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Biomass energy with carbon capture and storage (BECCS): a review

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Abstract

This is a review paper intended to provide an overview of debates relating to BECCS or bio-CCS, which are alternative terms for the coupling of bioenergy with carbon capture and storage (CCS). The paper follows from a workshop held in December 2009, hosted by the Scottish Centre for Carbon Capture and Storage at the University of Edinburgh, organised by Tyndall Manchester at the University of Manchester and funded by the Tyndall Centre. The principal rationale for BECCS is that whereas the current atmospheric concentration of CO_2 is more than 380ppmv and rising, achieving the European policy aspiration of not exceeding a global temperature rise of 2°C is likely to require atmospheric concentrations of below 350ppmv CO_2e. In theory, BECCS has the potential to help to bring the atmospheric CO_2 concentration to below present levels, or at least to contribute to its reduction by delivering "negative emissions". By capturing and storing the CO_2 absorbed from the atmosphere by bioenergy feedstocks, BECCS can, in theory, deliver power and heat production with net negative emissions. Yet, while BECCS enthusiasts have drawn support from scenarios of large scale global bioenergy supply and its co-option into BECCS systems, the assumptions of sufficient accessible CCS capture, pipeline and storage infrastructure and that large scale bioenergy supply can be reconciled with competing uses of land (and water) are both uncertain. 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 BECCS system (a percentage that is dependent, of course, on system assumptions). Financially, significant incentives will be necessary to establish either BECCS or CCS; neither are currently competitive in Europe, given carbon prices within the EU ETS which is also not currently designed to credit negative emissions. Nonetheless, in cost terms, bioenergy compares well with other carbon abatement options, particularly if wastes or residues are used as fuel, and modelling suggests that BECCS would be an important component of energy systems intended to reach 350pmv CO_2e. We judge that BECCS can and likely will play a role in carbon reduction, but that care needs to be taken to minimise the risks of disincentivising inherently low carbon energy systems via lock-in of fossil CCS. Care also needs to be taken not to exaggerate the potential of BECCS, 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.

1. Introduction

Biomass co-firing with CCS (BECCS) offers a near-term route for implementing one of the few options for reducing levels of atmospheric carbon. Given likely overshoot of both 450 and 550ppmv of atmospheric CO_2, even assuming substantial international emissions reductions, options such as Bio-CCS or BECCS are gaining in prominence. As with all policy and technological options with potentially large-scale consequences, BECCS is controversial. In this report we use the term BECCS to refer exclusively to the process of combustion of biomass for energy, the CO_2 emissions from which are captured and stored in geological formations. 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, animal feed or other chemical feedstocks.

As part of the Tyndall Centre Transition programme, a workshop on Biomass energy and CCS (BECCS) was convened at the University of Edinburgh in December 2009, organised jointly between the Tyndall Centre and the Scottish Centre for Carbon Storage. The workshop was set up to review the BECCS debate as it currently stands, seeking to identify areas of disagreement and consensus and identify research goals. The scope of the workshop, and the current working paper, have been restricted to address BECCS specifically and not Carbon Capture and Storage from Fossil Fuels (FECCS) or Biochar[1]; although both approaches are related to the BECCS debate and some of the issues relating to BECCS apply also to FECCS and Biochar.

This paper aims to provide an overview of the key issues relating to the use of BECCS as a climate change mitigation option. While referring to the UK in particular, the paper is relevant to BECCS in any nation. Although it is based on presentations and discussions held during the one-day workshop, it is supported by additional analysis drawing on the broader literature in order to provide more detailed background to the debate and expand on some of the ideas originating from the workshop. Following a very brief overview of the workshop structure, we present an introduction to the mitigation context, the concept of and background to the development of BECCS. In the second section of the paper, there is a discussion of the key issues and controversies relating to the potential development of BECCS.

2. BECCS workshop

The workshop was attended by 42 people, drawn from academia, industry and the NGO community. There were seven presentations, as described briefly in Table 1, followed by three breakout groups charged with trying to identify specific research goals relating to i) technological opportunities (including co-firing and fossil CCS infrastructure); ii) socio-economic and development impacts (positive, negative; scale,

[1] Biochar is derived via pyrolysis of biomass to form a stable black carbon material (biochar), enabling carbon to be sequestered in soil, improving soil fertility in the process (Shackley *et al.* (2009).

ownership and governance issues); and iii) land use and ecological impacts (including opportunities for afforestation; role of the CDM; biodiversity) respectively.

A key proponent of both the biochar and BECCS concepts was Peter Read; having been involved in the planning of the workshop, Read sadly passed away in November 2009, shortly before the workshop. The two introductory presentations included some reflection of Read's contribution and inspiration to the debate.

Table 1. Worksop presentations.

