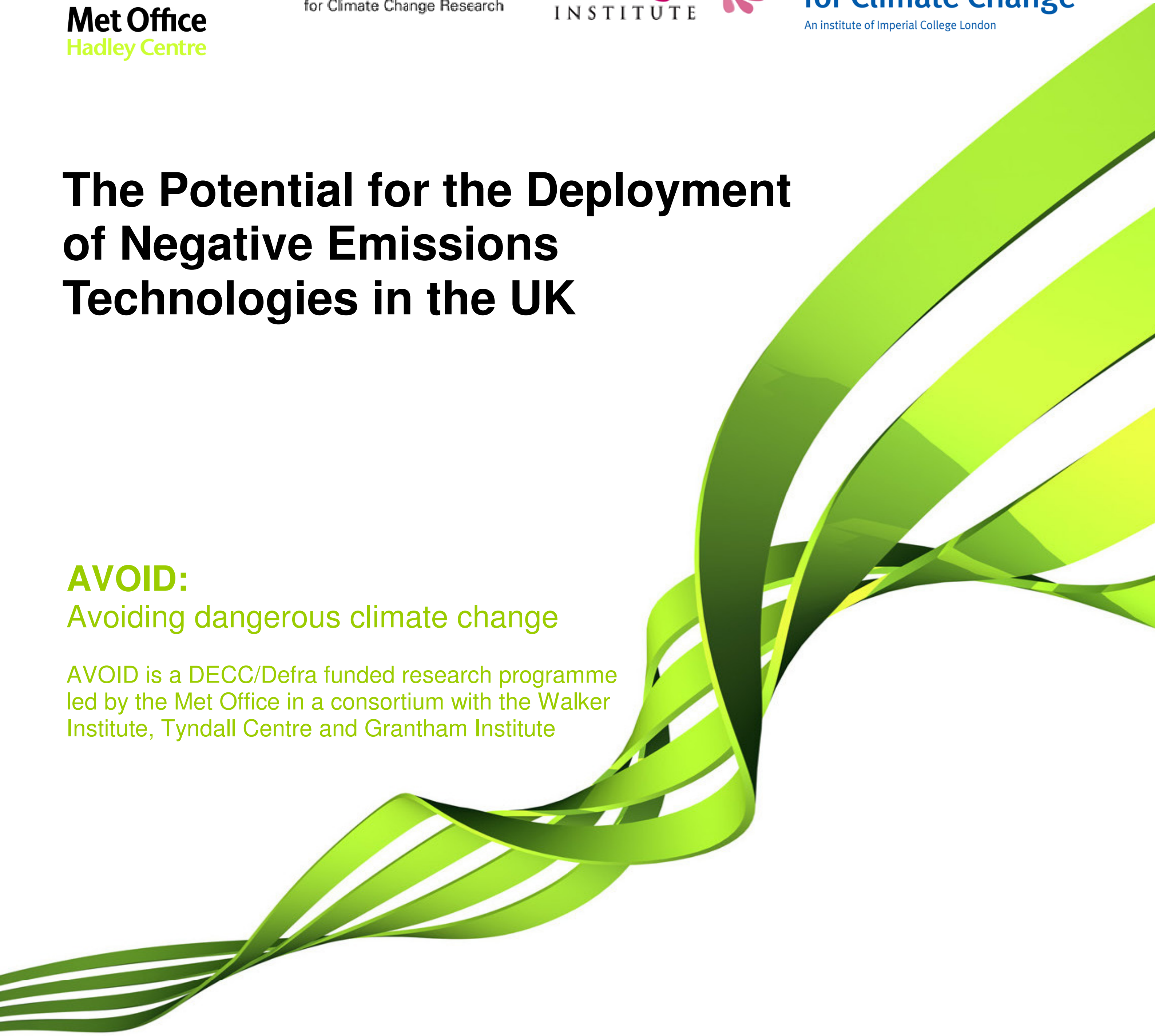
The Potential for the Deployment of Negative Emissions Technologies in the UK



AVOID:

Avoiding dangerous climate change

AVOID is a DECC/Defra funded research programme led by the Met Office in a consortium with the Walker Institute, Tyndall Centre and Grantham Institute

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Date: 30/07/2010

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Key outcomes / non-technical summary

- A mix of technological options to remove CO_2 from the atmosphere could be viable at a reasonable scale and a reasonable cost in the order of magnitude of \$100/tCO_2 over coming decades. In the longer term this may allow a cap on CO_2 emission trading/tax costs and support a rational carbon price.

- Some options 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.

- A practical potential exists for negative emissions amounting to about 10% of UK current emissions by 2030, which may provide flexibility in delivering long-term GHG reduction targets by offsetting emissions that are difficult to capture (e.g. from agriculture and transportation).

- Some other options (e.g. direct air capture) may be viable in the longer term but will take longer to scale up. The key advantage of some direct air capture devices is flexibility in location, which will be helpful to offset large CO_2 positive transport systems.

- There are currently many unkowns in the costs of the more forward looking technologies, including R&D pilot and scale-up support, and life cycle analyses. Research to define these costs is essential if these technologies are going to be available in the timescales discussed.

- Some of the options have potential significant environmental impacts and these would need to be investigated in detail as an integrated part of the evaluation of these options.

- If bioenergy carbon capture and storage is to be considered part of the mix, appropriate policy support and integration with the general CCS strategy should be deliberated as early as possible.

This report should be referenced as

McGlashan N., Shah N., Workman M., 2010: *The Potential for the Deployment of Negative Emissions Technologies in the UK.* Work stream 2, Report 18 of the AVOID programme (AV/WS2/D1/R18). Available online at www.avoid.uk.net

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2 Key Conclusions

- The work summarised in this report represents the output from an initial scoping study. 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. This in the longer term may allow a cap on CO_2 emission trading/tax costs and support a rational carbon price.
- 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. Nevertheless all the technologies could have a useful role to play as GHG reduction targets bite.
- Overall, we found that the practical domestic potential exists for negative emissions amounting to about 10% of UK current emissions; this may provide significant flexibility in delivering long-term GHG reduction targets by offsetting emissions that are difficult to capture (e.g. from agriculture and transportation point sources).
- Some other options may be viable in the longer term but will take longer to scale up, probably at least 20 years. The key advantage of some direct air capture devices is flexibility in location, which will be helpful to offset large CO_2 positive transport systems.
- Some of the options have potential significant environmental impacts 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 work on the costs 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.

3 Introduction

The Department for Energy and Climate Change (DECC) commissioned this report on “Scope for technologies that can achieve negative emissions by removing CO_2 from the air” through the Grantham Institute for Climate Change, Imperial College London, as part of the Avoiding Dangerous Climate Change (AVOID) programme.

CO_2 is long-lived in the atmosphere, and it seems increasingly likely that CO_2 emissions will overshoot the limit on the cumulative total needed to limit a global temperature rise to below 2°C above pre-industrial levels (Allen *et al.* 2009). It may therefore become necessary to remove CO_2 from the atmosphere. A range of options have been identified, which are at various stages of development. This report presents the output from an **initial** scoping study which aims to provide consistent performance and cost estimates for 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 five case studies looking at five different technologies which exemplify alternative strategies for achieving negative emissions: Artificial trees; Soda/Lime process; Cquestrate; Biochar; Biomass Energy with Carbon Capture and Storage (BECCS).

This work is primarily based on a literature survey, thermodynamic and related calculations and some additional assessment of the robustness of the literature claims, to determine stretch targets for deployment rates and to convert performance and cost data into a consistent form for comparison.

There remain key uncertainties/gaps and considerable further work is required in certain areas. The conclusions should therefore be regarded as preliminary and subject to revision in the light of further research. Further details of data sources, coefficients and calculations will be contained in a forthcoming more detailed version of this report.

3.1 Overall findings

Five different technologies have been considered in this report, which represent the major types of air capture or negative emissions technologies under consideration globally, the attributes of each are summarised below:

Type of air Capture	**About**	**Potential**	**Potential Barriers to Adoption**
Artificial Trees	Emulate action of natural trees by absorbing CO_2 directly from the atmosphere using chemical absorbents, relying principally on wind to effect mass transport of air across an absorbent;. The absorbent is then regenerated, releasing almost pure CO_2	Significant but in practice is limited by the early stage of the technology	'clean' energy input; linking a geographically distributed network to a viable CO_2 transport network; clear planning blight issues,
Soda/Lime process	Direct chemical scrubbing technique using a traditional absorption/scrubbing tower arrangement for the primary absorption stage. The CO_2 saturated absorbent is regenerated using a two stage chemical process, followed by calcination.	Significant but in practice is limited by the investment required in the technology - quite capital-intensive	'clean' energy input; linking a geographically distributed network to a viable CO_2 transport network; clear planning blight issues,
Cquestrate	Accelerate CO_2 naturally absorbed by the ocean by artificially increasing the pH of surface waters with the addition of alkali	Significant even relying on indigenous limestone deposits. Rollout potential is limited by rate at which the ships necessary can be built.	unknown consequence for the marine environment
Biochar	Biochar one of three products produced by the combustion of biomass in a low-zero oxygen environment, which can then be land filled or used to enrich agricultural land, effectively locking the carbon.	range from to 2.0 to 9.0 % of gross UK emissions in 2008 - limited by UK biomass availability.	Potential bioenergy related environmental impacts – need proper life cycle analysis of biochar production from different feedstock streams. More research is also needed on the stability of carbon in the char and its interactions in different conditions.
Biomass energy with carbon capture and	Direct combustion of (low grade) biomass fuels in a conventional power plant with the capture of greenhouse gas emissions	Range from 4.0 to 15.5 % of gross UK emissions in 2008 - limited by	The ability for CCS technology to be introduced in a timely manner. Potential

storage (BECCS)	generated using carbon capture and storage technology. The capture of the emissions is fundamental to establishing the technology's negative emissions credentials.	UK biomass availability	environmental impacts from land use change.

The table below includes a summary of the main findings from our calculations. For each technology where possible the following values have been calculated to achieve a negative emission of 1% of the UK current CO2 output – i.e 5.68 Mt CO_2/yr

- The number of units of equipment – e.g the number of artificial trees or calcination plants.
- Amortised cost of the units - based on an interest rate of 5% and a 10 year payback period.
- Work input considered as electricity
- Heat input considered as natural gas
- Aggregate cost of energy
- Raw material required
- Raw material cost

In addition, the long term potential and rollout periods as well as the average cost per tonne of CO_2 are assessed, including

- Long term potential negative emissions' for UK
- Roll out time to achieve the long term potential or 10% of UK' current CO_2 emissions
- Total cost of capture in $/tonne CO_2

1. Overall costing and energy requirement for each of the five technologies – number of units, raw material input based on a nominal collection rate of 5.69 M.te$_{CO2}$/yr – i.e. 1% of the UK's current CO_2 emissions (Brackets = negative numbers).

	Technology	No. of units installed/afloat	Amortised cost of units ($/te$_{CO2}$)[1]	Work input (PJ/yr)[2]	Heat input (PJ/yr)	Cost of energy ($/tonne$_{CO2}$)[3]	Raw material input (M.t/yr)[4]	Raw material cost ($/te$_{CO2}$)	Long-term UK potential (M.te$_{CO2}$/yr)	Rollout time for 10% of UK's CO_2 (yr)	Total cost ($/tonne$_{CO2}$)
Artificial Trees [Lackner, 2009]	Today: 500 m^2 trees – @ $200,000ea	158,000	186	64.7	N/A	12.4	min	min	Practically unlimited, water constraints to be explored	Too many uncertainties at this early stage of development to meaningfully calculate	206.1
	Future: 500 m^2 trees – @ $20,000ea	158,000	18.6	64.7	N/A	12.4					40.5
Soda/Lime Process [Keith et al., 2006]	Contactors – 110 m ø x 120 m	204	11.2	15.5	N/A	3.0	min	min	Practically unlimited		142.8
	NaOH regeneration system[5]	N/A	87.8	35.7	481	40.8					
Cquestrate – CaO basis	Calcination plants[6]	N/A	49-61.6	2.16	28.3	27.3	7.61	min	Practically unlimited	10	51-63.9
	Bulk carriers – 360,000 DWT[7]	0.5	2.19	0.31	N/A	0.10					
Biochar	400 t/day slow pyrolysis kilns	60	Non-linear scale effects of increasing power plant capacity make too speculative to calculate	2.41	(118.1)	(74.9)	5.12	costs of feed stocks in 2030-50 too speculative to calculate	26.7	12.1	
BECCS	Raw materials	N/A		N/A	N/A	N/A	2.96		46.2	11.2	
	Power plants	N/A		(96.8)	N/A	(330.6)					

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[1] Costs amortised over 20 years with 5% interest rate and an assumed equipment life of 20 years – scrap value ignored. For the BECCS figures it was assumed that the power stations had an 90% availability

[2] Energy cost based on work (electricity or shaft work) at $19.4/GJ (¢7/kWh) and heat at $4/GJ (natural gas)

[3] Electricity is assumed to be sold from BECCS plants at $11.1/GJ (4¢/kWh)

[4] Raw material assumed to be CaCO3 for Cquestrate

[5] Based on figures from Rao and Rubin [Rao and Rubin, 2002] for amine scrubbing system for CO_2 capture that is non-ideal for a limekiln and hence conservative.

