first projects under a demonstration programme would receive a more generous level of support than later projects in order to attract investment. Other options might be direct expenditure by government to procure large scale demonstration projects, the provision of subsidised finance from government or public financial institutions, or making insurance available to provide comfort to investors regarding technology and policy risk.

As technologies mature, the support mechanisms ought to become less generous as costs fall and public finance and insurance provision can be withdrawn as the market matures. The key at this stage is to ensure that credible mechanisms exist to properly incentivise the deployment of mature negative emissions technologies at a level deemed appropriate by public policy makers. In the longer term, policy frameworks could be developed to be technology neutral, so there could be competition between carbon negative technologies, or even competition between all low carbon technologies based on cost per tonne of CO_2 abated or extracted.

The sooner investors have visibility on how such mechanisms might remunerate mature and operational negative emissions technology projects, the easier it will be to attract private capital into earlier stages of research, development and deployment. It is, therefore, important to develop these support mechanisms as soon as is practical to provide visibility on the route to market.

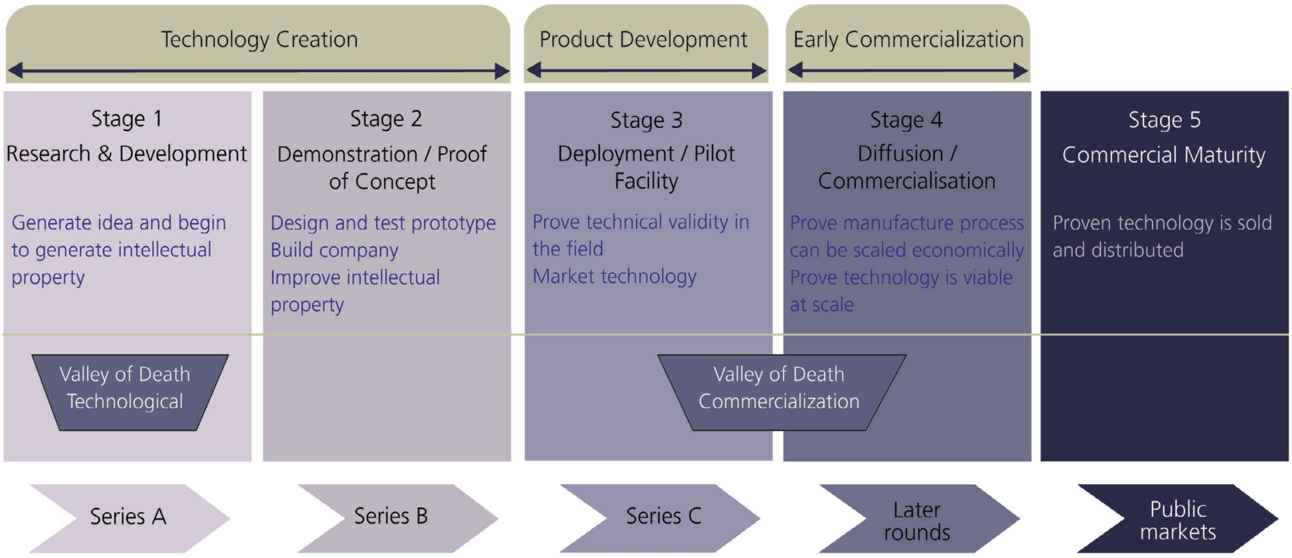

Figure 6. Stages of technology development

Carbon Credits

One relatively straightforward step to achieve this greater visibility could include recognising negative emissions technologies under existing international frameworks, by allowing them to generate Certified Emission Reductions (CERs) or Removal Units (RMUs), which were both created by the Kyoto Protocol. The former can be generated from Clean Development Mechanism (CDM) projects in developing countries, while the latter is issued in respect of emission reductions resulting from land use, land use change and forestry (LULUCF). Similarly, as the European Union Emissions Trading Scheme (EU ETS) develops, negative emission technology projects could be permitted to generate EU Allowance Units (EUAs).

Incorporating negative emissions technologies into the international carbon market, the EU ETS or other emerging carbon markets, is unlikely to have any impact on credit supply fundamentals in these markets during the short term. But it will be able to provide more certainty and a clearer route to market for private investors in negative emissions technologies today. Over the longer term, however, as negative emission technologies start to become operational and generate credits, they could increase the supply of credits which would, all things being equal, reduce the market price. To counteract this affect, caps in emission trading schemes might need to be reduced to maintain prices.