Introduction	Prof Stuart Haszeldine, Scottish Centre for Carbon Storage, University of Edinburgh, UK
Peter Read's legacy	Simon Shackley, UL Biochar Reseach Centre, Universtiy of Edinburgh, UK
Bioenergy and fossil CCS: policy and technology synergies	Prof Andre Faaij, Copernicus Institute, University of Utrecht, Netherlands
The BECCS system	Henrik Karlsson, Biorecro, Sweden
Challenges for BECCS implementation in the UK	Scott Laczay, Imperial College, London, UK
BECCS and the carbon markets: regulation and finance	Dr Francisco Ascui, University of Edinburgh Business School, UK
CCS, BECCS and the escape from carbon lock-in	Philip J. Vergragt, Clark University and Tellus Institute, USA

3. The mitigation challenge

In his introduction to the BECCS workshop, Stuart Haszeldine, presented research carried out by Raupach *et al.* (2007) which shows that growth rates in emissions since 2000 are steadily increasing at rates higher than those modelled in the even the most fossil fuel intensive of the IPCC emission scenarios. These scenarios were developed during the 1990s and are still used as a backdrop to much of the research on climate change mitigation and adaptation. Overlaying actual emissions onto emission pathways described by the IPCC scenarios, including those relating to stabilisation targets for atmospheric CO_2, concentrations provide a dramatic illustration of the scale of the challenge (Raupach *et al.*, 2007).

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)[2] (Meinshausen 2006 quoted in Anderson and Bows (2008)), a target significantly harder than the 450 or 550 ppmv targets outlined in the IPCC Fourth Assessment report (IPCC 2007). Furthermore, through analysis of emission pathways following from current emission levels, (Anderson and Bows 2008) demonstrate the importance of the point at which atmospheric concentrations reach a peak (comparing 2015, 2020, 2025); the later the peak occurs, the more extreme the rate of emission reductions required and the higher

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

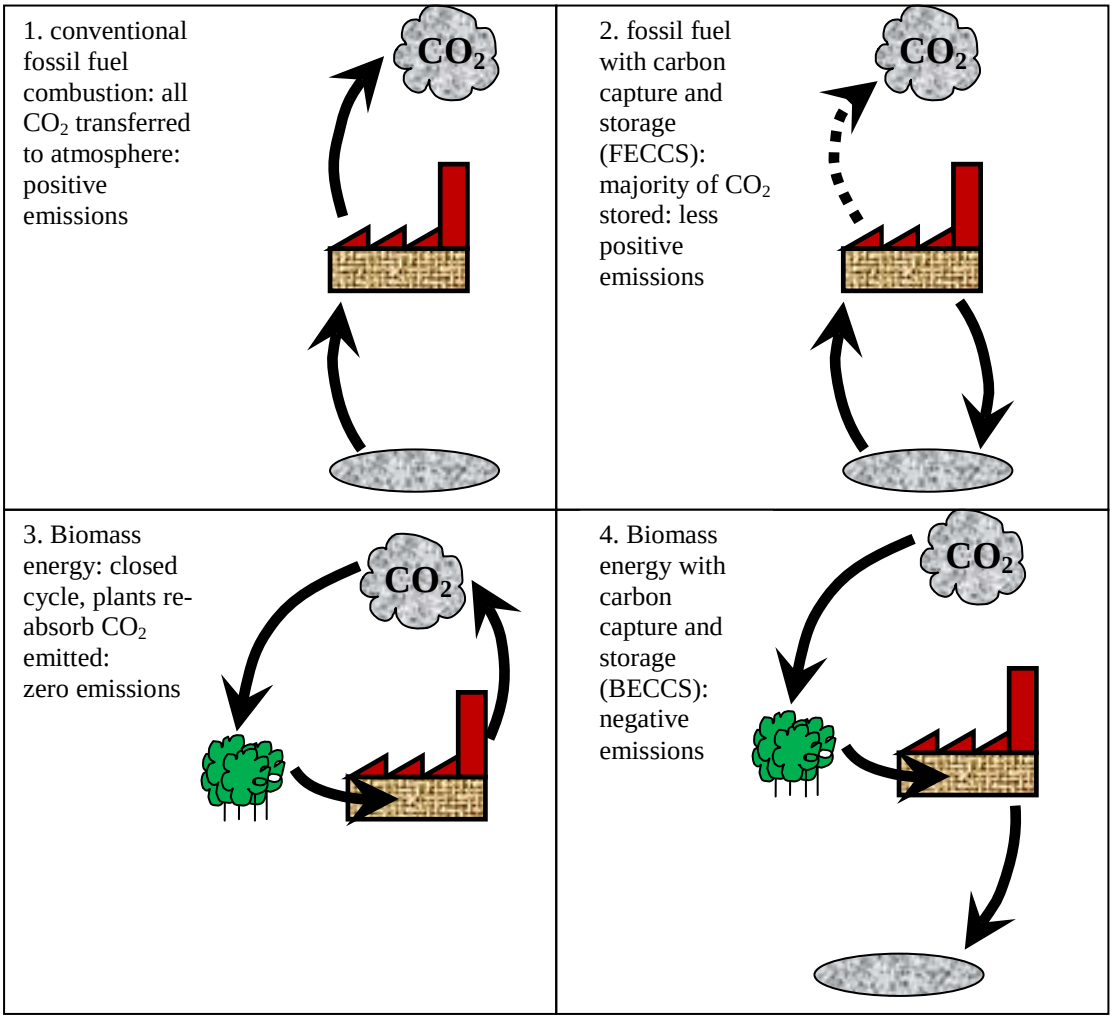
the resulting atmospheric concentration (and consequently the higher the predicted global temperature rise). CO_2 has a long atmospheric lifetime, so large scale mitigation becomes increasingly urgent as it is delayed; mitigation targets need to address cumulative emissions rather than snapshot targets set for a future year, which could deliver a range of final atmospheric concentrations by the target year depending on the preceding emission profile. (Anderson and Bows 2008) 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.

