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Biomass Energy with Carbon Capture and Storage (BECCS or Bio-CCS)

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Abstract
In terms of climate mitigation options, the theoretical potential of Biomass Energy with Carbon Capture and Storage (BECCS) is substantial; introducing the prospect of negative emissions, it offers the vision of drawing atmospheric CO_2 concentrations back down to pre-industrial levels. In practice, the scale of the forestry and accessible CCS infrastructure required are among the obstacles to the large scale deployment of BECCS in the near term. While biomass co-firing with coal offers an early route to BECCS, a quite substantial (>20%) biomass component may be necessary to achieve negative emissions in a co-fired CCS system. Smaller scale BECCS, through co-location of dedicated or co-combusted biomass on fossil CCS CO_2 transport pipeline routes, is easier to envisage and would be potentially less problematic. Hence, we judge that BECCS can, and likely will, play a role in carbon reduction, but care needs to be taken not to exaggerate its potential, given that (a) there are few studies of the cost of connecting bio-processing (combustion, gasification or other) infrastructure with CO_2 storage sites; and (b) that scenarios of global bioenergy potential remain contentious.

Keywords
BECCS, Bio-CCS, bioenergy, carbon capture and storage

1. Introduction

Biomass co-firing with CCS (BECCS) potentially offers one of the few near-term options for reducing levels of atmospheric carbon. Given that the accepted target of limiting the increase in post-industrial temperatures to 2°C is looking increasingly challenging[1], options such as

BECCS are gaining prominence. In common with other policy and technological options with potentially large-scale consequences, BECCS is controversial; here we present some of the key issues relating to the use of BECCS as a climate change mitigation option.

In this article we use the term BECCS to refer exclusively to the process of capturing and storing, in geological formations, CO_2 emissions from the combustion of biomass energy. The term Bio-CCS has also been used in the context of biological sequestration, for example using captured CO_2 (from fossil fuel processes) as a feedstock to produce algal biomass which is subsequently converted to plastics, transport fuel or animal feed.

1.1 The mitigation challenge

Growth rates in global emissions since 2000 have steadily increased at rates higher than those modelled in even the most fossil fuel intensive of the IPCC emission scenarios[2]. These scenarios, developed during the 1990s, are still used as a backdrop to much of the research on climate change mitigation and adaptation. The sharp contrast between actual emissions and the emission pathways described by the IPCC scenarios, including those relating to stabilisation targets for atmospheric CO_2 concentrations, dramatically illustrates the scale of the challenge[2].

Current atmospheric concentration of CO_2 is more than 380ppmv and rising; achieving the policy target of not exceeding a global temperature rise of 2°C is likely to require atmospheric concentrations below 350ppmv (CO_2e)[1],[3] a target significantly more challenging than the 450 or 550 ppmv targets outlined in the IPCC Fourth Assessment report.[4] Furthermore, analysis of emission pathways demonstrates the importance of the point at which atmospheric concentrations reach a peak;[3] the later the peak occurs, the more extreme the rate of emission reductions required and the higher the resulting atmospheric concentration (and consequently the higher the predicted global temperature rise). CO_2 has a long atmospheric lifetime, so large scale mitigation becomes increasingly urgent as it is delayed; rather than snapshot targets set for a future year, mitigation targets need to address cumulative emissions. Anderson and Bows,[3] for example, argue that without an almost immediate (i.e. by 2015) step change in emissions we are heading for atmospheric concentrations of 650ppmv or more by the end of this century.