[6] These are calcination plants using oxy-fuel capture system and the amortised cost of equipment, plus operating cost and the fuel bill is included.

[7] Bulk carrier financial cost based on the price of one carrier of $125 million, multiplied by 1.5 to account for the cost of the ships operation and maintenance; and also the cost of additional port facilities.

From our initial analysis of the cost estimates, air capture technologies appear to be 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 the potential is there for below $\$100/tCO_2$. But these numbers carry a strong health 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.

From our initial comparison of the current technologies under consideration, Biomass enhanced CCS (BECCS) has the most immediate ‘negative emissions’ potential – at least 10% of current UK CO_2 emissions by 2030. And BECCS could be a net generator of cash in the UK. However, there are limits in scope given the finite amount of biomass that can be economically generated in the UK, and a full Life Cycle Analysis is needed to understand the impact of large scale biomass plantation development on wider ecosystem services and soil organic carbon emissions from direct and indirect land use changes. Full lifecycle analysis such as this remains challenging, but is essential prior to full scale roll-out. However, in terms of the technology itself, there are no technological challenges for BECCS and demonstration and commercial plants could be developed in the very short term.

Apart from BECCS, the initial cost estimates for other direct air capture technologies included in the study, such as Klaus Lackner’s artificial trees, are not on the face of it prohibitive. But these have yet to be shown to be achievable. Estimates of energy costs also appear reasonable – a 1ppm global reduction contribution would require <2% of current global electricity demand. However, air capture requires a large surface area of absorbent to be exposed to the atmosphere. Thus if the air capture 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 Lackner’s artificial trees, we could need around 1.5million units for 10% of UK CO2 emissions. Care will need to be take in the location of these since access to low carbon power and a CO_2 transport system or sink, as well as possibly water, will be needed. Biochar, like BECCS, also needs to be subject to full life cycle analysis, to ensure its full impact is understood.

4 Context

A robust strategic plan is needed to achieve the UK target of 80% cuts in greenhouse gas emissions by 2050. Withdrawing CO_2 from the atmosphere directly is part of the current technology mix under consideration to achieve those 80% cuts. Through capturing CO_2 from the air, historical CO_2 emissions can be sequestered and the aggregate amount of CO_2 in the atmosphere reduced accordingly. 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. Air capture technologies offer the potential to allow the accumulated level of atmospheric CO_2 to be reduced at an augmented rate, over and above natural processes, but only if the rate of anthropogenic emissions are reduced to lower levels.
- Where more established CCS methodologies are impractical or uneconomic to apply. This may be the case in certain countries or, within countries in isolated geographic locations, or more generally, due to technological advances – i.e. air capture may be worth doing because it is the cheapest option.
- Where non-fossil fuel alternatives to certain activities are unavailable and some emissions reductions are nonetheless deemed imperative. This principally applies to some 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.
- As an alternative to lifestyle change; until anthropogenic emissions are significantly reduced, capture technology can be seen as a lifestyle choice – i.e. energy users can enjoy the convenience of fossil fuels, provided they pay to clean up the consequences of their use through air capture.

On the face of it therefore, air capture technology has enormous potential given its ability to collect CO_2 released from any source, from any time, using a “device” or devices that can be located anywhere. This document deals with the practicalities of certain classes of air capture and addresses the likely energy, financial and environmental implications of the use of specific technologies.

5 Definitions and Classes of Technologies for Capturing CO2 from the air

Air capture of CO_2 involves the separation of a gas at low partial pressure, from a mixture of inert and not so inert gases. Separation of gases, in general, can be conducted using one of only a few methodologies. These include membrane separation, selective condensation, and chemical scrubbing. Of these, due to the low ambient partial pressure of CO_2 in the atmosphere, the first two methods can be ruled out immediately; in both cases there would be a requirement to pressurise large amounts of the atmosphere, which is uneconomic. However, CO_2 is a sour gas and therefore reacts readily with bases of all kinds. As a result, many alkali scrubbing agents are able to reduce the residual partial pressure of CO_2 in a gas stream to vestigial levels. Hence chemical scrubbing is a viable air capture methodology; directly or indirectly, all proposed air capture methods rely on chemical scrubbing of some kind. This may be using simple scrubbing agents such as $NaOH$ in a scrubbing tower; or $Ca(OH)_2$ dissolved in sea water. The linkage is more tenuous with biomass based systems, but photosynthesis can be seen as natural chemical scrubbing.[8]

Gibbins and Chalmers [Chalmers and Gibbins, 2010] categorised carbon capture systems into three classes: 1, 2 and 3 – depending on whether they are: carbon positive (despite the addition of some CCS); near carbon neutral; or potentially carbon negative (air capture), respectively. Class 3 was further subdivided into classes 3A and 3B:

- 3A systems are those that capture CO_2 directly from the air;
- 3B systems are those that use biomass in a conventional CCS power plant of some kind – i.e. Biomass energy + CCS (BECCS).

We have further broken down class 3A. Air capture is fundamentally a post-combustion scrubbing technique; a critical issue is whether or not the captured CO_2 is sequestered in geological formations. This is an important distinction, as to sequester fluid CO_2 into an underground sink the CO_2 must be compressed to high pressure. A significant proportion of the net work input into the process is consumed in this final stage, and processes that do not need to compress CO_2 could, at least in principle, be cheaper to operate. Further, the capital and carbon investment in compression and injection equipment can be avoided, and a reduced CO_2 transportation network has the potential to lead to further cost savings. As a result, type 3A has been split into two distinct divisions, 3AA and 3AB. The examples of 3A technologies selected for further study have been chosen to represent the major types of air capture; the choice is not intended to be an endorsement of a particular 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 were favoured.

> **3AA:** Technologies that output a stream of essentially pure CO_2 at pressures potentially suitable for geological storage – *ca.* 110 bar. These methods can be viewed as a subset of traditional post-combustion CCS technology as they all use some form of scrubbing system. The apparatus performing the scrubbing can be either static, 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/slurry absorbent. A key cost of these technologies is that the CO_2 collected in the absorbent must be desorbed, compressed, transported, and injected into a geological sink. An example of each of these methodologies will be examined in this report:
>
> i) ***Artificial trees.***
> ii) ***Soda/Lime process***

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[8] Air also contains other sour gases, principally SO_x and NO_x – especially in industrial areas – and these are likely to react with any alkali based absorbent. Hence distributed air capture systems designed for CO_2 capture may well also absorb these pollutants – intentionally or not – but this will not be considered further in this work.

3AB: Technologies that sequester CO_2 at low partial pressure by fixing the CO_2 in a stable mineral form, which is then stored geologically. These processes may and often do involve traditional CCS at least in part, as they generally require fossil fuel to supply the necessary energy input. As a result, a traditional CCS plant is required to collect CO_2 if the energy input is sourced from fossils fuels. However, the amount of fossil CO_2 generated is generally less than the amount of CO_2 collected from the atmosphere. An advantage of these processes is that the CO_2 caught from the atmosphere does not require compression to high pressure, and therefore, there is likely to be a net saving in energy terms. The costs associated with transportation and injection are also reduced. Specific technologies that fall into this class are:

i) ***Cquestrate***
ii) **Biochar**

We have evaluated the potential for overall negative emissions associated with the technologies through a series of different methods and metrics. These are inspired by considering the dominant part of the overall life cycle regarding greenhouse gas emissions. The methods and associated assumptions are as follows:

i. **Method 1** - Theoretical negative emissions process efficiency. This focuses on just the conversion process itself - *i.e.* that which is sequestered relative to that which is emitted and ignoring the impact of LCA of emissions during the production process and transport of the raw materials or the end to end system around the process technology. It is a useful proxy of process technology negative emissions effectiveness and the calculation that is subject to the least uncertainty;

ii. **Method 2** - net process negative emissions balance. This is the net impact of the emissions produced throughout the end to end process from the raw material production, processing and transport against that which is sequestered in the process technology. In the case of biomass technologies, this will be sensitive to the LCA impact of getting the feedstock to the plant, the theoretical negative emissions process efficiency - the notional carbon neutral nature of biomass is assumed but does not take into account a reference fuel for any electricity that is produced. For artificial trees, the lime soda process, Cquestrate and biochar this method has been used; and

iii. **Method 3** - For BECCS, due to the fact that the process generates electricity, net negative emissions reference balance method has been developed. This is the net impact of the emissions produced throughout the process less those that are carbon neutral (i.e. that which will be re-sequestered by biomass) against that which is sequestered relative to a reference fuel. The energy system that is being substituted for by biomass combustion for electricity generation and the emissions from the feedstock production cycle is taken into account.

In the next sections, we present the detailed reviews of each technology (in no implied order).

6 Review of Type '3AA' Systems

6.1 Artificial Trees

6.1.1 Summary

- Artificial trees emulate the action of natural trees by absorbing CO_2 directly from the atmosphere. Chemical absorbents scrub CO_2 from the atmosphere; the absorbent is then regenerated, releasing almost pure CO_2 that can then be compressed and exported into a CO_2 transport network. Energy input is required to drive this process in the form of 'carbon neutral' electricity.
- The UK negative emissions potential is significant, and in practice is limited only by the financial resources dedicated to the technology.

- Estimate of the financial cost of the technology vary from $206 $/t CO_2 for immediate, but small scale implementation; to around 40 $/t CO_2 after widespread national rollout [Lackner, 2009]. The principal economy of scale being the cost of building the units, which is anticipated to fall markedly if mass production were to occur.
- The key difficulty with the technology is supplying the necessary 'clean' energy input. A further difficulty will be the need to link a geographically distributed network of trees with a viable CO_2 transport network. Finally there are also clear planning blight issues, particularly if wind turbines, local to the trees, are used to provide the necessary power input – the trees themselves, as proposed, are passive and notionally silent.

6.1.2 Detailed evaluation

An artificial tree, put simply, is a device which mimics the processes used by biological plant life to scavenge/scrub/withdraw CO_2 from the atmosphere. In nature, plants combine CO_2 from the atmosphere with H_2O from their sap chemically, forming various hydro and oxy-hydrocarbons. These chemicals are used as the 'building blocks' of the fibrous or woody stems of the plant. 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 in the 'normal' manner.

Energy is required to effect the chemical transformation in both real and artificial trees – photosynthesis for the former. An industrial energy source is required to drive artificial trees and this represents a major cost of the technology. Energy is also required to compress the CO_2 collected in the trees to high pressure so that it can be transported to a site suitable for geological storage. A number of suggested configurations have been proposed, but in all cases the basic methodology is the same.

The key proponent of artificial trees to date has been Klaus Lackner [Lackner, 2002]. Lackner's trees are essentially passive devices that present to the atmosphere a large surface area of CO_2 absorbing materials – akin to the leaves of natural trees. The trees can be arranged as a series of discrete, sail-like structures. Practically any geographic location is feasible, provided there is a source of energy to power the trees, water if found to be necessary and also a nearby sequestration site to take the CO_2 they generate.

Wind is used to drive a current of CO_2 laden air across the trees' absorbing surface, so that mass transfer of CO_2 to the absorbent takes place. The current of wind then carries the CO_2 denuded air from the trees' surface. As a result, the wind provides sufficient air change to expose the absorbent to fresh, and hence CO_2 'rich', air continually.

The absorbent is supported on a substrate and is re-cycled as it becomes saturated and regenerated either thermally or using moisture swing in the base of the tree – releasing essentially pure CO_2. The latter can then be compressed and transported to sites suitable for geological storage using any of the accepted transport methods, though pipelines seem the most appropriate given the distributed nature of the trees – many trees are required to effect an environmentally significant amount of carbon capture.

To estimate the interfacial area required, assuming a capture efficiency of 30% and, with an average wind velocity of 1 m/s, Lackner [Lackner, 2002] calculated that a tree with a frontal area of 50 m^2 facing the wind would be able to capture 1 tonne of CO_2 per day. Using estimates of the likely mass transfer coefficients he went on to show that such a tree would need between 2,500 and 25,000 m^2 of interfacial surface area. This equates to a surface area multiple of between 50 and 500, which is easily achievable if absorbent geometries similar to modern filter systems are adopted.

Ideally, to achieve the maximum environmental benefit from each tree, the electricity to drive the fleet of artificial trees must be obtained from carbon neutral sources. One suggestion, is to use wind turbines, built adjacent to the trees to provide this power. There are number of benefits of this configuration, apart from savings in planning and installation cost. The artificial trees are able to take power as it becomes available from the wind turbine, and the trees may become part of a load matching system helping smooth out the variable supply curve of wind power systems. However, if the trees themselves are utilised at less than 100% duty cycle there would be an inevitable increase in their notional capital cost per unit of capture.

Potential sites for this type of scheme comprise any location that might be conventionally described as 'stranded wind power'. In principle, artificial trees can be located anywhere; there is no requirement for them to be adjacent to a source of CO_2. However, the need to maintain a connection with a CO_2 transport network, assuming this is by pipeline, will still restrict location. Nonetheless, artificial trees may be able to utilise otherwise inaccessible energy sources. The term ‘stranded energy’ defines those sources of power or fuel sufficiently distant from major consumers of energy such that it is uneconomic to transmit or transport the energy. However, the ability to service remote installations is also a factor.

From a UK perspective very little of the country’s energy reserves can be said to be stranded. Globally however the situation is different, and installing artificial trees may well be the only economic means of utilising the large amount of wind power available in the Great Plains of the US for instance.