This can be a simple process, but would require an acceptance that longer term it might become necessary to have a negative cap in emissions trading schemes. For example, a 120% emission reduction target on 1990 levels by 2050. Negative targets can support carbon prices in emissions trading schemes as new forms of credit supply emerge, such as negative emissions technologies or LULUCF, but they could very well be necessary anyway if emissions surpass atmospheric constraints.

Additional Long Term Support

While credits could provide valuable revenue for negative emissions technologies, additional long term support might be needed to (1) provide additional revenue certainty given current emission trading scheme carbon price volatility in the absence of price floors and (2) to cover additional costs that may be associated with negative emissions technologies.

This additional long term support could take the form of Feed-in-Tariffs (FIT) or Emission Reduction Underwriting Mechanisms (ERUMs)[51] for each tonne of CO_2 successfully extracted and sequestered. The FIT would provide a direct performance payment, while an ERUM would be a 'put option' for project developers and would only be activated if market prices for a project's 'output' was below a strike price. The level of the FIT or the strike price for the ERUM could be set administratively or via reverse auctions, but would need to be at a level able to motivate investment decisions.

Support should also be able to differentiate between negative emission technologies and better incentivise those technologies that, in addition to extracting and sequestering carbon successfully, have the smallest environmental footprint (e.g. extent, externalities) or are able to generate other important co-benefits (e.g. improving soil fertility, addressing ocean acidification).

An example of a negative emissions technology that could score highly in this regard is biochar, which can be added to the soil to improve fertility. Given the potential for biochar to be deployed via existing agricultural markets and systems, agricultural policy could be used to incentivise and encourage its use. The EU Common Agricultural Policy which is being reformed[52] in order to, amongst other things, better promote sustainability in European agriculture, could be a potent vehicle for doing this.

Role of the Development of Carbon Capture and Storage and Negative Emissions Technologies

Carbon Capture and Storage (CCS) demonstration projects are being procured by a number of governments around the world. In addition to the benefits of these deployments for CCS technology development, these demonstration programmes could provide an opportunity to test Bioenergy with CCS (BECCS) and prove important negative emission capacity.

As CCS is at the cusp of deployment and its constituent technologies are relatively mature, BECCS could be the most quickly deployable negative emissions technology. The additional costs of BECCS versus conventional CCS are unlikely to be significant and will relate almost entirely to sourcing suitable biomass feedstock to co-fire in increasing proportions within a CCS enabled plant.

Despite this and the significant benefits of having a genuine negative emissions technology deployed, the UK Government has not included BECCS as part of the four CCS demonstration projects it has committed to take forward. Nor has the European Union encouraged or supported a BECCS approach through the European funding provided for CCS in the New Entrants Reserve (NER) 300 and the European Energy Programme for Recovery (EEPR).

If the nine EU publicly funded coal fired CCS demos, representing 2.43 GW of plant capacity, were BECCS with 50% co-firing from sustainable energy crop feedstock, 90% CO_2 capture efficiency, load factors of around 40% and consuming 1.9 M oven dry tonnes (odt) of biomass per annum, this could remove from the atmosphere approximately 2.2 $MtCO_2$ annually. If undertaken for 40 years – the lifetime of new plant – this is equivalent to 1/85th ppm*. In the UK if the 3 coal fired CCS demos representing 1.05 GW of plant capacity were 50% co-fired BECCS with the same capture efficiency, load factors and consuming 0.8 M oven dried tonnes (odt) per annum would sequester just over 0.9 $MtCO_2$ annually (or 1/200th ppm over 40 years). These are not transformational rates of negative emissions, however, this is not an insignificant contribution and it would be better to have a CCS demonstration programme that was actually scrubbing carbon from the atmosphere, instead of one that was merely making conventional power stations less polluting.

Given the direct contribution BECCS can make to reducing CO_2 concentrations in the atmosphere, it would make sense for the UK, EU and other governments to urgently re-appraise their CCS demonstration programmes to ensure that BECCS is included from the start. This should not be challenging given the fact that biomass in already co-fired in fossil fuel plant with limited loss in plant efficiency[53].

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 two of the other four options we investigated (air capture and lime soda) 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.

Other Concerns

In addition to policy creating credible cash flows able to make negative emissions projects economic, investors and project developers will need to be reassured about other aspects of the regulatory regime, in key markets as well as globally. Issues surrounding international regulation and the extent of possible liabilities, as well as greater certainty over sequestration and storage will need to be resolved[54]. The sooner we can begin to address these issues and resolve them to investor and developer satisfaction, the sooner capital will flow into research, development and deployment.