1.2 The negative emissions concept

Given the scale and urgency of this mitigation challenge, to achieve a 450ppmv target the pursuit of a broad portfolio of mitigation approaches, including the adoption of both CCS and bioenergy, is essential in addition to measures to reduce energy demand; if we are to avoid dangerous or abrupt climate change,[5] opportunities for more radical emission reductions may also be necessary. Linking large scale biomass energy to CCS (BECCS) has been proposed as a potential response to abrupt climate change and a means of achieving negative emissions.[6-10] The Biosphere Carbon Stock Management (BCSM) concept was developed by Peter Read[11,12] as a 'be prepared' approach, intended to enable the achievement of greater emission reductions. BCSM works on the principle that it should be technologically easier to

[1] CO_2equivalent i.e. including the effects of all six greenhouse gases.

improve the way we manage land-use, taking advantage of biological fixation to remove CO_2 from the atmosphere and at the same time producing biomass based fuels (a process that Read terms 'de-fossilisation') than it is to achieve decarbonisation of fuel use. Such a system could theoretically deliver zero or negative emissions energy systems if the CO_2 emitted within the closed cycle were to be captured and permanently stored. Hence BECCS has the potential to facilitate the transition to a carbon neutral society by offsetting emissions sources which are more difficult or more expensive to abate, such as transport.[13] Moreover, analysis of the costs and feasibility of meeting atmospheric CO_2 stabilisation targets using global energy-economy models suggests that while it may reduce the cost of reaching a 450ppm target, BECCS could become critical in meeting a 350ppm target.[10,14]

In their analysis, Read and Lermit consider the widespread use of BECCS on a global scale as a form of what they term "*benign geo-engineering*". The Royal Society produced a comprehensive review of geo-engineering in which they define the concept as: "*deliberate large-scale intervention in the Earth's climate system, in order to moderate climate change*" [15] and identify two classes of approach: techniques which remove carbon dioxide from the atmosphere and those which manage solar radiation. BECCS could have the potential for removal of CO_2 from the atmosphere at a scale that, in conjunction with other conventional mitigation options, could deliver pre-industrial CO_2 concentrations[16] and compares favourably in economic terms with other potential methods for air capture, such as using sodium hydroxide[17]. However, BECCS lies somewhere between conventional emissions reduction and a geo-engineering carbon dioxide removal approach. The Royal society include it in their review for comparative purposes only, while stating that it is "*not normally regarded as geo-engineering*".

Read and Lermit (2005) argue that the large scale removal of carbon from the ground to be converted to atmospheric CO_2 via fossil fuel combustion that has occurred since the industrial revolution is in itself geo-engineering. They argue that reversing this process may again require further geo-engineering, hence their use of the term *benign geo-engineering* in the context of BECCS. Whether or not the approach constitutes geo-engineering could be considered to be a question of scale; while Read and Lermit envisage BECCS on a massive scale, here we also examine how elements of the concept might be relevant on a less radical scale in the nearer term, while exploring the scope for more ambitious deployment in the future.

2. Biomass Energy with Carbon Capture and Storage

2.1. Biomass and CCS

Biomass used for heat and power generally derives from one of three sources: forestry residues (from forest management and sawmills); energy crops or agricultural residues; biodegradable waste products (e.g. sewage sludge, food waste etc). Globally, biomass supplies some 10% (50 EJ) of the total primary energy demand (mostly for cooking and heating in traditional applications).[18] Currently, most of the biomass used in heat and electricity generation derives from residual or waste products (from forestry, agriculture and municipal sources) with further potential for expanding these sources.[18] Further opportunities

also exist for increased bioenergy production from purpose-grown lignocellulosic energy crops, particularly those grown on marginal or degraded lands; diverting land use for energy crops raises many sustainability issues and does not necessarily deliver reductions in greenhouse gas emissions.

Various reviews of estimates of biomass energy potential are available [13,18-21] and present a wide range of values. The many inherent uncertainties and differing approaches to quantifying the potential for bioenergy production makes the results of estimates difficult to compare. In general terms, however, there is agreement that the potential is sufficient for bioenergy to make a significant contribution to global energy supply.[19,21,22] The more extreme estimates of the biomass energy potential, such as those envisaged within Read's vision, have been challenged on the grounds that they exploit uncertainties in estimates of feedstock supplies, environmental implications of such large scale production, social and ethical challenges associated with extensive land use change, and potential failure through pursuing a single approach rather than a portfolio of options and costs.[13] It should be noted that the uncertainties around the potential scale of bioenergy supply are as much political and social as technical.