Energy Penalty: As discussed above, to effect air capture, work or high grade thermal energy is required to drive the process. Lackner [Lackner, 2009] has estimated the energy input required to drive an artificial tree. This analysis concluded that work (electricity) input alone was sufficient; any heat requirement (in the regeneration process for instance) being supplied from heat recovery in the CO_2 compression process. Assuming electricity as the source of energy – his figures are presented in Table 1.

Table 1. Energy input (as electricity) associated with artificial trees – from [Lackner, 2009].

Item	Work input
Theoretical vacuum pumping	91 MJ/t_{CO2}
Theoretical CO_2 compression	489 MJ/t_{CO2}
Estimated lost work	557 MJ/t_{CO2}
Total	**1137 MJ/t_{CO2}**

Lackner’s estimates are based on an initial assumption of thermodynamic reversible processes to calculate the minimum work input and then a second law efficiency is applied to estimate the actual work input. For the compression processes an overall efficiency of 50% was assumed, but no discharge pressure was stated. An outlet pressure of 110 bar has been used in this text. Although higher efficiencies are possible at power station scale, this figure is realistic given the small size of the compressors in each tree.

Economics: Lackner [Lackner, 2009] has analysed the likely financial cost of artificial trees, both to build and operate. He argues that the build cost will depend on the eventual design of tree adopted; however, in reality the technology involved is relatively straightforward and likely to be amenable to mass production. Deployment on the site is also likely to be relatively straightforward. Lackner estimates that once in production, the cabin-sized units would cost about $20,000 each ex. works, including all equipment and material; and that this would constitute about 20% of the total financial cost of the system’s installation and operation.

Just as for their energy penalty, the main cost of operation of artificial trees is in the CO_2 recovery from the sorbent filter material. However, Lackner has shown that the cost of the recovery step in air capture is similar to that anticipated in a conventional post-combustion CCS process and that the long-term price of air capture could drop to as low as $30/tonne of CO_2. However, we believe that this latter figure should be treated with some scepticism.

The table below includes a cost breakdown using Lackner’s figures mostly, but a less optimistic energy price. To construct the table, the capital cost of each tree – assumed to be 150% of the manufacturing price - was amortised over 20 years at an interest rate of 5%. This interest rate has been used throughout. The service life is based an assumption that the trees would require replacement after 20 years. In addition, the trees are assumed to have no net scrap value – i.e. dismantling costs are covered by the scrap value of materials. A yearly operating/ maintenance cost (excluding energy) was added to the capital repayment charge, which was assumed to be an additional 20% of the capital charge. The trees are assumed to have a nominal area of 500 m^2 each and be able to collect 3650 t CO_2/yr. The energy required to drive the trees was assumed to be sourced from carbon neutral sources hence the net negative emissions are equal to the 3650 t CO_2/yr figure.

Lackner gave estimates of the cost to build and install a small numbers of 500 m^2 trees using current technology as \$200,000. Most of this price is due to two items: the material cost of the resin based absorbent – a specialist product at present – and the regeneration chambers – bespoke manufactured items at present. Both of these items are expected to fall in price dramatically if the trees are produced in large numbers. This would leave the compressors and pumps contained in each tree the principal capital cost. Using current prices for these items and the anticipated long term cost of the resin and regeneration chambers, Lackner arrived at a price for mass produced trees (ca. 100,000/yr) of \$20,000 installed.

To estimate the energy cost of running each tree a unit electricity price of 7¢/kWh was adopted, which equates to 19.4¢/MJ. This alters Lackner's figures slightly, as these were based on a lower unit charge of 4¢/kWh that was considered too optimistic.

Amortised financial costs associated with artificial trees – based on Lackner [Lackner, 2009**].**

Item	Cost today	Estimated long term cost
Manufacturing/installation/operation – 500 m^2 units	\$184/t_{CO_2}	\$18.4/t_{CO_2}
Energy	\$22.1/t_{CO_2}	\$22.1/t_{CO_2}
Total	**\$206.1/t_{CO_2}**	**\$40.5/t_{CO_2}**

Rollout Potential: Lackner suggests that small 500 m^2 artificial trees could be installed in large arrays or '*air capture parks'* – similar in some respects to photovoltaic arrays. Even so the number of these parks would itself need to be quite large, particularly in a country like the UK that lacks large areas of wilderness. Each park would require connection to both a source of ideally carbon neutral electricity, and also a CO_2 transport network so that the CO_2 generated can be transported to the sinks available. Note that "UK-owned" capture facilities need not be located in the UK; they may be located in more energetically favourable regions.

Based on the 500 m^2 collector size, a million units would collect 0.36 G.t_{CO2}/yr. In simple terms to absorb the equivalent of 1 ppm_{CO2} in the atmosphere – i.e. 7.81 G.t_{CO2}, – would require 21.7 million units globally. This figure compares reasonably with other mass produced items of similar size such as automobiles. In a UK context to collect 10% of the UK's emissions would require ca 1.5 million units.

Considering the equipment required to provide the necessary energy used by the trees, using the energy requirement presented in Table 1, the 21.7 million trees required for 1ppm/yr, will consume 2470 TWhr of electricity globally, which equates to an average demand of 281 GWe. This is less than 2% of the global electricity capacity, which was estimated by the US's EIA to be 19.0 TWe in 2010 [Anon, 2006]. Building this additional energy generation capacity appears achievable, especially if the trees are built simultaneously and adjacent to wind turbines or other source of carbon neutral energy.

6.2 Lime/Soda Process

6.2.1 Summary

- This technology is one of a range of direct chemical scrubbing techniques that can be viewed as cousins of post-combustion scrubbing systems. The technique described below is a cyclic process that requires energy input alone (fuel rather than electricity) and outputs a stream of essentially pure CO_2 that can then be compressed and exported into a CO_2 transport network. The technology components are well understood and exist in other industries. The technology could be quite capital-intensive given the dilute nature of the feedstock and the need for a high temperature calciner.
- The UK negative emissions potential is significant, and in practice is limited only by the financial resources dedicated to the technology.
- The estimated financial cost of the technology is \$143 \$/t_{CO_2}, though lower values may be possible after scale up.
- The principal difficulty with the technology is supplying the necessary 'clean' energy input (particularly low-carbon heat). A further difficulty will be the need to link a geographically

distributed network of the scrubbing towers with a viable CO_2 transport network. Finally, there are also clear planning blight issues, although the contactors are passive and notionally silent.

6.2.2 Detailed evaluation

This process has been advocated by David Keith *et al* – see for example [Keith et al., 2006] and is similar to the artificial tree concept used above whereby chemical scrubbing is employed to remove CO_2 from the air. The difference is that Keith *et al* propose a more traditional absorption/scrubbing tower arrangement for the primary absorption stage. Another key difference from artificial trees is the means by which the CO_2 saturated absorbent is regenerated using a two stage chemical process, followed by calcination requiring substantial heat addition. Two chemical loops are embodied in the process and it is claimed this offers thermodynamic advantages as each process can be operated close to equilibrium.

The underlying chemistry of the process consists of four discrete reactions. The first step is the absorption of CO_2 from air using $NaOH$ generating Na_2CO_3, ie Soda, in a scrubbing tower or contactor. The Na_2CO_3 solution generated in the tower is then reacted with $Ca(OH)_2$ in a reactor called a causticizer, to regenerate the $NaOH$ which is returned to the contactor – this is the lime-soda reaction. The waste product from this process is $CaCO_3$, which precipitates and then filtered from the $NaOH$ solution continually. This $CaCO_3$ is then converted to lime (CaO) using the calcination reaction, slaked and returned to the causticizer. These processes are repeated indefinitely. The output from the process is a stream of CO_2 generated in the calciner, which if fossil fuel fired must have an associated CCS system of some kind to maximise the negative emissions of the overall system. Fig. 1 shows the generic arrangement.

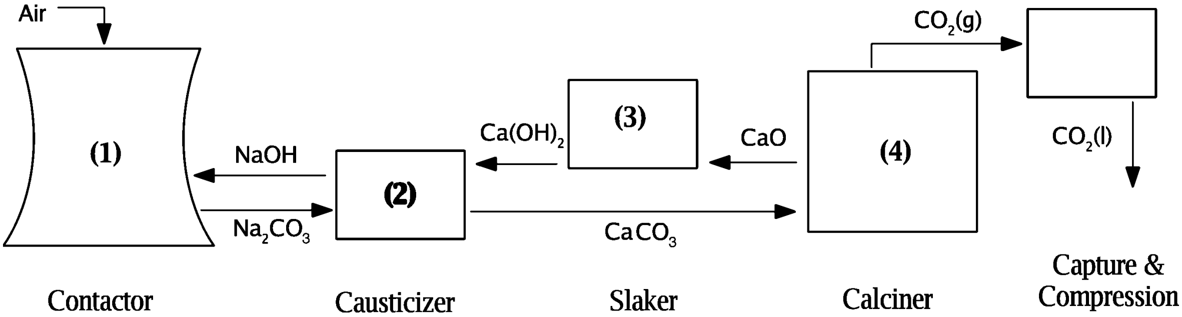

Fig 1. Proposed arrangement of equipment to implement Lime-Soda cycle [Keith et al., 2006].

The key components of this system are located in the field. For the scrubbing tower itself, a spray tower fitted with structured packing is proposed, designed to allow maximum contact between the air and $NaOH$ solution – see Fig. 2. In the design, the downward flow of the $NaOH$ solution spray would entrain air, which therefore is scrubbed in a co-flow arrangement.

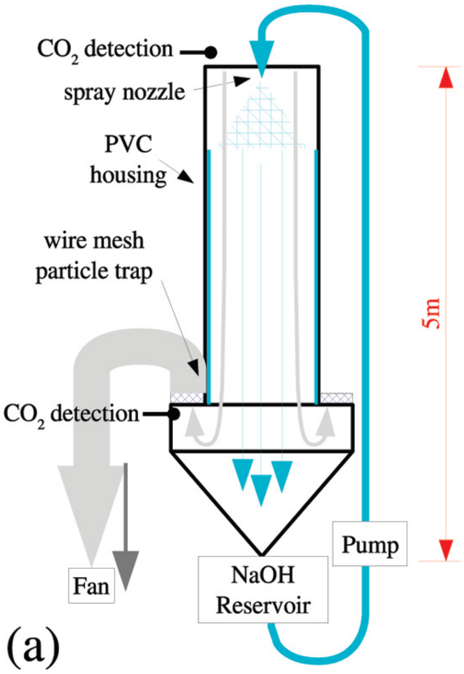

Fig 2. Proposed arrangement of scrubber for Lime-Soda cycle [Keith et al., 2006].

In the causticizer, $CaCO_3$ precipitates from a liquor of $NaOH$, which is formed in the reaction; $CaCO_3$ has a very low aqueous solubility and can be removed by filtration. This process was the traditional means of generating caustic soda – the original lime-soda process – before electrolytic methods became dominant from the early 20th century onwards [Thorpe and Whiteley, 1937]. Hence, there is considerable experience in operating causticizers industrially, although much of this dates from the early 20th century and will need to be re-learned.

Energy Penalty: The reactions occurring within the lime soda process involve very low energy expenditure when summed together as the process consists of two chemical loops with both *Na* and *Ca* acting catalytically. However, the actual energy penalty will be far from zero, due to inevitable losses. The amount of energy loss will depend somewhat on the extent of energy recovery from the exothermic reactions inherent to the process. In particular, it should be possible to supply the necessary heat addition to the causticizer using heat released by reactions in the slaker, as these are both low temperature processes. However, heat released in the contactor, where the reactions are also exothermic, is likely to be lost to the atmosphere. In addition, large amounts of energy are required to calcine the $CaCO_3$ generated in the causticizer, which, due to the nature of the calcination process, must occur at high temperature (of the order of 900°C). As a result, the only practical means of calcination is to use fuel to supply the necessary energy input. To minimise the CO_2 release due to this process some form of CCS system must be implemented.. This CCS system also requires energy input. Table 2 summarises the expected energy penalty as anticipated by Keith [Keith *et al*., 2006]. This table is broken into heat and work input. It is assumed in these calculations that burning natural gas is used to supply thermal energy input and electricity is used for the work input element.

Table 2. Energy costs associated with lime/soda process from Keith [Keith et al., 2006].

Item	Heat input (natural gas)	Work input (electricity)
Contactor – fan and pump work as electric	N/A	272.7 MJ/t_{CO2}
Calcination process – thermal + electric	4640 MJ/t_{CO2}	81.9 MJ/t_{CO2}
CO_2 capture at lime kilns – thermal + electric	3820 MJ/t_{CO2}	545.5 MJ/t_{CO2}
Total	**8460 MJ/t_{CO2}**	**900.1 MJ/t_{CO2}**

Economics: Keith *et al* [Keith et al., 2006] have estimated the financial cost of a soda/lime system in recent work. They estimated the cost of a complete system based around a tower type contactor, with associated equipment. Allowance was made for the work consumed by the various fans, pumps and cooling tower systems required for each contactor and those used in the CCS system – assumed to be an amine based CCS system. The price of electricity was taken as 7¢/kWh or 19.4¢/MJ as for all other estimations in this work. To estimate the costs of the *NaOH* regeneration system each process plant was considered while the calcination stage was assumed to take place using cement plant technology burning natural gas priced at $4/GJ. All capital costs are amortised with 5%/yr discount rate and 20 year plant life

Table 3. Amortised financial costs associated with lime/soda process from Keith [Keith et al., 2006].