3.1 The negative emissions concept

Addressing this urgency to act on global emissions, Faaij used data from IIASA and from the IPCC (IPCC 2007) to illustrate that a 450ppm target (at least) can be feasible if a broad portfolio of mitigation approaches is pursued, within which the adoption of both CCS and bioenergy are essential. However, given the scale and urgency of this mitigation challenge, if we are to avoid dangerous or abrupt climate change (Schellnhuber *et al.* 2006) opportunities for more radical emission reductions may still be necessary, in addition to measures to reduce demand and conventional approaches to reduce emissions associated with energy supply.

The Biosphere Carbon Stock Management (BCSM) concept was developed by Peter Read (Read and Lermit 2005; Read 2008) as a 'be prepared' approach enabling the achievement of greater emission reductions in order to avoid potential abrupt climate change. BCSM works on the principle that it should be technologically easier to 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 (what Read terms 'de-fossilisation') than it is to achieve decarbonisation of fuel use. Such a system could deliver zero emissions energy systems; if the CO_2 emitted within the closed cycle were to be captured and permanently stored it could achieve net zero or even negative emissions. This is illustrated in a set of diagrams shown in Figure 1 presented by Karlsson during the workshop. The concept of negative emissions introduces the potential for BECCS to have a role alongside other mitigation approaches to actually reduce atmospheric CO_2 concentrations for example, or to facilitate the transition to a carbon neutral society by offsetting emissions sources which are technically, socially or economically more challenging to abate, such as transport for example (Rhodes and keith 2008). Using a global energy-economy model to analyse the costs and feasibility of meeting atmospheric CO_2 stabilisation targets, Azar, *et al.* (2006) found that whilst it has only a marginal effect on the cost of reaching a 450ppm target, BECCS could become critical in meeting a 350ppm target. It should be noted, however, that while there is industrial experience of the components that make up a BECCS process, a fully integrated BECCS (or even FECCS) system is not currently a commercially proven technology. This report sets out to explore some of the issues associated with bringing the technology towards maturity.

Figure 1. BECCS and negative emissions concept (after Karlsson, BECCS workshop presentation)



4. Biomass energy and CCS

The use of biomass for energy is nothing new: it was probably the first energy fuel used by man. However, traditional applications have been small scale and localised, producing heat inefficiently from direct combustion; in modern bioenergy applications biomass is used to produce heat, electricity or transport fuels. In recent years, bioenergy has been used to co-fire existing coal fired electricity generation at most of the large plants in the UK. Co-firing enables bioenergy to be utilised at a higher level of efficiency than is often achieved in a dedicated biomass plant and qualifies for UK Government Renewable Obligation credits (until 2016) (Colechin and Malmgren 2005).

Carbon capture and storage is a relatively new concept, albeit an approach that is rapidly gaining currency on a global scale. The technologies relating to the separate processes of capturing, transporting and storing CO_2 underground have been practised

at an industrial scale for several decades; the least well developed stage of this CCS chain is large scale permanent storage in geological formations (although, for example, at the Sleipner gas field in Norway CO_2 has been injected into the Utsira formation beneath the North Sea at rate of 1 MT CO_2 pa since 1996 (Gale and Torp 2004)). In the UK, the government is committed to funding four CCS commercial scale demonstration plants, funding of £1billion was announced for the first of these in The Comprehensive Spending Review October 2010 (DECC, 2010); in addition no new coal plants will be built in the UK without CCS. Across Europe there should be 12 EU-funded demonstration plants by 2015 and beyond 2020 all new fossil fuel power generation plant should be equipped with CCS (subject to technical and economic feasibility). To date, there are around nine CCS demonstration projects in operation (in for example, Australia, France, Germany *inter alia*) and many more in planning stages.

Bringing the two together, 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 (Keith 2001; Moellersten and Yan 2001; Obersteiner, *et al*. 2001; Keith and Rhodes 2002; Read and Lermit (2005). 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*" (Royal Society 2005) and identify two classes of approach: techniques which remove carbon dioxide from the atmosphere and those which manage solar radiation. BECCS does 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 (Lenton and Vaughan 2009) and compares favourably in economic terms with other potential methods for air capture, such as using sodium hydroxide (Keith, Ha-Duong et al. 2006). 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 removal of vast quantities of carbon from the ground to be converted to atmospheric CO_2 via fossil fuel combustion that has occurred on a large scale since the industrial revolution onwards 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 will examine how elements of the concepts might be relevant on a less radical scale in the nearer term, while exploring the scope for more ambitious deployment.