Although biomass produced within the EU (and some other non-EU countries) operates within a legal framework for sustainable forestry and agriculture, any significant expansion in biomass use is likely to lead to an increase in imports from further afield, requiring sustainability criteria which can be used by bioenergy importers across the EU. Currently, the 2009 EU Renewable Energy Directive,[23] includes environmental sustainability criteria and verification requirements for biofuels. Non-transport uses of biomass in the UK are covered by the Renewables Obligation (RO) (applying to electricity generation) which includes a sustainability reporting requirement for biomass. A Biomass Sustainability Working Group has been established, with membership across government departments, the Environment Agency, NGOs and industry, to develop the UK position on biomass for heat and electricity production. Finally, the UK is also part of the Global Bioenergy Partnership (GBEP), a product of the G8 process launched in 2006 under the auspices of the Commission for Sustainable Development, which provides a forum for developing policy frameworks operating at a high level of policy dialogue.

In summary, the key concerns cited in relation to bioenergy (and biofuel) crops relate to competition for use of productive land between bioenergy and food crops; impact on biodiversity and deforestation; negation of greenhouse gas benefits if bioenergy crops are grown on land with existing high carbon stock e.g., wetlands / forested area; potential negative impacts on communities (e.g. land rights, poverty, workers rights).[24, 25]

Although the three key components of CCS (CO_2 capture from power stations, transport of CO_2 to a storage site and long term underground storage) are individually relatively well understood, with significant operational experience, the key challenge for CCS lies in developing fully integrated large-scale commercial processes. As more demonstration projects come online, CCS moves closer to commercialisation but currently remains an immature technology.

Rhodes and Keith[26] present the technical possibilities of applying CCS to biomass in the production of electricity, hydrogen and liquid biofuels via gasification, post-combustion capture and oxyfuel combustion (with CO_2 capture), observing that there is the potential to apply any of these three major capture options within a variety of biomass energy systems, including CHP systems.[27] In addition, CO_2 can be captured during biomass conversion to secondary fuels (for example bioethanol production from sugar fermentation). [28, 29] Hence a key advantage of BECCS is that it can be used to address emissions from both electricity generation and other, harder to mitigate, sectors such as transport, although the potential emission reductions from transport are lower since tailpipe emissions from the resulting fuels remain.[22] As of early 2011, a handful of dedicated BECCS projects are currently in the construction or operation phase (located in the USA and the Netherlands), all of which are ethanol production facilities.[30]

There are no specific technical obstacles to introducing biomass CCS to the transport and storage stages of the CCS processes, since the CO_2 stream produced by the capture process is independent of the plant feedstock. The infrastructure development, consisting of specialised CO_2 pipelines routing to storage sites, will be built around existing large point sources. Unless located close to a storage hub, landing point, or existing large point source equipped with CCS, in the near to medium term it is this lack of infrastructure that is likely to present the main economic barrier to dedicated biomass-CCS. In addition, economies of scale may further improve the relative costs of transport and storage from larger fossil or co-fired plant compared with the smaller dedicated biomass plants.[14]

A study commissioned by the UK Department of Energy and Climate Change has reviewed the technical constraints associated with developing a CO_2 transport network associated with large scale CO_2 storage. Focusing on offshore pipelines, the study assumes that there is limited opportunity for the re-use of existing pipelines, due to the age of the network and the specific properties of CO_2;[31] much of the costs of CO_2 transport are associated with the capital outlay of building a new pipeline or adapting an existing one. The main technical risks to a pipeline developer (regardless of whether within a BECCS or fossil CCS system) are identified as sensitivity to CO_2 moisture content (rendering the CO_2 highly corrosive), and uncertainty associated with structural characterisation of aquifers (see below), which has implications for transport and injection regimes. There are also significant commercial risks associated with CO_2 pipeline development relating to fuel process and carbon prices and CCS legislation *inter alia*.[31]