Item	Cost
Contactors – 110 m ø x 120 m + equipment	$11.2/t$_{CO2}$
Contactor – energy	$3.0/t$_{CO2}$
NaOH recovery system – equipment	$87.8/t$_{CO2}$
NaOH recovery system – energy	$40.8/t$_{CO2}$
Total	**$142.8/t$_{CO2}$**

Roll-out potential: Keith suggests using contactors of ca. 110 m diameter by 120 m tall. Just over 1300 units of this size would be required to collect 0.36 G.t$_{CO2}$/yr. In a UK context to collect 10% of the UK's emissions would require ca. 2000 units. These units can in principle be located anywhere, but as for artificial trees, would need to be connected into a suitable CO_2 transport grid. Each unit would also require connection to a source of either *NaOH* or *CaO,* alternatively a supply of energy could be used to drive the calcination of $CaCO_3$ locally. The contactors would also need to be supplied with 'carbon neutral' electricity to drive pumps and the CO_2 compression system. There would also need to be a connection to a CO_2 transport network.

For the towers and associated systems, the materials needed for construction, concrete and steel, are readily available, and no special processes are required in their construction. In operation, only the minimal amount of readily available and cheap chemical feedstock is required as the process is cyclic. Hence, to construct the 2000 units, assuming suitable sites can be found, the rollout potential is only limited by the financial resources made available and the ability to link these sites into a CO_2 transport network. It is anticipated that the necessary electricity, along with the natural gas for the calcination process can be supplied by extending the existing networks.

7 Review of Type '3AB' Systems

7.1 Augmented Ocean Disposal Processes

7.1.1 Summary

- CO_2 is absorbed by the oceans naturally, but this process can be accelerated by artificially increasing the pH of surface waters with the addition of alkali. This can be achieved using lime, or similar alkali, which would be manufactured using techniques already practiced by the cement industry and then the dispersal of that lime in areas of the ocean with significant circulation.
- The UK negative emissions potential is significant even relying on indigenous limestone deposits and assuming rapid escalation of lime production facilities is possible. In practice, the rollout potential is likely to be limited by rate at which ships necessary to carry and disperse the lime can be built. We estimate within 30years, 10% of UK current CO_2 emissions could be accounted for.
- The estimated financial cost of the technology is $64 $/t$_{CO2}$.
- The key risk factor is the yet unknown consequence for the marine environment associated with the change of surface water chemistry wrought by this process. The transport and dispersal may also be bottlenecked by shipbuilding capacity.

- An interesting opportunity for process integration would be to use spent lime sorbent from solid looping CCS processes as the feedstock for this process. Again this builds upon a system with a primary product (power and possibly heat) and may therefore find earlier deployment.

7.1.2 Detailed evaluation

This process works by decomposing (calcining) limestone, magnetite or dolomite thermally, generating *CaO*, *MgO* or a mixture of the two and a flue gas rich in CO_2. The *CaO/MgO* is then added to seawater – raising the latter's *pH*. Along with mitigating ocean acidification, the stated effect of the *CaO/MgO* additions is to increase the capacity of the oceans to absorb CO_2. There have been many technologies and processes that have been proposed which utilise the oceans as a carbon sink [Jones and Lu, 2003]. They essentially fall in to two categories: those that involve fertilisation to enhance ocean biological productivity; or weathering techniques to enhance the chemical capacity of the oceans to absorb CO_2. This study will focus on those that involve weathering techniques. Kruger (2010) summarises a variety of these techniques such as HCl removal from the oceans, enhanced carbonate dissolution, accelerated weathering of silicate minerals and the “Cquestrate” process.

This latter process has its origins in the work by Kheshgi [1995] who proposed adding lime from the ocean to raise its pH. The lime would come from calcining limestone, a very old and well-understood process. The Cquestrate concept takes advantage of the locational flexibility of the process to exploit stranded energy. This section will focus on this scheme (see www.Cquestrate.com).

The calcination of limestone is already performed by the cement industry on a large scale, which can be used for comparison purposes as it operates on a scale not dissimilar to that proposed to *Cquestrate*. Cement can be manufactured by two principle processes – the wet and dry processes respectively; however, most modern cement works employ the more efficient dry process described here. The feedstock for cement manufacture is typically a mixture of limestone, with varying quantities of clay and blast furnace slag – called the ‘meal’. The meal is calcined in a two stage process. Stage one consists of pre-heating or pre-calcining the meal; introduction of this heat recovery stage in more recent cement works has enabled cement manufacturers to improve the thermal efficiency of the process markedly. In the pre-heater, exhaust gas from the rotary kiln that follows is used to pre-heat the meal to high temperature. A significant proportion of the calcination takes place at this point. Continuing, the now heated and partially calcined meal passes to one end of a large rotary furnace, fired with fuel from the opposite, tail end. At the tail end of the furnace, the product cement exits at high temperature. Key to cement manufacturing is the very high temperatures present in the rotary furnace as this is required to effect the silicate forming reactions necessary to generate Portland cement as opposed to just lime. The solid product leaving the rotary furnace is typically in the form of clinker – i.e. large lumps of cement a few mm in diameter. Cement is generated by grinding clinker in to the familiar fine powder.

Cquestrate would modify ordinary cement production as the clay and slag additions are superfluous, hence much lower temperatures are required. This would have two effects: a reduction in the fuel burn required, as the lower temperature furnace would consume less energy; and because lower temperatures are required and the silication reactions avoided, it may be possible to dispense with the rotary furnace altogether. As described above modern cement works generally embody a pre-calcination reactor. This is principally a means of heat recovery from the hot exit gases of the rotary furnace; however, the bulk of the calcination can occur in this reactor and it may be possible to provide sufficient firing into this furnace to drive the calcination process to completion without necessitating a rotary kiln. One other change wrought by *Cquestrate* is that Dolomite or Magnesite may be used instead of Limestone. This simplified operation means that the long-term cost of lime manufactured in this way should be bounded by the equivalent cost of, say, Portland cement (around $70/t).

The heat required to generate CaO or MgO from the respective carbonate is considerable, and must be derived by burning a fuel of some kind. However, the thermal efficiency of modern cement kilns is very high and the energy input approaches the theoretical minimum. To this must be added the work required for rock crushing and milling operations, all of which require energy; the key processes here are preparing the meal prior to calcination and post kiln grinding of the clinker. The latter is required to ensure a specific grain size for the eventual product – the size of the CaO or MgO grains is important to ensure that there is neither too rapid or too slow a dissolution, once the alkali is dispersed into the oceans.

The principal fuel used by the cement industry is coal, due to its low cost; however, cement kilns are ideal places for using low grade and waste fuels of all kinds, including those with a large ash content – incorporation of ash into the cement is usually considered beneficial. For *Cquestrate*, there are potential problems associated with heavy metal contamination of the calcined product, due to the transfer of the bulk of a fuel's ash to the oceans. Hence, clean fuels (i.e. low ash and sulphur content) such as natural gas, some fuel oils and biomass are the likely fuel options for *Cquestrate* where production of clean, calcined product is the only aim.

Clearly, for *Cquestrate* to succeed, the CO_2 released by both the calcination process, and the fuel burnt to drive calcination, must be caught using a CCS technology of some kind. Two principle techniques are suggested by the authors of *Cquestrate*.

1) *Use of an oxy-fuel system.* This requires some means of air separation and would be an extension of existing oxy-fuel technology.
2) *Separating the heating process from the calcining process, by the use of direct contact heat transfer.* The suggested heat transfer fluid is either molten iron or high temperature steam generated in a separate vessel heated by another combustion process. The flue gases of the two processes (combustion and calcination) are treated separately with the flue gas from combustion having a low carbon dioxide content, whilst the flue gas from the calcination is pure carbon dioxide.

The authors appear to have rejected traditional post-combustion scrubbing methods and their cousin, calcium looping systems. This would seem to be an oversight as in a recent study [Barker et al., 2009], the cement industry examined pre, post and oxy-combustion type capture systems and concluded that both post and oxy-combustion methods are viable for the cement industry at least. The same study rejected so-called pre-combustion methods (i.e. de-carbonisation of the feed fuel) as these suffer from the weakness that CO_2 is still generated in the calcination stage requiring, therefore, two capture systems.

As for option 2) above, the use of indirect heating appears likely to have many technical difficulties. The nearest equivalent is so-called allothermal coal gasification using nuclear heat. Allothermal systems require an energy carrier of some kind – usually compressed He gas – to transfer heat to the meal or burden via high temperature heat exchanger. However, the difficulty and likely energy penalties associated with producing a hot energy carrier are considerable, and more traditional CCS methods are likely to be the best option for *Cquestrate* (and cement manufacture).

Material and energy balance: Key to the success of the *Cquestrate* process is that the amount of CO_2 absorbed by the oceans seeded with CaO, is greater than that released in the calcination process used to generate the CaO in the first place. This is due to bicarbonate formation and in practice each mole of CaO added to the oceans absorbs A_f moles of CO_2. The value of A_f has been estimated to be in the range of 1.79 to 1.7 [Kheskgi, 1995] - in this work the more pessimistic value of Kruger will be used.

The fact that the absorption factor, A_f, is greater than unity means that the amount of limestone that must be hewn, transported, calcined and then dispersed at sea, and therefore the overall cost of the technology, is inversely proportional to A_f. In practice, assuming fuel is used to fire the calcining plant in the first place, the CO_2 associated with fuel burn must also be considered. However, as will be shown later, this extra CO_2 is of the order of another 0.35 moles for a natural gas fuelled plant. Assuming that CCS is adopted at the lime kiln of 90% efficiency each the amount of CO_2 absorbed – 1.33 t_{CO2}/t_{CaO}. Therefore, *Cquestrate* from a mass transfer perspective looks attractive.

Following on from this it is a simple matter to estimate the quantity of material and energy required to generate a certain quantity of negative emissions. The unit used in previous sections will be adopted here: namely all quantities will be quoted in terms of the amount of material or energy required, either in M.te for materials or in MW for energy, to collect 0.0569 G.t_{CO2}/yr of CO_2 emissions, which is equivalent to 10% of the UK's annual emissions. Using the equilibrium figures above, annual lime production in would need to be 42.6 M.t_{CaO}/yr.

Energy Penalty: Another important aspect of *Cquestrate* is the thermodynamics and economics of the calcination reactions. The heat required to drive these reactions is considerable, and can be derived by burning a fuel of some kind. Alternatively, use of an external heat source may be feasible – nuclear or solar. The actual energy input required in a modern calcination kiln is remarkably close to the numbers given above – i.e. the thermal efficiency of modern cement kilns is very high. However, to make cement requires various rock crushing and milling operations, all of which require energy; the key processes are preparing the meal prior to calcination and post kiln grinding of the clinker.

To estimate the overall energy consumption of the calcination stage in *Cquestrate*, comparison will be made with the best practice in the cement industry. Worrell *et al.* [Worrell *et al.*, 2001] estimated the aggregate primary energy consumption for all the processes required in cement manufacture including: the kilns themselves; all stages of meal preparation; and final clinker grinding stage. Taking the lowest energy consumption in each case, the aggregate is equal to 4.04 GJ/t_{CaO}, of which, 3.50 GJ/t_{CaO} is consumed in the kilns. To arrive at these figures an electrical system efficiency of 33% was used. In addition a further energy is required to affect CO_2 capture at these plants. Table 4, gives a summary table of aggregated energy cost per tonne of CO_2 collected.

Table 4. Energy costs associated with *Cquestrate* - *CaO* assumed.

Item	Heat input	Work input
Calcination process – thermal + electric	2729 MJ/t_{CO2}	48.2 MJ/t_{CO2}
CO_2 capture at lime kilns – thermal + electric	2247 MJ/t_{CO2}	320.9 MJ/t_{CO2}
Transport – shipping + 30% for land transport	N/A	10.2 MJ/t_{CO2}
Total	**4976 MJ/t_{CO2}**	**379.3 MJ/t_{CO2}**

Economics: To assess the likely financial cost of operating *Cquestrate*, the cost of cement production will be used as a benchmark. Barker *et al* [Barker *et al.*, 2009] has assessed the cost of operating a cement works with and without CCS. They assumed a dry process plant with 5-stage pre-calciner of nominal output 1 million tonnes per annum. Both post-combustion, using a standard amine absorbent, and oxy-fuel systems were examined. Based on optimised configurations for each capture technique, plant capital cost was evaluated, along with the cost of each tonne of CO_2 avoided and the cost of each tonne of cement generated. For the purposes of this report, the latter figure will be assumed to be representative of the cost of producing a tonne of *CaO* – these are shown in Table 5.

Table 5. Costing of a modern lime production plant both with and without capture – assuming coal or petroleum coke feed. (Currency conversion 1 $ = 1 €)

Production Cost	*No Capture*	*Post-Combustion Amine*	*Oxy-fuel*
$/tonne cement	65.6	129.4	81.6
Abatement Cost			
$/tonne cement		63.8	16.0
$/tonne CO_2 captured		59.6	34.3
$/tonne CO_2 avoided		107.4	40.2

As can be seen from Table 5, installing an oxy-fuel system is the cheapest option and only increases the cost of a tonne of cement by $16. This is to be expected given the large amount of CO_2 released from the calcination reaction, which makes post combustion systems uneconomic for cement production [Barker *et al.*, 2009].