4.1 Using Biomass for energy

Biomass is a broad term applied to any non-fossilised material of a biological origin and there are many different types of biomass that can be used as a source of energy, including fuelwood, charcoal, agricultural wastes, livestock manure; it can be an

energy crop specifically grown for use as a fuel, a waste product or harvested directly from natural ecosystems. Biomass can be used either directly for heat or to generate electricity, or can be converted into a biofuel (in liquid or gaseous form) for use in other applications such as transportation. Here we will use the term bioenergy to refer to all forms of biomass energy and biofuels. This is clearly a very broad category and consequently the degree of sustainability in the use of biomass energy varies widely depending on the type of biomass, the management of the source and its scale of use. Here we focus on biomass energy for electricity production rather than biofuels or direct use of biomass for heat, although the latter applications may be referred to. 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) (IEA Bioenergy 2009). 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 (IEA Bioenergy 2009). 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 (see below) and does not necessarily deliver reductions in greenhouse gas emissions.

The UK target, under the EU Renewable Energy Directive, is for 15% of final energy consumption to be from renewables by 2020 (currently 3% of energy is from renewable sources) and increased use of biomass will play a significant role in efforts to meet that target. Table 2, shows the growth in biomass use in the UK over the past 19 years. In the UK, biomass contributes roughly 80% of overall renewable energy use; this proportion has remained fairly stable over the last decade, despite large increases in the use of other renewable energy sources. In 2009, 43% of all renewable electricity generation was from biomass (currently, 7% of electricity derives from renewables in the UK).

Table 2. Use of Biomass in the UK

	UK		
	1990[1]	2000[1]	2009[2]
Biomass % of Total energy use -	0.3%	0.9%	3%
Biomass % of Renewable energy use	55% (0.56 mtoe)	79% (2.0mtoe)	80.7% (5.55 mtoe)
% of renewable electricity generation			
- Biomass	10% (0.6TWh)	39% (3.88TWh)	42% (10.636 TWh)
- Biomass co-firing	nil	nil	7.2% (1.81TWh)

1. DUKES 2009; 2. DUKES 2010

4.2 Biomass energy potential

Much of the focus on increasing bioenergy production is currently directed at biofuel production and the desire to develop non-fossil alternatives for transport fuels, and while this report concentrates on biomass use in the context of electricity supply, the two cannot be considered independently. Analysis of future global biomass potential is typically based on large scale modelling exercises and is reliant on a complex interaction of assumptions. The uncertainties associated with these long-term estimates are very large and, inevitably, there is no clear consensus on the scale of potential greenhouse gas reductions from biomass energy. Various reviews of estimates of biomass energy potential are available (for example, (Rettenmaier *et al.* 2008; Rhodes and Keith 2008; IEA Bioenergy 2009; Offerman *et al.* 2010) 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 (Offerman *et al.* 2010). 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, potential failure through pursuing a single approach rather than a portfolio of options and costs (Rhodes and Keith 2008).

It is evident that developing bioenergy at a scale sufficient to have a substantial impact on global greenhouse gas emissions will entail significant widespread land use change. During the workshop, Faaij discussed the land use implications of exploiting the 'realistic' potential for sustainable bioenergy. Increasing global population brings with it increased demand for agricultural land for food production. Current agricultural practices (in particular livestock) present a great threat to biodiversity through habitat loss, such that satisfying this increasing demand without deforestation (and the consequent increase in greenhouse gas emissions) remains a challenge, irrespective of biofuels. In addition, subsistence farming accounts for more than 60% of land use change emissions; any efforts to address land use change should thus target poverty; bioenergy can play a role in addressing this. For example, land productivity can be improved by growing 2nd generation biofuels (lignocellulosic energy crops) which could deliver three times the net energy yield per hectare compared to 1st generation crops and the use of perennials on marginal lands may bring the additional restorative benefits to the land.

Any vision of large scale of bioenergy uptake will inevitably hold significant implications for developing countries, raising a host of ethical issues. Rhodes and Keith (2008) refer to the concept of "biomass justice", advocating a process adaptive management to biomass energy development that takes a more incremental approach. Exploiting the potential for large scale biomass production sustainably will, in many contexts, rely on significantly improved governance and regulatory regimes; the level of realism with which ambitious scenarios are viewed is thus somewhat dependent on levels of optimism over whether or not appropriate institutions can be established.

While there is clearly scope for increasing biomass energy production compared to current levels, there remain substantial risks associated with large scale bioenergy supply.

In the UK, the Renewable Energy Strategy sets out opportunities for domestic biomass supply and suggests that UK sources could deliver 10% of current UK energy demand by 2030, at a cost of less than £5/GJ (DECC 2009). By increasing recovery of wood from both managed and currently unmanaged woodland, increasing production of perennial energy crops (to around 1 Mha, and without resulting land use change) and increasing supply of energy from waste, the UK biomass Strategy estimated that the potential biomass resource in the UK could be equivalent of 96.2 TWh (8.3mtoe) (DEFRA 2007). In a subsequent detailed study modelling the spatial yield, demand and costs of energy crops in England and Wales, (Bauen *et al.* 2010) estimate that the order of 75 TWh (6.4 mtoe) biomass energy (predominantly from willow) could be produced at a cost approaching that of traditional fossil fuels (3.1-3.4 £/GJ), with an increase in the land area used for energy crops to 1.5 Mha (defined as the area of environmentally compatible bioenergy potential in the UK (EEA 2007).