In the UK, there is significant offshore storage potential in both hydrocarbon fields and deep saline aquifers. Reasonable capacity estimates are available in the case of hydrocarbon fields which are well surveyed structures; although estimates do exist for saline aquifers they are typically based on existing geological survey data and are highly uncertain. Detailed site specific surveys would be required to assess with more confidence the potential for indefinite CO_2 storage (in terms of both suitability and capacity) at saline aquifers. Given these caveats, the total storage capacity in UK offshore saline aquifers has been estimated to be up to a maximum of 14GT CO_2, although a figure of 7GTCO_2 is considered to be a more realistic

estimate;[32] in hydrocarbon fields the capacity is estimated at 7.3GT CO_2[2]. To put these figures in context, the total CO_2 emissions from large point sources in the UK (2005) was 258 $MTCO_2$,[32] suggesting storage capacity for CO_2 captured from domestic point sources for a period could be in the order of 60 years. The equivalent estimates for Europe as a whole are 117Gt CO_2 (of which 96 $GTCO_2$ is in saline aquifers, over 50% of which is located across Spain, Germany, UK and Norway).[32] Beyond Europe, estimates of storage capacity are highly variable, with many based on "top down" estimates that do not account for specific characteristics of potential storage sites.[33] An exception to this is the GEODISC study which carried out a detailed analysis matching sources to sinks for Australia.[34]

2.2 Cost effectiveness of BECCS

The costs associated with CO_2 capture and transport are likely to be higher at a BECCS plant than at fossil-only CCS plant since dedicated bioenergy power or heat plants are typically smaller.[14] However, Luckow et al. suggest that an expansion in the use of biomass energy in, for example biomass IGCC plants, could deliver the economies of scale associated with coal-fired plant, incurring relatively small cost penalties (around 3% above coal) associated with the lower energy density of biomass feedstocks.[22] In addition to BECCS applied to large scale electricity generators, other point sources could also be suitable. For example, there are significant opportunities for BECCS within the pulp and paper industry in Scandinavia – which, with high energy consumption and a supply of biomass, present a clear potential.[8, 27]

The IEA greenhouse Gas R&D programme carried out a techno-economic study to explore the performance and costs of post-combustion CO_2 capture technology for a range of cases of biomass single- and co-fired power plants.[35] A greater loss in efficiency, and consequently higher costs, associated with the capture equipment was observed in the standalone plant – considered to be a result of addition of a flue gas desulphurisation unit (FGD) and cooling processes to achieve necessary flue gas quality prior to capture, proportionally larger volumes of flue gas associated with a standalone plant leading to larger process equipment (with greater power requirements) and a more dilute CO_2 stream. Indeed, various studies have attempted to quantify the emissions reductions and costs associated with different BECCS options, these are summarised in Table 1. These are based on different assumptions and technologies and, while they cannot be used in direct comparison (hence no attempt has been made to convert these figures into common units), they do provide an indication of potential costs and emissions benefits. There are many examples of costs estimates for FECCS,[36-38] here we include only those that explicitly include a biomass component.

The IEA study concludes that negative emissions at the standalone biomass plant could be achieved a supercritical circulating fluidised bed boiler with only 10% biomass co-firing. It should be noted, however, that this study only modelled the capture process and although this stage is the most energy intensive component of the CCS process, the economic and energy costs of transportation and subsequent storage of the CO_2 need to be taken into consideration. Furthermore, we would argue that any claims of negative emissions can only be made in the context of a full Life Cycle Assessment. In another study, based on data from a Circulating

[2] This figure excludes all fields below 50MT capacity on the grounds that they are unlikely to be economically viable

Fluidised Bed (CFB) facility in Finland, negative emissions were only achieved with a biomass component above 20%.[39]

Table 1 here

Estimates of the costs of BECCS are inevitably highly uncertain – they are dependent on many variables and assumptions and there is the added uncertainty of little commercial experience of a full scale CCS plant. The results presented in Table 1 describe cost estimates for the capture component alone; a full BECCS system will include transport and storage of CO_2. These costs will depend on, for example, whether existing pipelines are being re-used, or new pipeline infrastructure is required, whether transport is onshore or offshore, the distances and terrain involved, whether a there is a network for CO_2 transport or point to point transport is required. Costs will also be affected by storage site properties such as compartmentalisation of aquifers, which would require additional injection wells.[31]