One technology ignored by Barker *et al* was calcium looping, as part of a CCS scheme on a fossil fuel power plant, whereby the spent sorbent could be used directly to raise ocean pH. This would then obviate the need for the construction of a dedicated process for the production of the lime and reduce the economic and energy penalties significantly since they would be associated with the power plant CCS scheme.

An alternate costing was performed by Jenkins *et al.* [2010]. They found that the long-term cost of lime production could be about €32-50/tonne with carbon capture. Given that the process is simpler than the Portland cement process, and may entail, say 20% lower costs, from our perspective a figure of \$65/tonne of lime and \$51/tCO_2 sequestered.

Rollout potential: To implement *Cquestrate* the following processes must be undertaken:

A. Extraction of Limestone/Dolomite The amount of mineral extraction required is probably feasible given the almost unlimited supply of $CaCO_3$ and to a lesser extent $MgCO_3$. The US geological survey [Anon, 2009b] puts it more succinctly stating:

> *"Domestic and world resources of limestone and dolomite suitable for lime manufacture are adequate."*

Lackner [Lackner, 2002] collated the resource size of a variety of mineral carbonate and bicarbonate sources. Taking just the limestone, he estimated the global resources as being approximately 90 x 10^{18} tonnes. This is many times that required to remove all of the CO_2 in the atmosphere.

B. Infrastructure for the transport of the mineral to the calcination plant and from the plant to a deep water port: The cost of transport on land is significant for bulk materials in general, especially when their price to mass ratio is low. Ideally, therefore, any alkali production would take place as close to the coast as possible. Three commodities must be shipped limestone, clinker product, and coal assuming the latter is used as fuel for the calcination.

For the UK it is likely that the calcination plants would be built local to the country's two deepwater ports - Immingham and Port Talbot. This would allow for both the import of coal and conceivably limestone and also the dispersal of the calcined product. Using the cement industry as a benchmark, large amounts of clinker product are transported on land typically by train so an augmentation of the existing rail network serving these two ports would be required.

C. The calcination plant: To estimate the potential for escalating the production of *CaO/MgO*, comparison can be made with cement production. Annual global cement production is large; combining cement and clinker the world annual production is ca. 5.4 Gt (2009 figure from US geological survey's Mineral Yearbook [Anon, 2009b]). In recent years, cement production has increased dramatically, principally due to the increased output from China. To estimate the potential for increasing production given the almost infinite demand that Cquestrate would make for *CaO/MgO*, the period between 2000 and 2006 in China can be used as a benchmark, when production increased at a rate of 0.25 Gt/yr or 0.050 Gt/yr/trillion$\$_{GDP}$. Taking this figure and adjusting for the world GDP – 14.0 times greater than China's – yields a global escalation rate of 0.7 Gt/yr. Given that it is necessary to produce 11.4 Gt/yr of alkali to achieve the 1ppm/yr/CO_2 reduction target. This would imply that the target could be achieved in just over 16 years.

D. Transport at sea and construction of bulk carriers: A simple calculation can be made of the scale of the transport operation based on the requirement for 1% of UK CO2 emissions – i.e. 5.69 M.te$_{CO2}$. The ships are assumed to be 360,000 DWT cape class bulk carriers (the largest ships available) and have a maximum cargo of 350,000 tonnes. Based on an average round trip of 2100 Nautical miles, each ship could perform 24 trips per year. With this duty each bulk carrier could disperse sufficient alkali to absorb the equivalent of 2% of UK CO_2.

A number of factors limit the roll out of this operation. Critical in our view is the scale of the ship building programme needed.. There are only 40 shipyards in the world able to build cape size bulk carriers and, typically, from laying down to launch each ship occupies the yard for 12 months. The roll out time for a UK based implementation of Cquestrate is affected by the market for large ships, and in particular, whether or not Cquestrate is implemented internationally or just by the UK.

A further restriction is the number of ports in the world that are able to handle the largest bulk carriers. From a UK perspective, only two ports can handle ships of over 150,000 DWT.

Immingham on Humberside, which has a capacity of 200,000 DWT and Port Talbot in South Wales, which is restricted to 180,000 DWT. Considering the location of the two ports, these are located on the North and Irish Sea coasts respectively and would clearly form the hub of a large scale industrial system - generating lime from locally hewn limestone and imported or perhaps indigenous coal. Such a centralised system would clearly have implications for the local environment, as Port Talbot in particular is located in an already congested region. For this reason, and the desirability of increasing the capacity of the ports so that the largest cape size bulk carriers could be handled, additional porting facilities would probably need to be built.

In practice it is our view that one need not take a UK-centric perspective on roll-out but rather support roll-out where it makes the most sense from an economic, energetic and GHG point of view. This will most likely result in roll-out elsewhere, but perhaps with major returns related to IP etc in the UK.

7.2 Biochar

7.2.1 Summary

- Biochar is produced by the combustion of biomass in a low-zero oxygen environment, called pyrolysis. This produces three products - a solid fraction known as char, a liquid fraction and a gaseous fraction. The latter two products can be used to generate energy and the char can be land filled or used to enrich agricultural land, where it has been known to enhance crop yields, - effectively locking the carbon and achieving negative emissions. This multiproduct nature again provides a driving force for early deployment. There is, however, some uncertainty on how much char would be used as a soil conditioner and how much might find its way into BECCS-type applications.
- Based on UK biomass availability upper bound negative emissions projections range from to 2.0 to 9.0 % of gross UK emissions in 2008. In reality the feedstock streams that are allocated to pyrolysis and char production will be dependent upon economics of feedstock production and the merits of burying or combusting char.
- The process technology is considered to be a small scale and non-capital intensive which suggests that the process lends itself to farmers, small landowners and local authorities in developed nations and in developing nations will assist in rural diversification and poverty alleviation [UKBRC, 2009].
- There are substantial uncertainties with the pyrolysis process technologies. Present projections are based on small scale systems and the potential impact of scaling up processes, improvements from learning by doing and agronomic / yield benefits of adding biochar to soils make the calculation of the economics of biochar production at the commercial scale extremely difficult to deduce. It has been suggested that subject to feedstocks being produced at <$100/odt the abatement cost will be around $30 to $40/tonne [DECC Workshop, 2009].
- The literature database for biochar is limited and much work remains to be undertaken along the entire biochar value chain. The most salient areas of uncertainty that require further research include: influence of pyrolysis and feedstock on biochar yield and stability; the stability of carbon in the char and its interactions in different conditions; storage capacity of the char in soils and effects on yields in different climates; and the life cycle and economics of biochar production from different feedstock streams.

7.2.2 Detailed evaluation

Biochar production involves converting biomass into char by thermal processing or pyrolysing in a low or zero oxygen environment. The pyrolysis 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. A concept diagram is shown in Fig 3.

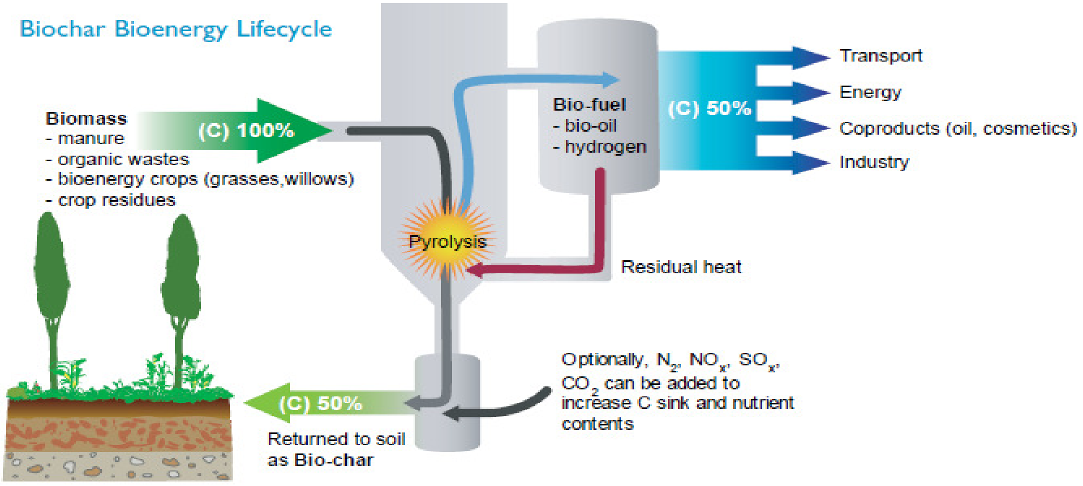

Fig 3. Concept diagram of low-temperature (slow) pyrolysis bioenergy with biochar sequestration. Typically, about 50% of the pyrolysed biomass is converted into biochar and can be returned to the soil [Lehmann *et al.*, 2006].

Biomass feedstock is characterised by a high chemical oxygen content, high moisture levels and low mass and volume specific calorific value. As a result, if the quantity of char produced is maximised, much of the calorific value of the biomass ends up in the char or in the latent heat of the water vapour driven off in the pyrolysis process. However, by modifying the pyrolysis process significant amounts of liquid fuels can be generated, but only at the expense of reducing the amount of char generated. Hence, there is a trade-off between maximising negative emissions and generating renewable bio-fuels. However, the need to trade off negative emissions (via biochar) against energy production from the limited supply of raw material is obviously largely avoided if the biomass is burnt in power stations with CCS – i.e. BECCS – see next section.

Advocates of biochar state that, the process could generate a potential carbon sink of 1 Gt_C/yr by 2030 [UKBRC, 2009] rising to 5.5 to 9.5 Gt_C/yr by 2100 [Lehmann *et al.*, 2006]. For the UK, if all of the biomass resource was made available for pyrolysis to biochar production, it has been estimated that between 5.7 and 8.0 Mt_C/yr could be sequestered [Wallage *et al.*, 2009].

Despite the recent proliferation of literature on the subject, there remains much uncertainty in all areas of the biochar process technology in particular: the pyrolysis process itself; the retention of carbon by the soil; and the impact if any that biochar has on soil quality. In addition unlike BECCS, biochar is considered to be a small scale and non-capital intensive process technology suitable for farmers, small landowners and local authorities in developed nations, while in developing nations it may assist in rural diversification and poverty alleviation [UKBRC, 2009].

Pyrolysis methods: The yield of char, liquids, and gases from pyrolysis of biomass is influenced by the conditions of the process. In general, high temperatures accompanied by short residence time yield more liquid product – generally described as fast pyrolysis. To maximise the yield of char and hence the negative emissions potential, lower temperatures and longer residence times are required – so called slow pyrolysis. Table 6 summarises the review of Bridgewater [Bridgewater, 2007] and gives typical yields for various modes of pyrolysis.

Table 6. Typical product yields off char, liquid and gases for different modes of pyrolysis [Bridgewater, 2007**]**

Mode	Temperature (°C)	Residence time (s)	Yield – dry basis		
			Char	Liquid	Gas
Fast	500	*1*	*12 %*	*75 %*	*13 %*
Intermediate	500	15	*20 %*	*50 %*	*30 %*
Slow	400	60+	*35 %*	*30 %*	*35 %*
Gasification	800	60+	*10 %*	*5 %*	*85 %*

The situation is further complicated by the fact that the properties of the biochar are also highly dependent on the feedstock used [Downie et al., 2007], which again has an impact on char sequestration potential.

Scalability of Biochar: The Scalability of biochar process technology is dependent on the following main factors:

- Global / UK biomass potential;
- The scalability of the pyrolysis process technology
- Logistical considerations for large scale biomass feedstock supply chains.

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 [IEA, 2009; Berndes et al., 2003; Smeets et al, 2007; Dornberg et al., 2008]. Similar disparities exist for the UK biomass potential. The key reasons for these discrepancies are:

1) Definitions and boundary conditions for feedstocks / feedstock streams are highly varied from one study to the next, which makes direct comparison between studies problematic.
2) The most widely used feedstocks for the production of heat and electricity from biomass, at present, are forestry and agricultural residues and various organic wastes, rather than sugar, grain, and vegetable oil crops, which are used for liquid biofuels production for transport.
3) Most of the divergence of forecasts in biomass production stems from disagreement about the level of agricultural productivity achievable – especially in developing countries [IEA, 2009]. Critically, this affects the amount of land required for food production and hence that left over for fuel production.
4) Most studies consider biomass plantations as the most important source of biomass for energy, but the productivity of these is contentious [Berndes et al., 2003].
5) The potential impact of an expanding bioenergy sector and its interaction with other land uses, such as food production, biodiversity, soil and nature conservation, and carbon sequestration has been insufficiently analysed [Berndes et al., 2003].

The current contribution of bioenergy to UK primary energy was ca. 112.2 PJ [UKERC, 2010]. Adapting Dornburg *et al*. [Dornberg *et al*., 2008] one projection for the high and low category and 2 for the medium is made in table 7 - these will be used for UK based scenarios of negative emissions potential from Biochar and BECCS.

Table 7: Selected UK Biomass Assessment Potential Studies (See Appendix X for detail of studies).

Range	Study	Potential in 2030 (PJ)
Low Range 0 - 299 PJ pa	Carbon Trust 2005 - Biomass Sector Review	300
Medium Range 300 - 799 PJ pa	Kilpatrick 2008 - Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities.	517
	UK Biomass Strategy 2007	678
High Range 800 -1000+ PJ pa	E4 Tech 2009 - Biomass Supply Curves for the UK: A report for DECC.	1,084

Due to scale issues, as would be expected the extent of primary energy forecast for the UK is also 3 orders of magnitude smaller than global estimates.