Providing an overview of the situation in the UK, Laczay described to the workshop the key challenges to domestic biomass production for electricity production in the UK, these include: land availability; competition from transport sector for biofuel production; lack of existing mature/large biomass supply chains; lack of market signals; matching supplies to point of use.

4.3 Controversy and Bioenergy

In recent years, climate change mitigation has tended to dominate the global environmental protection debate, despite severe threats remaining from other global environmental challenges. During his workshop presentation, Faaij outlined some of these global challenges including biodiversity losses, the looming food crisis, issues surrounding water use, soil losses, poverty alleviation, all of which, despite being strongly interlinked, are typically addressed individually within the international arena, often leading to conflict. Faaij illustrated how both bioenergy and climate change cut across all of these issues, stressing the importance of considering this broader context.

A growing awareness of the complexities associated with a large scale increase in the use of bioenergy has exposed various controversies which we will describe in the following section. The way in which concerns emerge and become established was illustrated by Faaij during his workshop presentation; in 2007 food prices started to rise sharply, a trend that the press widely associated with increases in biofuel production; however, closer inspection shows that the greatest price increases were for rice (which is not used as an energy crop) whilst the price for sugar (the largest bioenergy feedstock) remained flat during this time. Faaij attributed this effect primarily to changes in exchange rates - food prices subsequently falling to levels similar to before the spike with no corresponding change in bioenergy production. Clearly, the relationship between increased bionenergy production and food prices is not straightforward and concerns over future impacts as bionergy production increases remain valid. However, the above example illustrates how other effects can be

masked and how a story can gain momentum and become established within the broader consciousness.

In the context of a variety of concerns over the impact of bioenergy production on, for example, deforestation, food price rises and degree of reduction in GHG emissions, in 2008 the UK government commissioned an independent review into the indirect effects of biofuels, the 'Gallagher review' (RFA 2008). Gallagher concluded that, while a sustainable bioenergy industry is possible, much tighter policy and regulatory standards must be developed and enforced to ensure that detrimental effects of certain land use changes are avoided, including a requirement that biofuels are not grown on agricultural land that would otherwise be used for food production. Prior to this in 2008, the Environmental Audit Committee had also called for a moratorium on biofuel targets (EAC 2008) stating that it considers "policies that encourage demand for first generation biofuels are damaging".

In summary, the key concerns cited in relation to bioenergy 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).

4.4 Certifying Sustainability

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. This has led the drive to develop sustainability criteria which can be used by bioenergy importers across the EU. Although questions remain as to the ability of certification to guarantee sustainable global biomass productions (Tomei and Upham 2009), do at least raise awareness of the issues and enable production to be monitored.

As stated, the 2009 EU Renewable Energy Directive (EC 2009), includes environmental sustainability criteria and verification requirements for biofuels and bioliquids. These were informed by a study on sustainability criteria and certification prepared for DGTREN (Vis *et al.* 2008) which recommended initial obligatory minimum criteria which should lead the way for additional voluntary criteria to be implemented as the market becomes established. The final Directive includes sustainability criteria for biofuels that specify that: greenhouse gas emission savings should be at least 35%, rising to 50% in 2017 and 60% in 2018 for new installations; biofuels shall not be made from raw material obtained from land with high biodiversity value (primary forest, protected ecosystems, biodiverse grassland), high carbon stock (wetlands, continually forested areas) or from peatland (unless evidence that no drainage of previously undrained soil is involved).

Every two years, starting 2012, the Commission will report to Parliament on national measures (in countries producing biomass) taken to respect these environmental sustainability criteria but also on social criteria (e.g. food prices, particularly in

developing countries; land use rights. The above requirements relate to biofuels, a separate sustainability scheme for use of solid biomass and biogas in electricity, heating and cooling was adopted in February 2010 (EC 2010). This provides recommendations for voluntary sustainability criteria which may be used at a national level which match the greenhouse gas performance and conservation issues adopted for biofuels and in addition recommend differential national support schemes to favour installations with high energy conversion efficiencies. The Commission report on sustainability criteria to be produced in 2012 will evaluate the effectiveness of the current system on provision of sustainability criteria and the feasibility of introducing mandatory requirements, thus representing a first step towards formal certification.