For BECCS, these issues are intimately related to broader CCS policy discussions, particularly on storage, as well as on work to ensure suitably sourced biomass feedstocks (the starting biomass materials used to produce bioenergy). Similarly, for other air capture technologies the main barriers to securing greater regulatory certainly will be in the areas of sequestration and storage. But augmented ocean disposal, because of the uncertainty over environmental impact and the laws that prohibit or limit ocean dumping, could face significant and complex regulatory issues that other negative emissions technologies do not.

Public opinion is likely to play a critical role in shaping regulatory developments. Consequently, investors and developers could be less open to deploying capital into solutions that have a greater chance of receiving modest public support. For example, Solar Radiation Management (SRM), a suite of geo-engineering options (opposed to negative emissions technologies), will almost certainly face additional public scrutiny because of its localised impacts, potential unforeseen consequences and non-permanence, amongst other things. While negative emissions technologies which fail to adequately prevent or minimise the adverse impacts of deployment on communities and the natural environment, are also likely to experience greater levels of public scrutiny.

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*The life cycle impact of domestically or internationally sourced biomass makes a small, around 6%, difference in the amounts of negative emissions generated.

Research Agenda and Technical Challenges

The research agenda of the negative emissions technologies discussed in this report are summarised in Table 8. The table includes general research needs for negative emissions technologies as well as the key features of each of the five exemplars and the technological challenges faced for each of them. Particular emphasis is given to cost reduction as these technologies are mostly at an early stage of development with the exception of BECCS.

	Feature	Technical and environmental 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 given these considerable uncertainties associated with our estimates as it has a bearing on the economic role of the technologies within a portfolio of mitigation technologies.[55] There is also the general need for research on negative emissions technologies in the following key areas: • How to engage the public[56,57,58]. • How best to establish governance[54]. • Development of policy for scale up and assessment of their impacts with existing laws and conventions[59]. • Their environmental impact and wider sustainability issues. • Their impact on existing and role in future international climate agreements[60] 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	Reducing the specific energy input and water requirements of type '3AA' technologies such as artificial trees is a key goal. The thermodynamic minimum energy input of separating CO_2 from the air is surprisingly low, and yet most sorbent technologies have low 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	A significant energy input is required to dehydrate and compress CO_2 from low pressure to a pressure suitable for sequestration – in essence this requires the liquefaction of CO_2. Although liquefaction is an old technology there may still be scope for improving the thermodynamic efficiency of the systems dedicated to artificial trees. 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	The lime soda chemical reaction set is one of many potential direct scrubbing technologies applicable to the direct scrubbing of the atmosphere. The relative poor performance of the technology as examined here relates directly to the high heat of reaction between CO_2 and sodium hydroxide and the consequential high energy input into the regeneration process. As has been demonstrated with artificial trees, significant improvements can be achieved by the development of new, novel sorbent types.
	Scrubbing tower	The size of scrubbing towers is a trade-off between the need to expose a large surface area of gas to the sorbent, without incurring an excessive pressure drop. Pressure drop is a particular problem in this instance as it is impractical to drive such a large quantity of air though the contactor hence natural draft has been specified. As a result to minimise the contactor's size careful design and optimisation of the tower internals is required. This lies outside standard normal chemical engineering conditions and it is likely there is considerable scope for reducing the size and hence cost and footprint of the towers.
	Sorbent regeneration system	Allied to the development of new sorbents is the improvement in the sorbent regeneration systems. Such processes are often far from the thermodynamic ideal. A number of options exist for improving the efficiency of these systems including conversion of batch to continuous processes: reducing pressure and heat transfer losses by careful design, and arranging chemical reactions to occur closer to optimum temperatures.
Augmented ocean disposal	CaO/MgO production	Most of the technology proposed for generating the required CaO and MgO stem from traditional cement and lime industry technology. A key point is that cement requires much higher temperatures than is strictly necessary to calcine limestone or dolomite. As a result, there is significant potential for the development of improved calcination processes, based on the lime industry and tuned to the particular needs of this process.