With regards scale of pyrolysis technology, there is as yet no `dominant design'. Slow pyrolysis plants range from 48 to 96t/d commercial plants; to gasification stoves in developing nations able to produce a few kg/hr. Fast pyrolysis systems are better developed with plans for 400t/day systems [Bridgewater, 2007].

In order to develop the full potential of Biochar an efficient and large scale logistical chain will have to be established. The IEA [IEA, 2009] highlighted the key issues that will need to be considered.

- **Energy density:** Biomass has a low energy density and a high moisture content when compared with fossil fuels. This affects both the behaviour of the fuel in combustion and the fuel's transport cost.
- **Economics:** The economics of bioenergy plants generally become more favourable with increasing scale. However, feedstock costs typically rise as required feedstock volumes increase, due to longer transport distances involved in supplying such large quantities of biomass. Densification of the biomass at source can mitigate this effect somewhat.
- **Seasonal variability**: The availability of locally sourced biomass is inherently seasonal making medium (month) to long term (annual) storage essential. There are also seasonal variations in moisture content and chemical composition.
- **Transportation**: Due to the low energy density of the biomass, transportation by boat is far superior to train or truck [Whittiker et al., 2009]. Low density biomass energy carriers such as chips and bales are often transported by truck and maximum economic transport distances are typically limited to around 100km.
- **Quality of feedstock:** Feedstock quality for electricity production from direct thermal combustion technologies is less quality sensitive than for biomass intended for conversion to transport fuels.

  In order to overcome these issues, the key areas that require development are:

  - Advanced densification (thereby increasing energy density);
  - pre-treatment technologies (thereby facilitating storage without degradation of feedstock quality and energy density); and
  - diversifying procurement geographically and by biomass types (thereby reducing the impact of seasonal availability of different feedstocks).

Negative Emissions Potential: The net negative emissions for biochar are affected by the steps involved in the growing, harvesting, processing, storing and transporting the biomass that is eventually pyrolysed. For this study, we have assumed that the pyrolysis process is slow as this optimises the amount of char generated and hence the higher potential for negative emissions.

Char (or biochar), contains a carbon content of between 60 to 90% [Guar and Reed, 1995]. The carbon is fixed though a fraction is relatively mobile (termed the labile and super-labile fractions). Most of the remainder will mineralise eventually (over a period of 100 to 1000 years). A very small proportion is inorganic (ash). Char can be used as a source of fuel or for soil amendment. It is claimed that adding biochar to the soil has the added benefit of increasing crop yields due to improvements in soil quality and water retention and also can act as a substitute for man-made nitrate fertilizers. Only a few groups - e.g. [Hammond, 2009] and [CSIRO, 2009], have examined the effectiveness of biochar in this regard, and the results are inconclusive.

Pyrolytic liquids (bio-oils) can be used for generating heat, power or chemicals. As fuels, they can be used as a substitute for gas oil [CSIRO, 2009] and may also be upgradable to transportation fuels [Bridgewater, 2007] - though this final use is still at a development phase.

Synthesis gas or syngas is the gas product of pyrolysis. It consists mainly of carbon monoxide, carbon dioxide, methane and hydrogen in varying proportions. The energy can be used directly as a fuel source for pyrolysis heat production, generating heat and electricity or as an intermediate for synthesising liquid fuels and industrial chemicals.

The total mass of the products is equal to the mass of the feedstock material as there is no loss as ash – it remains trapped in the char. In terms of energy balance, however, some energy is lost as heat from pyrolysis and some energy is also required to run the pyrolysis process (dry the feed, heat to temperature and drive the equipment). In this study, this loss of energy is considered notionally carbon neutral - the CO_2 released due to the production of the biomass is therefore not considered in the carbon balance. Assuming at least some char is buried in the soil or in landfill, and it is stable for a long period of time, the process therefore becomes carbon negative.

Phases in the biochar life cycle where CO_2 may be sequestered / avoided [Gaunt and Lehmann, 2008] are:

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

The biomass feedstock available for undergoing pyrolysis in these calculations is based on net availability of feedstock after food needs of a growing global population, biomaterials and bio-fuels for the transport sector. In addition due to the generation of 3 products during pyrolysis - carbon and energy allocation will be based on mass and energy content, respectively. However, as the intention of pyrolysis and biochar is carbon sequestration rather than energy generation, the need for a reference fuel is not required.

The ability for biochar to retain carbon is fundamental to the process as a negative emissions technology and the subject of much debate and research [Biofuels Watch, 2008] and [Lehmann et al., 2009] and is affected by both the feedstock and the pyrolysis process [Anon, 2009g], [Brownsort, 2009] and [Hammond, 2009]. For the sake of the calculations here, it has been assumed that char has a long term stability in soils - whereby super labile (5%) and labile (10%) carbon fraction is released relatively rapidly (within 5 to 10 years) and the stable fraction has a mean residence time of 1000 years which mineralises linearly in that time [Lehmann et al., 2009]. With a reference scenario of 200 years, this translates into 68% of the char's carbon being retained in the soil and hence sequestered. It was assumed that all of the CO_2 released during the pyrolysis process, and that generated by combustion of the gaseous and liquid bio-fuels produced, escapes into the atmosphere.

Based on the biomass assessments as outlined above a spreadsheet model was used to estimate the actual performance of biochar as a negative emission technology. The model framework and assumptions are as follows[9]:

- Feedstock supply chains were broken down into 5 separate streams - Agricultural Residues, Wood / Forest Residues, Perennial Energy Crops, Conventional Energy Crops and Wastes for all biomass assessments reviewed for the UK and globally;
- Coefficients for the energy composition per oven dried tonne (odt) of each feedstock stream according to the study classification were derived;
- Life Cycle Assessment (LCA) in terms of GHG and energy balance for production, harvesting, storage, processing and transport to the bio-energy plant gate for each feedstock stream according to the study classification were derived;
- Percentage carbon content of the feedstock according to the study classification were derived;
- The feedstock is subject to slow pyrolysis process. The LCA GHG emissions were allocated to biochar based on % carbon allocation in the pyrolysis process;
- Avoided emissions from the use of biochar in soils has not been taken into account due to the uncertainties in the figures for this area. This will lead to the calculations underestimating the negative emissions potential of biochar;
- Substitution of fossil fuel by liquid and gaseous fraction has not been taken into account (though the emissions for biomass are assumed to be carbon neutral and therefore negative emissions calculated are absolute figures); and
- Biochar production is assumed to on a commercial rather than small scale.

During the compilation of the data set, a hierarchy was observed in terms of impact of each feedstock on net CO_2 emissions. This hierarchy runs from the most efficient to the least as follows: wastes, perennial, wood / forest residues, conventional energy crops and agricultural residues[10].

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[9] For details of these feedstock supply chains, coefficients for energy per oven dried tonne, GHG and energy balance and carbon content of different feedstock streams refer to a forthcoming more detailed version of this report.

[10] The impact of supply chain on GHG footprint ranges from an additional 0.2% (by mass) GHG for every tonne of carbon emitted from the bio-energy plant per tonne of wastes burned and 35.6% for agricultural residues. The impact of the feedstock mix on the negative emissions profiles for the LCA component of the process technology will need to be considered as this will demonstrate the impact of this variable on negative emission process efficiency as well as where the future improvements in the GHG profile may be made.

Table 8. Negative emissions and energy potential of biochar in the UK for 2030

Study	Primary energy[1] (PJ)	LCA (PJ)[2]	Energy in syngas (PJ)	Carbon sequestered [3] (Mt$_{CO_2}$/yr)	Total carbon emitted in the process[4] (Mt$_{CO_2}$/yr)	Net negative emissions [5] (Mt$_{CO_2}$/yr)
Carbon Trust [2005]	295	7.9	101.4	12.8	19.0	10.7
Kilpatrick *et al.*, [2008]	512	15.6	176.2	23.2	35.2	18.6
UK Biomass strategy [2008]	628	12.7	216.1	33.1	47.4	29.4
E4 Tech [2009]	1079	15.3	371.3	51.8	72.2	47.9

1. Study biomass potential less 4.7 PJ allocated to transport biofuels.
2. Energy utilised in the process of producing, harvesting, processing and transporting the feedstock to the pyrolysis plant and allocated to the syngas on an energy basis.
3. Total carbon sequestered by Biochar undergoing slow pyrolysis with a Carbon Stability Factor of 68 % (see appendix 1).
4. Carbon emitted during the process incorporating that from LCA from production, harvesting, processing and transporting and the 56.8% lost from the pyrolysis of the feedstock, labile, super labile fraction and linear decay of stable fraction after 200 years. The LCA allocation to biochar was based on % carbon allocation for the process of 63.4%.
5. Net negative emissions is that which is captured by the stable carbon fraction within the biochar less the emissions from LCA of feedstock production, harvesting, processing and transporting - this figure takes into account that the carbon emitted from the biomass and not stored in the biochar system is carbon neutral. The LCA allocation to biochar was based on % carbon allocation for the process of 63.4%.

Table 8 shows the potential for biochar in the UK at the year 2030 based on indigenous biomass: Biochar's negative emissions potential ranges from 10.7 to 47.9 M.t$_{CO_2}$/yr (the equivalent figures for fast pyrolysis are from 2.64 to 15.2 M.t$_{CO_2}$/yr). Compared to the UK's current net CO_2 emissions of 569 M.t$_{CO_2}$/yr, the potential for UK centred biochar is modest. Hence, imports of biomass would be necessary for biochar to make a significant impact on UK CO_2 emissions. In addition compared to using the same biomass in BECCS complaint power stations, the net negative emissions are approximately half.

Table Table 88 also shows the energy content of syngas produced by slow pyrolysis process and takes account of the energy used in the feedstock production processes and the energy loss in the pyrolysis process [Downie et al., 2007]. For the UK, from 101 to 371 PJ of primary energy could be recovered. This compares with the current UK electricity consumption of about 1,364 PJ in 2008.

The Economics of Biochar: The substantial uncertainties with the pyrolysis process technologies which are based on small scale systems, the potential impact of scaling up processes, improvements from learning by doing and agronomic / yield benefits of adding biochar to soils make the calculation of the economics of biochar production on the commercial scale extremely difficult. Though it has been suggested that subject to feedstock being produced at <\$100/odt the abatement cost will be around \$30 to \$40/t$_{CO_2}$ which is similar to costs typically cited for the cost of CCS or offshore wind [DECC Workshop, 2009].

Risks and future work: The biochar process technology requires a substantial amount of research along the entire value chain for its negative emissions credentials to be fully verified. [The Royal Society, 2009a]. Particular areas where research is considered to be required are:

- Influence of pyrolysis on biochar yield and stability
- Mean Residence Time (MRT)
- Effects on productivity
- To Burn or Bury Biochar

Roll-out potential (Negative Emissions Curves): Based on a spreadsheet analysis[11], UK negative emissions projections for biochar production have been extrapolated to 2030 and are shown in Fig 44. From this, the required pyrolysis plant build rates have been estimated these are given in Table Table 99.

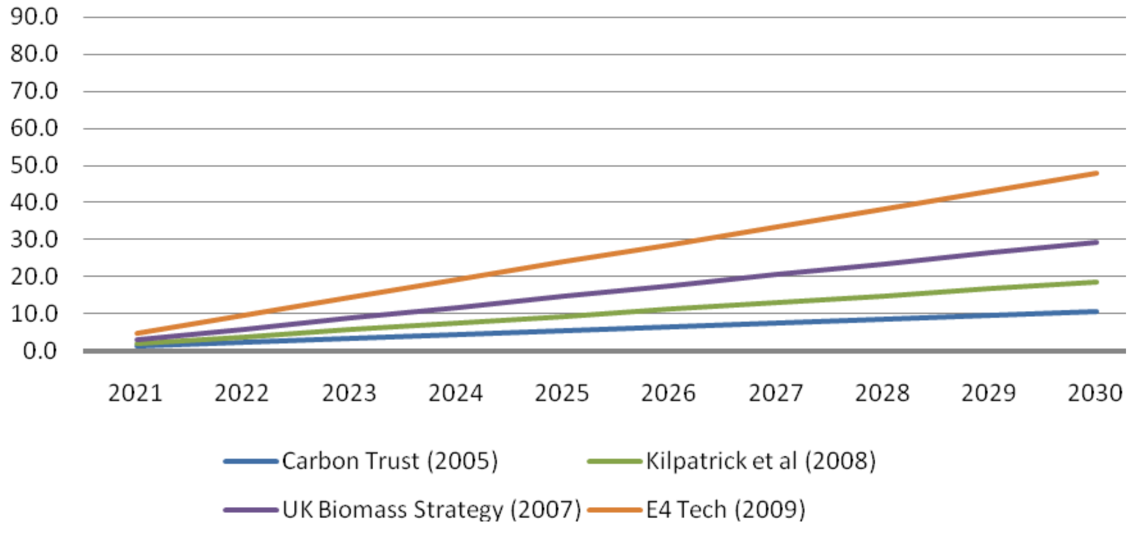
Table 9. Input and output data and for the Biochar negative emissions curves

				Quantities of biomass odt in 2030[3]	
Biomass Assessment Study	No of 400 t/day slow pyrolysis plants[1]	Required build rate from 2020 - 2030[2] (yr^{-1})	Total net negative emissions in 2030 (M.t$_{CO2}$/yr)	Wood/ forest residues (M.t/yr)	Perennial energy crops (M.t/yr)
Carbon Trust [2005]	109	11	10.7	13.6	-
Kilpatrick et al., [2008]	205	20	18.6	3.67	13.9
UK Biomass strategy [2007]	345	35	29.4	4.09	3.70
E4 Tech [2009]	471	47	47.9	11.2	30.2
Central prediction[4]	282	28.3	26.7	8.14	15.9

Notes:

1. No of 400t /day slow pyrolysis plants required to burn feedstock potential running at 97% capacity during the year requiring 141,620t of biomass pa^{-1}
2. Build rate for slow pyrolysis plants based on odt feedstock potential over the 400t /day slow pyrolysis plants feedstock requirement.
3. Quantities of biomass in odt for each projection in 2050 for global and 2030 for UK studies.
4. The central prediction is an arithmetic average.