At a more aggregated level, the role of different mitigation options under global scenarios directed at meeting targets for atmospheric concentration of CO_2 has been explored. The results suggest that, while the introduction of BECCS could deliver a small reduction in the overall costs of meeting the 450ppmv target (by 2100), it could deliver a significant improvement in the cost, or even feasibility, of reaching a 350ppmv target (partly a result of negative CO_2 emissions in the longer term enabling CO_2 emissions to be higher in the near term) (14). Furthermore, other analyses using global-economy models reinforce the argument that BECCS may be necessary to achieve concentrations approaching 350ppmv over the course of this century. [10, 22]

2.3 Economic instruments

CCS entails a significant initial capital outlay with subsequent increased operating costs (compared to a plant without capture) and with no intrinsic advantage beyond CO_2 reduction. Its deployment thus depends on clearly regulated limits to CO_2 emissions or on a carbon price that makes it economical to install and run within a market-based system, with long-term confidence in a CO_2 emissions penalty. Several studies explore the influence of carbon price on viability of BECCS (compared with other technologies); as carbon prices increase, the cost of electricity from biomass with capture decreases, which, Keith et al (2006) note,[17] is the most that can be said with certainty about BECCS costs. Considering a biomass gasification combined cycle plant with CO_2 capture, BECCS could be competitive with coal or gas (without capture) at a carbon price of around \$100/tC and cheaper at around \$160/tC.[14, 17, 22, 26] With reference to the EU ETS (Emissions Trading Scheme), an ETS certificate price of €48-55/tCO_2 (€176-202/tC) could be necessary for a biomass co-fired plant with capture competitive with an equivalent plant without capture and €65-76/tCO_2 (€238-278/tC) for dedicated biomass plant with capture.[34, 35] At the time of writing, the current EU ETS price is only €15/tC.

Various conceptual challenges have been identified within existing markets requiring policy formulation in order to explicitly incorporate delivery of negative emissions via BECCS.[40] Whilst not seen as insurmountable, investment in the technology (whether from governments or the private sector) will require creative solutions to resolve these concerns; this type of regulatory uncertainty can play a key role in stalling investment in new technologies.

Typically, cap and trade systems are set up in terms of allowances of emitted CO_2 and not 'credits', as negative emissions might be considered. Furthermore, whilst emissions of greenhouse gases can be measured, accounting for negative emissions is more challenging due to the need to protect stocks of vegetation over substantial periods of time. Experience in the ETS and other trading schemes suggests that accounting issues associated with BECCS may in practice be overcome through assuming fungibility for forestry offsets. For example, a vertically integrated BECCS operation involving single-company ownership of a forestry plantation and a BECCS powerplant regulated under EU ETS and selling renewable electricity would in principle make financial sense. Nonetheless, conceptually, BECCS does not 'fit' the current carbon market; at an operational level, the existing EU ETS does not recognise a 'BECCS credit' or negative emissions.

At a global level, the Kyoto Protocol has its emphasis on capping emissions from Annex 1 countries, from which it does not incorporate carbon sinks, with the exception of forestry and land use – there is no class of credit that would cover BECCS. It is possible that it could be incorporated into the carbon pool approach currently adopted within the Kyoto Protocol for managing CO_2 'storage' in harvested wood products.[41] In contrast to a cap and trade system, the CDM operates as a baseline and credit scheme in which proof that an emission reduction relative to a baseline has taken place, via a CER (Certified Emission Reduction) that is traded. While biomass energy in developing countries is included in the CDM, CCS is not; although it is under discussion it is proving to be contentious. Arguments put forward against inclusion of CCS in the CDM (typically by environmental campaigning organisations and some developing countries) relate to the untested nature of CCS, the concern that it will dominate other more sustainable technologies (such as renewables) and doubts over the net emissions benefits.[42]