	Feature	Technical and environmental challenges
	Lime kiln CCS technology	Implementing CCS on lime kilns is already an active area of research due, principally, to the interest of the cement industry. A number of technology options have been explored from traditional post combustion scrubbing and oxy-fuel systems, but also the use of calcium looping which offers the potential for significant savings if lime and electricity production is combined.
	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. At present only traditional methods of distribution have been considered – namely conveyor or rail car on land and ship borne at sea. Other options that need to be explored include pipeline transport. Pipelines are currently used on land to ship limestone slurry, but they have not been implemented for subsea transport.
	Biological effects	This technology involves a major intervention in the chemistry of surface ocean waters, and on a global scale. Understandably, there is concern that this will affect the marine environment, perhaps severely. Before this technology can be implanted, therefore, detailed studies including local pilot studies would need to be carried out. In addition new monitoring techniques, designed to check the health of the marine environment, would also need to be developed.
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 bioenergy 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[61].	
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 standardisation of the body of work in order to match the different characteristics of biochar produced from different pyrolysis process to facilitate the matching of its requirements for end use. There is no 'dominant design' for pyrolysis process technologies. Existing plants range from 48 to 96 t/d commercial plants to gasification stoves in developing nations able to produce a few kg/hr. How the technology for these plants will develop is subject to much uncertainty.
	Mean Residence Time of Char	Mean Residence Time (MRT) of the carbon in char is fundamental 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. The ability for the carbon in char to have an MRT and therefore be sequestered for periods over >1000 years is vital for the process technology to be effective.
	Effects of Char on Soil	Effects on soil properties and productivity are poorly understood. The ability to store large quantities of biochar in the soil without any detrimental impact is vital to ensure optimisation of the economics and negative emissions potential of the technology. Detailed assessment of the research need with specific reference to soil properties can be found in CSIRO[62].
	Most efficient Use of Char	Char has value as a fuel or as a soil enhancement product. Therefore there will be a trade-off between whether or not to burn or bury bio-char. The decision to do so will be highly dependent on economics (see for example [27,63,64,65]).
BECSS	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. See [66,9,67] and [68] for details of the research needs for CCS and CO_2 storage. A number of energy system models assume that this will be widespread by 2020 for advanced nations and worldwide rollout by 2025.
	Integration of biomass combustion with CCS technology.	There are a number of differences between 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. Research to assess these impacts needs to be undertaken to understand if there are any serious issues in this area. The Energy Technologies Institute Bioenergy programme has a work stream looking at this particular area.

Table 8. Summary of the technological and environmental challenges faced for each of the exemplar technologies.

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, albeit with considerable cost uncertainties. 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[69] and the Energy Technologies Institute[70]) 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, 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 may have 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 mitigation 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, but they should not be used as an excuse for delaying effective global mitigation efforts.

Type of air Capture	Cost Competitiveness*	Rollout Limitations	Technical Challenges & Environmental Impacts
Artificial Trees	**~95 $/tCO$_2$e**	• Significant electricity demand of technology • Carbon transport and storage network development	• Novel sorbent technologies need to be developed to reduce energy input and water requirements • Improving thermodynamic efficiency • Linking a geographically distributed set of sites to a viable CO$_2$ transport and storage network
Soda/Lime process	**~155 $/tCO$_2$e**	• Substantial energy requirement • Carbon transport and storage network development	• Novel sorbent technologies need to be developed to reduce energy input • Need to reduce size of scrubbing towers • Improving thermodynamic efficiency • Linking a geographically distributed set of sites to a viable CO$_2$ transport and storage network
Augmented Ocean Disposal	**~90 $/tCO$_2$e**	• Availability of required shipping capacity • Conflict with international protocols on ocean disposal	• Improving calcination processes • Building suitable transport infrastructure to integrate the sub-processes • Unknown consequences for the marine environment
Biochar	**~135 $/tCO$_2$e**	• Availability of biomass for energy and competition with other uses • Poor understanding of carbon stability (Mean Residence Time)	• Scale up of slow pyrolysis technology • Need for better understanding of Mean Residence Time across feedstock streams and different soil conditions • Potential bioenergy related environmental impacts
BECCS	**~59-111 $/tCO$_2$e**	• Availability of biomass for energy and completion with other uses • CCS development requirements	• Realisation of CCS technology development at scale including a viable CO$_2$ transport and storage network • Integration of biomass combustion with CCS technology • Potential bioenergy related environmental impacts

Table 9. Summary table of costs, rollout limitations, technical challenges and environmental impacts for all technologies.

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*Cost competitiveness is based on an instantaneous cost calculated for continuous deployment over a year, but has not been validated on scale up beyond the scale required to achieve 0.1 ppm annual reduction in atmospheric CO$_2$.

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 Lackners' Group at Columbia University. For a more accurate assessment of the technology to be made, independent, full and accurate costings are required, preferably based on larger scale demonstrations.
- In published works on these technologies, no consideration has 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 may 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 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 applied to fossil fuel power generation. 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 Nth 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[71], 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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