Fig 4. Negative Emissions Curve (M.t$_{CO2}$/yr) for the UK ramp up of Biochar between 2020 to 2030 assuming linear increase in biomass production.



Based on the figures in Table 9, depending on the biomass projection chosen, for the UK between 109 and 471 400t/day scale slow pyrolysis plants would be required to produce the amount of char for the upper and lower projections, which translates into a build rate of 11 to 47 pa between 2020 to 2030, would enable between 10.7 to 47.9 M.t$_{CO2}$/yr to be sequestered.

Build rate precedents: Such is the nascent state of pyrolysis technological development there is no precedent available for the build rates of pyrolysis plants. At present, the largest commercially

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[11] Details of how the projected emissions curves were derived from the spreadsheet model and the global scale issues are discussed in a forthcoming more detailed version of this report

available slow pyrolysis plant, runs at a 2,628 t/year [Hammond, 2009]; this is < 2% of the rate that these projections are calling for, suggesting that there has to be an increase in plant scale by a factor of >50 within the next 10 years - the feasibility of which is not known.

The impact of the total life cycle costs associated with a large pyrolysis plant build programme has not been incorporated into the negative emissions projections. These costs are likely to be substantial depending upon the reference scenario. The impact of an international trade in biomass has been shown to have a minimal impact on negative emissions profile of BECCS – see section 8 below.

Biochar as a technology, has not yet been adequately researched and characterised - much work remains to confirm its carbon negative credentials and agronomic benefits. As a result it is not currently eligible for carbon credits. Furthermore, the biochar process technology does not lend itself to a reliable system of verifying how much carbon is stored. The monitoring, verification, and reporting of the process as a carbon negative technology would therefore be intricate and subject to practical difficulties.

8 Review of Type '3B Systems

8.1 BECCS – Biomass Energy with CCS

8.1.1 Summary

- Biomass energy with carbon capture and storage (BECCS) involves the direct combustion of (low grade) biomass fuels in a conventional power plant with the capture of greenhouse gas (GHG) emissions generated using carbon capture and storage (CCS) technology. The capture of the GHG emissions is fundamental to establishing the technology's negative emissions credentials.
- Based on UK biomass availability, the potential negative emissions projections range from 5Mt to 22 Mt/C pa^{-1}, which is the equivalent to 4.0 to 15.5 % of gross UK emissions in 2008.
- Optimistic, minimum costs of £125 - 150/tCO_2 captured have been calculated, which is offset by Renewables Obligation to £54 to 70/t CO_2 less the revenue from the sale of electricity which ranges from £29 – 68/MWh.
- The greatest areas of uncertainty in the process technology are the ability for CCS technology to be introduced in a timely manner and the impact of large scale biomass plantation development on the wider eco-sphere in terms of ecosystem services, biodiversity and from direct and indirect land use change.
- The BECCS process technology is considered to lend itself extremely well to compliance requirements due to the ease of monitoring, reporting and verification of negative emissions within any international GHG emissions mitigation framework agreement. ***Overall, of the technologies studied in this report, this has the greatest maturity and there are no major practical barriers to its introduction into today's energy system. The presence of a primary product will support early deployment.***

8.1.2 Detailed evaluation

Biomass energy with carbon capture and storage (BECCS) involves the direct combustion of biomass fuels in a conventional power plant fitted with CCS. By growing Biomass, CO_2 is drawn from the atmosphere by photosynthesis. This biomass is then harvested, stored, dried, and normally processed into to pellets, bales or chips. This raw fuel is then transported to the bio-energy power plant, where it can be used to generate power. Assuming CCS is installed at these plants, a significant proportion (approximately 90%[12]) of the CO_2 released in combustion can be captured and sequestered.

BECCS plants have the potential to generate negative emissions of CO_2. The extent of the negative emissions depends on the CO_2 capture efficiency, along with the efficiency of the processes involved in biomass production, its harvesting, storage, processing and transport to the power plant. Without CCS, Biomass plants are at best carbon neutral and can have a net negative emission even

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[12] Though this figure is variable, and could be higher, depending upon the economics of sequestering carbon.

once all the carbon expended in the supply chain of the biomass is considered. Figure 5 below is a simple schematic showing the main carbon and energy flows in the process.

Due to the fact that BECCS and Biochar are based on global and UK biomass potential - they share many of the same logistical problems in developing an end to end process. However, BECCS differs principally in the scale of the combustion facilities - national rather than local facilities - and the sequestration potential of BECCS is also quite different.

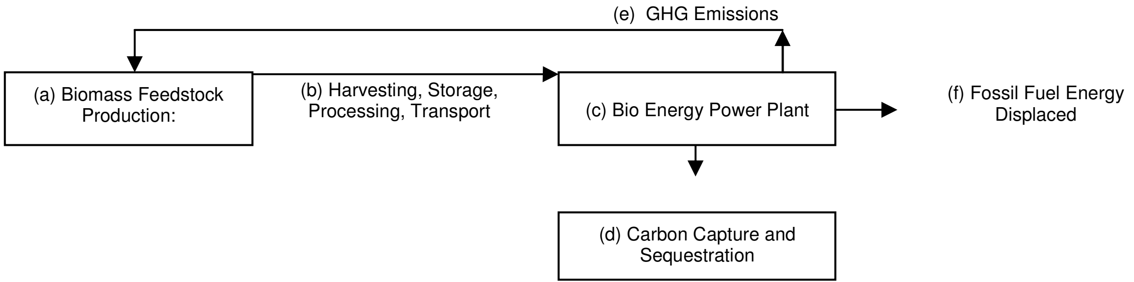

Fig 5. A schematic diagram of the carbon and energy flows associated with BECCS.

The energy flow mirrors the carbon flows with energy being utilised during the biomass production process through to transport to the biomass plant. The two key areas in the process that have the greatest impact on energy balance are those associated with the effectiveness of the bio-energy plant to convert biomass generated thermal energy to electricity, and the energy penalty associated with the CCS process. The energy conversion process is in effect the same as in a conventional fossil fuel power station – e.g. the UK's Drax Power Station generates electricity from coal and has an energy conversion efficiency of ca. 40% (Lower Heating Value (LHV)), though there are supercritical plants in Germany that are 45% efficient. Though present biomass and co-fired plants run at lower efficiency, for the sake of this study the efficiencies are assumed to be equivalent to those in coal power plants.

In order to scale up this process technology consideration of the following issues are required:

- Energy conversion efficiency in the thermal conversion to electricity production and Global / UK bio-energy plant potential rate of development; and
- Carbon capture and sequestration efficiency, energy penalty impact and potential rate of development;

Biomass potential and the logistical issues highlighted in the biochar section are also relevant to the BECCS process technology end to end supply chain development.

The calculations of negative emissions potential for BECCS for this study are based on primary energy potential of biomass feedstocks both globally and within the UK. It has been assumed that biomass is primarily developed for global population food needs, and that the remaining biomass potential is allocated to three other demands: biomaterials, biofuels for the transport sector first and what remains to electricity generation in the BECCS process. In terms of fossil fuel substitution, it is assumed that coal fired power plants are replaced by BECCS plants.

According to the IEA [IEA, 2009], a multitude of technologies exist, or are being developed, to convert diverse biomass feedstocks to a wide range of solid, liquid and gaseous fuels, and to heat and electricity. This study focuses on two technologies: direct thermal combustion for the generation of electricity and gasification combined cycle for the generation of electricity. A summary of the present conversion efficiencies and projected conversion efficiencies for 2050 are detailed in table 10, below.

Table 10: Summary of parameters for the two conversion technologies - adapted from Hoogwijk et al. [Hoogwijk et al., 2005].

	Electricity 1	Electricity 2
Conversion route/type of fuel	Direct Combustion	Gasification-Combined Cycle
Typical Scale (MW)	20 - 1200	20 - 1000
Status	In operation	Demonstration
Conversion Efficiency (%) (year 2000)	40	40
Conversion Efficiency (%) (year 2050)	50	56

UK and Global biomass power generation capacity is small at present. The current dedicated biomass power generation capacity in the UK is approximately 200 MW [Perry and Rosillo-Carlo, 2007]. For the levels of potential biomass production suggested in the estimates from table 7 (Section 6), the UK's biomass, power generation capacity would need to increase between 50 to 200 fold, respectively, to meet the lower and upper projections by 2030.

With regard to CCS potential the three key issues that need to be addressed are: What is the sequestration efficiency; what will the energy penalty be; and when will it be available on a globally deployable basis? For this study the following are assumed:

- The sequestration efficiency (i.e. the fraction of CO_2 collected) of CCS, is assumed to be 90% [Gibbins and Chalmers, 2010].
- The energy penalty for capture has been assumed to be fixed at 1.219 GJ/tCO2 [McGlashan and Marquis, 2007]. This figure is based on a review of conventional power plant fitted with amine scrubbing systems and is equivalent to an 11.4 % reduction in energy conversion to electricity. For this study, the energy required to transport CO_2 from the bioenergy power plant to storage reservoir and compress it at depth has not been taken into account; this is not likely to have a significant impact on the figures derived.
- That CCS technology will become available progressively, with demonstration projects being on stream by 2015 [Florin and Fennell, 2010] and full roll out in lead countries like the UK in the decade 2020 - 30 [Gibbins and Chalmers, 2010]

Negative Emissions Potential: In order to calculate BECCS negative emissions potential a spreadsheet model was developed within the following framework and assumptions[13]:

- Feedstock supply chains were broken down into 5 separate streams - Agricultural Residues, Wood / Forest Residues, Perennial Energy Crops, Conventional Energy Crops and Wastes for all biomass assessments reviewed for the UK and globally;
- Coefficients for the energy composition per oven dried tonne of each feedstock stream according to the study classification were derived;
- Life Cycle Assessment (LCA) in terms of GHG and energy balance for production, harvesting, storage, processing and transport to the bio-energy plant gate for each feedstock stream according to the study classification were derived section; and
- Percentage carbon content of the feedstocks according to the study classification were derived.

During the compilation of the data set and derivation of coefficients, the following observations were made with regards to each feedstock stream.

- There is a hierarchy of feedstock streams in terms of impact on the GHG profile per odt from production to transport to the bio-energy plant gate. This hierarchy runs from the most efficient to the least as follows: wastes, perennial, wood / forest residues, conventional energy crops and agricultural residues - see footnote 10.
- The lower energy composition of biomass feedstock relative to the reference fuel, in this case coal, is likely to result in a higher emissions factor per unit of energy output.

A number of different metrics can be used to evaluate negative emissions systems; in this work the net negative emissions reference balance will be used This is the net impact of the emissions

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[13] For details of these feedstock supply chains, coefficients for energy per oven dried tonne, GHG and energy balance and carbon content of different feedstock streams refer to a forthcoming more detailed version of this report.

produced throughout the process less those that are carbon neutral (i.e. that which will be re-sequestered by biomass) against that which is sequestered relative to a reference fuel.

Table 11. Negative emissions and net energy potential of BECCS based on projected biomass output in the UK for 2030

Biomass Assessment Study	Primary energy (PJ/yr)^1	Net energy output (PJ/yr)^2	Carbon sequestered^3 (M.t$_{CO_2}$/yr)	Total carbon emitted in the process^4 (M.t$_{CO_2}$/yr)	Net negative emissions relative to reference fuel^5 (M.t$_{CO_2}$/yr)	Reference ratio^6
Carbon Trust [2005]	295	82.0	26.7	6.30	21.3	642%
Kilpatrick et al [2008]	512	139.9	48.4	12.6	35.7	495%
UK Biomass strategy [2007]	628	158.4	69.3	13.6	45.4	776%
E4 Tech [2009]	1079	286.6	108	18.1	82.4	1343%
Central prediction	629	167	63.1	12.7	46.2	

Notes:

1. Study biomass potential less 4.7 PJ allocated to transport biofuels.
2. Variation emissions factor for biomass combustion for the production of electricity relative to a reference fuel of coal at 40 % conversion efficiency (1164.9 kg/CO_2 per MWh) and a conversion efficiency of 50% (788.3 kg/CO_2 per MWh) and reduced CCS energy penalty.
3. Total carbon sequestered by CCS system with an efficiency of 90%.
4. Carbon emitted during the process incorporating that from LCA from production, harvesting, processing and transporting and the 10% lost from the combustion of the feedstock.
5. Impact of the substitution of coal by biomass. The coal reference fuel is based on a conversion efficiency of 50% (0.788 t$_{CO_2}$/MWh) and reduced CCS energy penalty for 2050 to 0.804 GJ/t$_{CO_2}$. The lower emissions by coal per unit of electricity produced means that not all net emissions by BECCS would have been produced had coal been producing the electricity.
6. Reference Ratio – net negative emissions reference balance - see definition, section 5 above.