In the case of solid biomass, which would be used for BECCS, the legislators stated that: '*the wide variety of biomass feedstocks make[s] it difficult to put forward a harmonised scheme at this stage*' (EC, 2010). The Commission has further taken the view that the sustainability risks relating to domestic biomass production originating from wastes and agricultural and forestry residues, where no land use change occurs, are currently low (ibid). Observers note that although the Commission's environment department and several member states favoured binding sustainability criteria, it was the view of the Commission's energy and transport department that prevailed (EurActiv, 2010). The Commission's reasoning includes the further argument that, unlike in the case of some agricultural crops and energy crops (such as short-rotation coppice), biomass wastes and processing residues are not produced specifically for use in the energy sector, but result from other economic activity that would take place irrespective of its biomass energy potential (EC, 2010, section 2.1). In this respect, the use of waste biomass for energy is potentially of net environmental benefit and is regarded by the Commission as something to be encouraged rather than subjected to the additional costs of regulatory control.

The Commission further reasoned that, particularly where forest or agricultural residues are used, the greenhouse gas (GHG) savings of European feedstocks are high, generally above 80% savings compared to the fossil alternative, such that the risk of not achieving net reductions in greenhouse gas emissions is correspondingly lower than for biofuels. The difference is attributed to the typical processing (e.g. pelletisation) generally being less energy intensive than the processes required to make transport biofuels (EC, 2010). However, the high GHG savings offered by woody biomass do not take into account land use change which is not referred to in the Renewable Energy Directive.

At the same time, the Commission acknowledged the risk that increased demand for forestry or agricultural residues could lead to a reduction in soil carbon if too few residues are left on the land (ibid). The Commission further acknowledges that the limited level of sustainability-certified forestry, particularly outside of the EU, 'warrants vigilance' in the context of additional demand for biomass for bioenergy (ibid). Specifically, because of the relatively higher sustainability risks related to forestry, the Commission states that it will closely monitor progress in this field and, by 31 December 2011, reassess the situation, specifically reporting on whether national sustainability assessment schemes have 'sufficiently and appropriately' addressed sustainability issues and, perhaps conversely, whether these schemes have led to barriers to trade and barriers to the development of the bio-energy sector (ibid, sections 3.2 and 4).

Non-transport uses of biomass in the UK are covered by the Renewables Obligation (RO) (applying to electricity generation) introduced in 2002 which awards tradable certificates (ROCs) for electricity generation by renewable energy and includes a sustainability reporting requirement for biomass. The Renewable Energy Strategy, published in 2009 (HM Government 2009), sets out plans to extend the RO to meet a target of 30% renewable electricity by 2020, estimating that 30 – 50% of the UK's renewable energy could come from bioenergy. Although there is currently no single scheme of sustainability standards that applies to all of incentive schemes covering the use of solid biomass, the strategy calls for mandatory sustainability criteria (for large scale users/suppliers) applicable internationally. 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) which is a product of the G8 process and was launched in 2006 under the auspices of the Commission for Sustainable Development. It was set up to facilitate coordinated international R&D for all aspects of biomass energy from production to use (with particular focus on developing countries) and provides a forum for developing policy frameworks operating at a high level of policy dialogue.

4.5 Co-firing

To date, CCS is typically associated with coal (and to a much lesser extent, gas) fired power stations as a means of generating electricity using conventional fossil fuel technology with drastically reduced CO_2 emissions. Although, eventually, CCS could be applied to a dedicated biomass power station in pursuit of negative CO_2 emissions, it is unlikely that the two immature technologies would be brought together before CCS gains a true commercial presence. Co-firing, whereby biomass may be used as a proportion of the feedstock within a conventional coal-fired plant, represents a first step towards combining CCS and biomass energy. (Veijonen *et al.* 2003) estimate CO_2 emission savings to be proportional to the wood fuel component in a co-fired plant with up to 50% reduction in CO_2 associated with cofiring coal with 50% wood fuel, with additional benefits if biomass sources local to the power plant can be utilised or if co-firing avoids landfill disposal of the biomass fuel.

Co-firing was first deployed in the UK in 2002, reaching a peak of 15% (2.5TWh) of total renewable electricity production in 2005, falling to its current (2009) level of 7% (1.8 TWh) of renewable generation (see Table 2), with over 50% of the biomass from derived from imports (DEFRA 2007). A conventional plant may take up to 25% biomass fuel without any major boiler redesign (although other factors such as fuel transportation and preparation may limit applications to smaller percentages) (DUKES 2009).

A variety of bioenergy fuels can be used to co-fire a conventional fossil fuelled power station with relatively minor modifications and can enable bioenergy to be used more economically than in a dedicated biomass power station. This is due to a number of factors: large conventional plants operate at higher thermal efficiencies, the costs of

designing, planning and constructing a new dedicated plant can be avoided (along with some of the commercial risks) and generators can take advantage of Government incentives for the biomass component under the Renewables Obligation (Colechin and Malmgren 2005). These incentives are the main driver for the use of biomass in conventional plants, given different operational requirements and fuel costs that are more than double that of coal (Colechin and Malmgren 2005).