Should CCS become more established, the above concerns need not necessarily preclude its potential inclusion within the CDM. Nonetheless, any related accounting system would need to convincingly accommodate the issue and real possibility of non-permanence, should any negative emissions be reversed once a credit has been issued. Potential solutions to this problem have been explored within the forestry sector, for example: 'temporary credits'; 'buffers', whereby initially only a proportion of the credits are issued with the remainder issued as secure storage is demonstrated over time (although necessary storage timescales do not align with economic timescales); and mandatory insurance. There may also be relevant experience from the use of catastrophe bonds (also known as cat bonds), through which a specified set of risks is transferred to the bond investor that could be applied to CO_2 storage. While problematic, it should be noted that these issues are primarily related to the possible interface of BECCS with emissions trading and associated property rights rather than with renewable power or heat generation and associated carbon capture and storage.

3. Conditions for BECCS

This paper has reviewed the technologies and issues associated with combining biomass energy with carbon capture and storage - with the ultimate aim of achieving electricity generation associated with negative emissions. Although biomass energy is already widely used in power generation applications using a variety of feedstocks, CCS technology is still in its infancy; bringing the two together at a sufficient scale to achieve significant negative emissions will depend on strong political, regulatory and industrial will to make it succeed. Assuming that the basic logistics for supply of feedstocks and storage destination for the CO_2 are in place, key challenges to establishing a BECCS system are summarised below.

Biomass resource strategy. Firstly, from a strategic perspective and ahead of any of the specific issues relating to uptake of BECCS, is consideration of the use of biomass resources. This applies in particular to bioenergy crops and the land use implications of increased bioenergy production, but also to biomass from waste; any substantive uptake of biomass for power generation must take into account competing uses for biomass resources – such as between transport, electricity and heat applications, as well as ecosystem and livelihood services.

Assuring carbon neutral biomass - the assumption that biomass provides carbon neutral energy cannot be taken for granted: net emissions from bioenergy depend on many factors, such as how land use is affected by biomass energy production (whether it results in deforestation, is replanted or whether energy crops replace sparse vegetation on marginal land, for example) and the fossil energy required in biomass production, conversion and transport.[14] This presents particular challenges for emissions accounting.

Location. More specifically, the applicability of a BECCS plant depends on its geographical context – its location in relation to the supply of a suitable biomass resource, the surrounding energy infrastructure and availability of CO_2 storage and transport options.

Establishing BECCS actor networks. While there are expanding communities in both CCS and bioenergy, the linkages between the two remain relatively weak. The challenge will be to bring components (key individuals, organisations, technologies, ideas) together to establish a BECCS technology system.

Incentives and policy mechanisms. Any application of CCS, even without any potential additional complications introduced by a BECCS system, will require fiscal incentives and a policy framework that encourages its uptake. Without a clear mandate for large scale emissions reductions, there is no reason for BECCS to be implemented. BECCS does not fit into existing regulatory frameworks in their current form and accommodating BECCS within amended or new frameworks presents a variety of challenges. For example, providing for potential non-permanence associated with a failure in CO_2 storage, challenges in accounting for negative CO_2 emissions within a Cap and Trade system (such as the EU ETS) and consideration of the potential impacts on communities in developing countries, should large scale BECCS visions be realised.

Broader perceptions. As with any novel technology or approach, success depends upon the extent to which it is widely received. While research into the public perceptions of Fossil-CCS is providing valuable insights, the extent to which BECCS presents different acceptability issues is less well known. One of the very few studies to include the public perceptions of BECCS, examining public perceptions of CCS in several European countries via focus groups, found that negative perceptions of fossil CCS seem to lead to similar perceptions of BECCS, despite the likelihood of a very limited understanding of the nature of BECCS technology and implications.[43] A key argument for introducing BECCS is the urgency of achieving a CO_2 concentration target of 350ppmv, but it is far from clear that the need for and the scale of this challenge is widely understood. Research on the acceptability of fossil-CCS suggests this could be a critical element of the acceptability of BECCS.