Table 11 shows that the UK's negative emissions potential ranges from 21.3 to 82.4 M.t$_{CO_2}$/yr compared to the UK's net emissions of 569 M.t$_{CO_2}$/yr for 2008. The UK's biomass potential from locally grown biomass is small, and therefore to make a significant impact on UK CO_2 emissions, the import of biomass would be necessary. In terms of the requirement for sequestration capacity, current projections are that between 26.8 to 108 M.t$_{CO_2}$yr is needed. In and around the UK, it is estimated that we can store 150 Gt CO_2 [Gibbins and Calmers, 2010] – we are not therefore including storage as a technical limiting factor.

From table 10, for 2050, to assess the potential net energy output at 50% conversion efficiency and with an energy penalty for capture of 0.804 GJ/t$_{CO2.}$ a net electricity production of between 123.5 – 443.0 PJ, should be achievable. This compares with the UK's annual electricity consumption of 1,364.4 PJ in 2008 (9 to 32 %).

Economics: BECCS costs are similar to biofuel production but more expensive than fossil fuel CCS options due to the expense of the biomass relative to fossil fuel (Royal Society, 2009a).

Optimistic and minimum costs of £125 - 150/tCO2 captured have been estimated; these are offset by the Renewables Obligation subsidy to £54 to 70/tCO2. Costs are further offset by revenue from the sale of electricity which ranges from £29 - 68/MWh (DECC Workshop figures, 2009).

Knock-on Benefits: The development of a BECCS biomass supply chain of a size to impact global GHG trajectories suggests the need for the establishment of a robust global agricultural sector supporting both food production and biomass supply. Not only would this have the potential environmental benefit of improving management of land use with better soil restoration, the creation of vegetation filters and possible reduction of wildfire risk. It would also offer additional benefits; including a reduction in poverty by stimulating stagnant agricultural sectors especially in equatorial regions [UKBRC, 2008], but it would require significant reorganisation of the international trade system [Doornbosch and Stienblick, 2007]. The potential use of waste as a feedstock would also result in probable improvements in waste management and resource efficiency as the economic value of waste products is realised [The Economist, 2009].

Areas of Uncertainty: There are areas of uncertainty with regards the widespread implementation of the BECCS. The most critical are described below:

- The rollout of CCS technology – a number of energy system models assume that this will be widespread by 2020;
- The development of a large scale, biomass plantation and transport system;
- Potential impact on use of land for food production and bio-energy, especially in the developing world, which is likely to be a key supplier of biomass to the UK; and
- Potential positive and negative impact on water availability, soil quality, biodiversity and ecosystem services, soil organic carbon emissions from indirect land use change (ILUC).

In the last 30 years, the world population has increased by 123% from 3 Bn to 6.7 Bn, while the area of agricultural land has only increased from 4.51 to 4.93 BHa [The Royal Society, 2009b]. However, due to the anticipated rise in the world population, in the next 40 years, it is estimated that food production will have to increase by 45%. In principle, this can be achieved by improvements in productivity [The Royal Society, 2009b], however, increased land usage is likely. Expanding land use for the production of dedicated biomass crops is also potentially problematic due to above ground carbon loss. However, studies that imply that plantation based woody biomass results in significant loss of soil organic carbon (SOC) [Biofuels Watch, 2008] have been exaggerated. Many of the woody crops proposed for biomass dedicated for bio-energy production would actually involve no-till and no-till cover crops (i.e. the soil is not turned over but saplings are placed individually in the soil) and cropping regimes would greatly reduce the SOC loss and require limited fertiliser application reducing GHG balance paybacks to 3 -14 years [*e.g.* Kim et al., 2009] as opposed to the 17 to 420 years [Fargione et al., 2008] and 167 years [Searchinger et al., 2008] proposed. Indeed some no-till studies indicate that SOC improves [Galbraith, 2005].

The majority of biomass assessments available are resource based projections of bio-energy potential - that is they assess the availability of resources based on land availability, yield potential from a variety of agricultural regimes and the demand for food based on dietary requirements and population growth. Dornburg et al., [Dornburg et al., 2008], suggests that a realistic projection based on the world growing food needs will be of the order 220 to 500 EJ/yr; this is in line with [IEA, 2009] recent assessments and covers the range of lower three of the 6 biomass potentials used to frame the negative emissions potentials in this study. It is therefore likley that the higher assessments will only be attainable with the realisation of the full potential of algal based sources which have a high potential for the longer term, but are a relatively unexplored feedstock at the present stage of their development [IEA, 2009].

UK Applications of BECCS: Based on the figures given above, negative emissions are extrapolated to 2030 for the UK. From this, BECCS plant build rates and plantation rates needed to generate the levels of negative emissions have been modelled. Precedents as to the build and plantation rates are used as a proxy to indicate the validity of these being attainable. The state of the international trade in biomass and the requirements needed to attain the widespread BECCS roll out suggested in the scenarios is also discussed[14].

A summary of the data inputs and outputs for the spreadsheet model is shown in table 12, below. Graphical representations of these negative emissions curves for the UK can be seen in Figure 12.

For the UK, between 12 to 43 1 GW BECCS plants would be needed to consume all the biomass available from the lowest to highest projections, which translates into a build rate of between 1.17 to 4.28 GW/yr between 2020 to 2030. None of the UK biomass projections anticipated the need for plantations for the production of wood and perennial energy crops.

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[14] Details of how the projected emissions curves were derived from the spreadsheet model and the global scale issues are discussed in a forthcoming more detailed version of this report.

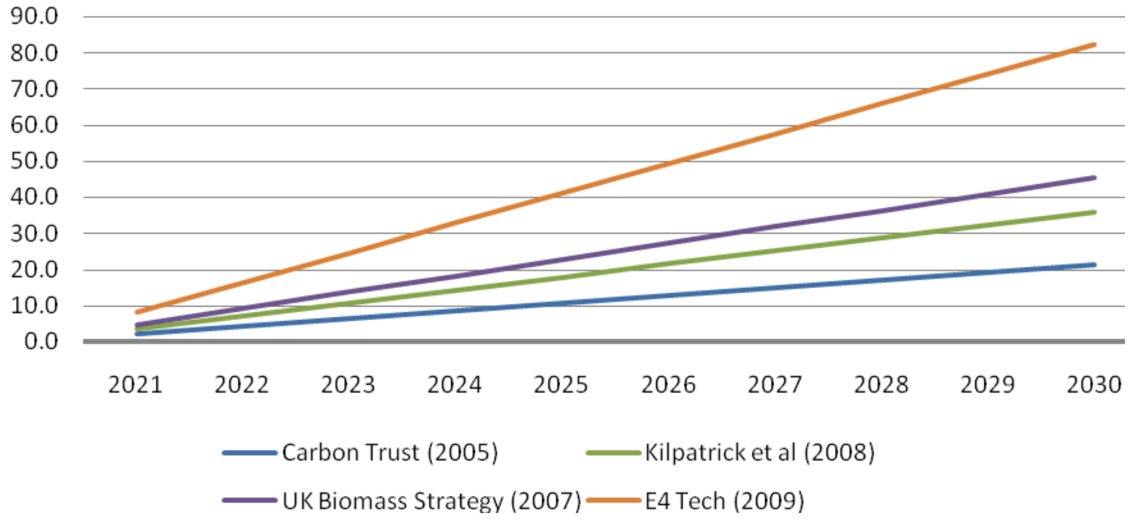
Table 12. Input and output data and for the BECCS process negative emissions curves

Study	No of 1 GW BECCS stations [1]	Required build rate from 2020 -2030[2] (yr^{-1})	Net negative emissions relative to reference fuel[3,4] ($M.t_{CO2}/yr$)	Quantities of biomass ODT in 2030[5] Wood/ forest residues (M.t/yr)	Perennial energy crops (M.t/yr)
Carbon Trust [Anon, 2005]	11.69	1.17	21.3	13.6	-
Kilpatrick et al [Kilpatrick et al., 2008]	20.30	2.03	35.7	3.67	13.9
UK Biomass strategy [Anon, 2007]	24.90	2.49	45.4	4.09	3.70
E4 Tech [Anon, 2009j]	42.78	4.28	82.4	11.2	30.2
Central prediction[6]	24.91	2.49	46.2	8.14	15.9

Notes:

1. No of 1 GW stations required to burn feedstock potential based on 1 GW station running at 80% capacity during the year requiring 25.23 PJ of biomass pa^{-1}.
2. Build rate for BECCS stations based primary energy feedstock potential over the 1 GW power station feedstock requirement.
3. Impact of the substitution of coal by biomass. The coal reference fuel is based on a conversion efficiency of 50% (788.3 kg/CO_2 per MWh) and reduced CCS energy penalty for 2050 to 0.804 GJ/tCO_2. The lower emissions by coal per unit of electricity produced means that not all net emissions by BECCS would have been produced had coal being producing the electricity.
4. The annual increment based of negative emissions based on linear growth of BECCS and biomass process technology over the period 2020 to 2050 for global curves and 2020 to 2030 for UK curves building up to biomass potential projections for 2050 and 2030 for each study.
5. Quantities of biomass in odt for each projection in 2050 for global and 2030 for UK studies.
6. The central prediction is an arithmetic average.

Figure 8*:* Negative Emissions Curve (Mt_{CO2}/yr) for the UK ramp up of BECCS between 2020 to 2030 assuming linear increase in biomass production and full utilisation.



Rollout rate: The UK's CO_2 emissions in 2008 were 569 Mt_{CO2}/yr (DECC, 2009), meaning that net negative emissions for the lowest to the highest projections in 2030 as a proportion of 2008 emissions were 4.0 to 15.5%. This is of course is based on locally supplied biomass and does not account for the additional BECCS capacity the UK might build if it were able to import large amounts of biomass.

Between 1991 to 2004, during the so called `Dash for Gas' period of power generation expansion 20.5 GW of gas power plant capacity was added in the UK; this translates into a rate of approximately 1.5 to 2 GW/yr. Only the lowest projection in 2030 falls within this precedent, the other projections requiring between 1.35 to 2.85 GW/yr. Even so, the escalation rate is not far from that achieved with relatively gentle market conditions, and these figures also ignore the possibility for retrofitting CCS to at least some of our existing coal fleet.

The simple implication of comparing existing precedents and the modelled BECCS built and plantation requirements is that only the lowest projections, in terms of biomass projected negative emissions potential, can be met using existing examples for the UK. This suggests that the realisation of the negative emissions curves for the UK would be feasible for the lowest biomass projections and that a dedicated programme would be required to attain any of the other projections based on biomass potential.

International Biomass Trade: It is likely that there will be regional surpluses of biomass in the future. Though the local use of biomass is presently more economically rational - subject to the logistical barriers being overcome the economics of long distance transport of biomass might become feasible allowing nations with lower costs and high biomass potential to export. Indeed a substantial international trade in biomass could develop albeit comprising a limited proportion of total biomass energy use.

International biomass trade was estimated that in 2006 to be ca. 1 EJ [Heinimö and Junginger, 2009]. Whereas the theoretical upper limit has been stated as being ca. 90 to 150 EJ [Hansson et al., 2006] in favourable conditions in the year 2050. This latter estimate took local production rates, usage potentials and potential bottlenecks in the supply chain into account. By comparison the world trade in oil is equivalent to 100 EJ [Hansson et al., 2006].

Conclusions in the Context of the AVOID Programme

The initial scoping work undertaken in this report has facilitated an assessment of the technical viability and materiality of a number of process technologies to remove CO_2 from the atmosphere. Based on the evidence reviewed - it has been concluded that, within order of magnitude accuracy, a number of technologies are in principle viable as negative emissions processes at a reasonable scale and reasonable cost. Though further work is required in order to validate initial findings on cost, environmental impacts from a life cycle perspective and the effects of scaling up the technologies.

In the context of the work within the AVOID programme the following is noteworthy:

- The ability to use the cost per unit of CO_2 avoided from the CO_2 removal technologies reviewed in the study with other mitigation measures such as nuclear, renewable technologies and energy efficiency measures is beyond the scope of the project. Furthermore, those that can be derived from this study must be considered in the context of the nascent state of the costing these technologies and the use of proxy cost data.
- The inclusion of negative emissions technologies, such as BECCS, in Integrated Assessment Models (IAMs) must be as transparent as possible in terms of impact and timing. The ability for the technologies to attain the negative emissions curves proposed in this study is predicated on a number of significant uncertainties. For example, in the case of BECCS, the curves are predicated on the timely rollout of CCS technology and the development of a globally efficient and environmentally sustainable biomass supply chain which are assumed to be evolving in 2020 and mature by 2030; the feasibility of this is predicated on a number of integrated variables which are extremely difficult to anticipate.

Acknowledgements

The contribution of colleagues at Imperial College and the University of Edinburgh is gratefully acknowledged, particularly Simon Buckle and Philippa Rogers at the Grantham Institute for Climate Change. We would like to acknowledge the helpful input by Dr Tim Kruger at Oxford Geoengineering.

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