The Renewables Obligation requires suppliers to source a proportion of their supply from renewable energy (currently 9.7%, increasing to 15.4% by 2014 / 2015) – there are no restrictions on the proportion of co-firing a generator is allowed but a supplier can only meet 12.5% of its obligation through co-fired ROCs (reducing to 5% in 2011). In addition, the 2009 amendment to the Renewables Obligation requires an increasing proportion of biomass to be sourced from energy crops[3] (rising from 25% in 2009 up to 75% by 2012) (Colechin and Malmgren 2005) and puts co-firing with non-energy crops into a band receiving 0.5 ROC per MWh to avoid any negative impacts on other renewables (DUKES 2009). Currently, beyond 2016 biomass co-firing will no longer be eligible for ROCs, implying that without other incentives, it will only continue beyond that date if it is economical in its own right (Colechin and Malmgren 2005) or if relevant legislation changes.

The main challenges to co-firing lie in the different properties of the different fuel types (calorific value, moisture content, volatile matter content, bulk handling characteristics such as dust generation, mechanical stability etc, combustion characteristics, etc) and any new biomass fuel type needs to be subject to full-scale plant trials before longer-term co-firing can be considered (Colechin and Malmgren 2005). Fluidised bed boilers are the most flexible and can use any type of wood fuels, but greater selectivity is required in the more commonly used pulverised systems (although precombustion gasification or pyrolysis of solid wastes or biofuels can extend the options) (Veijonen *et al.* 2003). To date biomass co-firing has not been demonstrated at ultra-supercritical temperatures (IEAGHG 2009). Other technical issues associated with introducing biomasss to a conventional plant include health and safety issues associated with introducing a more reactive fuel; plant flexibility (with potential electricity trading implications) (Colechin and Malmgren 2005). A large scale increase in biomass co-firing uptake could be beneficial in advancing the use of new technologies, such as gasification of lignocellulosic biomass (Hansson, *et al.* 2009).

5. BioEnergy with Carbon Capture and Storage – bringing it together

5.1 Carbon Capture and Storage

Capture

Although, the three key components of CCS (CO_2 capture from power stations, transport of the CO_2 to the storage site and long term underground storage of the

[3] The main energy crops in the UK being short rotation coppice (SRC) willow and poplar and Miscanthus

captured CO_2) 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 2005) 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); there is the potential to apply any of the three major capture options within a variety of biomass energy systems, including CHP systems (Mollerstein *et al.* 2006). In addition, CO_2 can be captured during biomass conversion to secondary fuels (for example bioethanol production from sugar fermentation, which releases a pure stream of CO_2 available for straightforward capture) (Mollerstein *et al.* 2003; Mollersten, *et al.* 2003).

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 on power plants using biomass (IEAGHG 2009). The study looked at four case studies ranging from a 75MWe standalone biomass plant to a 500 MWe co-fired plant (including both pulverised fuel and fluidised bed technologies and 10% biomass in each case), all using wood chips for the biomass component. CO_2 capture was modelled as standard post-combustion capture process using MEA solvent, assuming a 90% capture rate and energy penalty ranging from 10-16% depending on the boiler type.

A greater loss in efficiency associated with the capture equipment was observed in the standalone plant – this was considered to be a result of the 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. This performance penalty associated with the capture at a standalone plant also contributed to relative higher costs (see next section). A similar effect was seen in the co-firing cases whereby the higher efficiencies associated with a fluidised bed, compared with a pulverised plant, are lost when CO_2 capture is applied, due to additional need for FGD plant[4] and lack of heat recovery.

Various studies have attempted to quantify the emissions reductions and costs associated with different BECCS options, these are summarised in Table 3. In terms of CO_2, the IEA study presents negative emissions at the standalone biomass plant with CO_2 capture of up to -1755gCO_2/KWh and a negative emission rate of -32g/Kwh in the case of a supercritical circulating fluidised bed boiler with only 10% biomass co-firing (total CO_2 captured less CO_2 emissions from coal)[5]. 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.

[4] Limits to SO_x emissions can be achieved through addition of limestone to the furnace bed in an FBC plant

[5] In the co-fired pulverised coal with CO_2 capture case emissions estimated to be -31.3 g/KWh

In his workshop presentation, Scot Laczay (Imperial College) presented estimates of CO_2 emissions for biomass co-firing with coal at 5, 20 and 50%. Basing his figures on those achieved at a circulating fluidised bed (CFB) facility in Finland and assuming 28.5% plant efficiency, negative emissions were only achieved once the biomass component is above 20%, with negative emissions of -400gCO_2eq/KWh estimated with 50% biomass co-firing.

In addition to BECCS applied to large scale electricity generators, other point sources could also be suitable. For example, in his workshop presentation Karlsson discussed 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 (Moellersten and Yan 2001; Mollerstein *et al.* 2006). In a study modelling the sequestration potential from a temperate forest providing biomass for a CCS plant, (Kraxner *et al.* 2003) estimated that an average sequestration rate of 2.5 tC/ha/yr could be achieved sustainably.

Table 3. Comparison of emissions estimates from BECCS (in electricity generation) modelling exercises

Study	Technology	Net emissions	Costs	Assumptions
IEAGHG 2009	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, workshop presentation	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)	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, Nilsson et al. 2003)	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.

Transport and Storage

There are no specific technical implications of 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. For the case of biomass co-firing, 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 this lack of infrastructure is likely to present an additional (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 (Azar *et al.* 2006).