4. Conclusions

Biomass energy and CCS hold the potential to make a significant contribution to achieving necessary deep cuts in CO_2 emissions (whether deployed independently or as a combined approach in pursuit of negative emissions). Yet there are many potential obstacles to the realisation of its large scale implementation. Moreover, the suitability of BECCS is unlikely to be universal - some countries and regions will be much better suited to large scale biomass / BECCS applications than others. In Europe, for example, Sweden may be well placed, with relatively low power sector emissions (and hence limited opportunities for more conventional mitigation options), an established biomass energy system in the process industry and access to offshore storage sites. [28, 41] In the UK, there is a relatively small bioenergy resource, such that the focus in terms of BECCS is perhaps best directed towards co-firing rather than to dedicated biomass plants, at least initially. Once a CO_2 transport and storage infrastructure is established, there may then be the opportunity to establish smaller scale bioenergy power plants with capture adjacent to the large CCS installations.

We have described how the problems of carbon accounting may be more challenging for biomass energy than for other energy sources, due in part to land use factors that affect greenhouse gas emissions being difficult to measure and control. A life cycle approach becomes essential once negative emissions are to be claimed. Whilst the prospect of potential negative emission from BECCS could provide a crucial opportunity to make very significant emission cuts over a reduced time period, caution should be applied such that BECCS is not used as an argument to enable higher overall cumulative emissions (even with an equivalent stabilisation target).[10] Using BECCS or bioenergy as an argument for a 'temporary' increase emissions or delay in emissions reductions would be highly dubious as a climate mitigation strategy. Moreover, CCS does not represent an ultimate climate change mitigation solution; it may buy time as we move towards a society based on more sustainable, decarbonised energy systems. BECCS does not imply that we no longer need to develop renewable energy sources or that we can relax mitigation efforts, but it could enable lower atmospheric CO_2 concentrations to be achieved (i.e. to reach more stringent targets) or reduce the cost of doing so (10).

Rhodes and Keith recommend that, due to the uncertainties and complexities associated with achieving sustainability, bioenergy policy should be developed through a process of adaptive management.[13] This is intended to ensure an open, inclusive and iterative process that accommodates uncertainty. In the context of BECCS, this could to some extent be realised through the introduction of BECCS initially within co-fired systems or small dedicated bioenergy power plants – introducing manageable levels of biomass which can be carefully sourced, building an understanding of the CCS technology but with the benefits of large scale and established fossil plants. A modest introduction also avoids some of the challenges associated with carbon crediting by not taking individual plant into negative emissions in the first instance.

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Table 1. Comparison of emissions estimates from BECCS (in electricity generation) modelling exercises

Study	Technology	Net emissions	Costs	Assumptions
IEAGHG 2009(35)	CFB boiler, biomass only CFB, 10% biomass cofired	-1573gCO_2eq /KWh -32gCO_2eq /KWh	Cost of electricity: 0.1 euro/KWh 0.25 euro/KWh	Net plant efficiency 33.8% (LHV) Net plant efficiency 25.8% (LHV) 90% capture rate
Laczay 2009 (44)	CFB biomass cofired 5% 20% 50%	 195gCO_2eq/KWh -5gCO_2eq/KWh -405gCO_2eq/KWh	0.102 £/KWh 0.102 £/KWh (excluding all subsidies)	Plant efficiency 28.5% (LHV), 90% capture rate) The energy penalty of CCS verses an identical non-CCS system was 25% (accounting for redirected steam and electricity usage for CCS processes).
Rhodes and Keith (2005)(26)	Biomass IGCC Biomass IGCC, with Steam reforming	-140 gC/KWh -200 gC/KWh	8.2 cents/KWh 123 $/tC (33.6 $/t CO_2) 9.3 cents/KWh 135 $/tC (36.5 $/t$CO_2$)	44% capture rate; net efficiency 28% (HHV)[1] 55% capture rate; net efficiency 25% (HHV)
Kraxner et al. (2003) (45)	Average carbon sequestration, BECCS associated with single 'typical' temperate forest	2.5 tC/yr/ha		90% capture rate, scenario based approach to forest management

1. HHV – Higher heat value energy (heat gained) from combustion, with all products of combustion returned to original pre-combustion temperature; LHV – lower heat value (heat gained) from combustion, excluding energy released in water vapour.