During the workshop, Laczay presented results from a study commissioned by the UK Department of Energy and Climate Change exploring 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 (DECC 2009); 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 study then explores the cost implications of meeting the transport requirements associated with scenarios for maximum and minimum levels of uptake of CCS (from coal and gas fired plants only) taken from MARKAL modelling results. The maximum uptake scenario (corresponding to an 80% reduction in CO_2 by 2050 (MARKAL 33/80)) corresponds to a total of 3.2 GT CO_2. Assuming all CO_2 is routed through transport hubs at Thames and Easington for the Southern North Sea and Barrow for the East Irish Sea (and that all CCS power stations are located close to landing point hubs, thus avoiding the need for any onshore CO_2 transport), the total cost of developing necessary pipelines in the maximum adoption scenario (including compression and storage site injection costs) is estimated to be £3.5bn over the duration of the scenario (and assuming a 10% discount rate*).*

The main technical risks to a pipeline developer 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, detailed surveys and risk assessments are not widely available for potential aquifer storage sites, with 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* (DECC 2009).

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 as up to a maximum of 14GT CO_2, although a figure of 7GTCO_2 is considered to be a more realistic estimate (EU Geocapacity 2009); in hydrocarbon fields the capacity is estimated at 7.3GT CO_2[6]. To put these figures in context the total CO_2 emissions from large point sources in the UK (2005) was 258 MTCO_2 (EU Geocapacity 2009), or storage capacity for CO_2 captured from domestic point sources for a period 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). In October 2009, the UK Storage Appraisal Project was launched by the Energy Technologies Institute to review potential offshore storage sites. This large collaborative project should be completed in March 2011 and aims to provide a comprehensive assessment of CO_2 storage capacity in the UK.

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 and a very large range of estimates for global storage capacity (MIT 2007). An exception to this is the GEODISC study which carried out a detailed detailed analysis matching sources to sinks for Australia (Bradshaw *et al.* 2004).

5.2 Costs

Estimates of the costs of BECCS are inevitably highly uncertain – they are dependent on many variables and assumptions and there is insufficient commercial experience of a full scale CCS plant. However, (Rhodes and Keith 2005) suggest that BECCS is likely to be more costly than equivalent FECCS schemes. Because there is large initial capital outlay associated with the CCS process, only larger scale installations will be commercially viable, while bioenergy installations are typically small scale – presenting a potential mismatch of scale in establishing dedicated BECCS plant (Rhodes and Keith 2008).

Table 3 provides a comparison of some of the estimates available in the literature – these are based on very 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. There are many examples of costs estimates for FECCS (e.g. (Johnson and Keith 2004; Rubin, Chen et al. 2007; Hamilton, Herzog et al. 2008)), here we include only those that explicitly include a biomass component.

The results presented in Table 3 typically 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 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 can be a network for CO_2 transport or point to point transport is required. Costs will also be affected by storage site

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

properties such as compartmentalisation of aquifers which would require additional injection wells (DECC 2009).

CCS entails a significant initial capital outlay with subsequent increased operating costs (compared to a plant without capture) 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 increases the cost of electricity from biomass with capture decreases, which, as (Keith, Ha-Duong et al. 2006) note, is the most that can be said with certainty about BECCS costs. Considering a biomass gasification combined cycle plant with CO_2 capture, bio-power could be competitive with coal or gas (without capture) at a carbon price of around $100/tC and cheaper at around $160/tC (Rhodes and Keith 2005; Azar, Lindgren et al. 2006; Keith, Ha-Duong et al. 2006). With reference to the EU ETS (Emissions Trading Scheme), the IEA GHG study estimates an ETS certificate price of €48-55/tCO_2 (€176-202/tC) would be necessary for a biomass co-fired plant with capture to be competitive with an equivalent plant without capture and €65-76/tCO_2 (€238-278/tC) for dedicated biomass plant with capture (IEAGHG 2009). At the time of writing, the current EU ETS price is only €15/tCO_2.

On a more aggregate level, these analyses can be extended to explore the role of different mitigation options under scenarios directed at meeting targets for atmospheric concentration of CO_2. In particular, Karlsson referred to results from a global-economy model (the GET model) developed by (Azar, Lindgren et al. 2006) that suggest while the introduction of BECCS can deliver a small reduction in the overall costs of meeting the 450ppmv target (by 2100), it can 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). A sensitivity analysis of the key parameters of the model showed this key conclusion to be robust. Furthermore, similar analyses comparing three different global-economy models (GET, IMAGE/TIMER and MESSAGE) reinforce the argument that BECCS may be necessary to achieve concentrations approaching 350ppmv over the course of this century (Azar *et al.* 2010).

5.3 Emissions credits – conceptual challenges

During the workshop, Francisco Ascui of the Edinburgh Business School gave a presentation considering the role of BECCS within carbon markets. As discussed above, given the additional costs of implementing BECCS (compared with biomass energy without CO_2 capture and storage), compatibility within carbon markets is vital. Ascui identified various conceptual challenges within existing markets requiring policy formulation in order to explicitly incorporate delivery of negative emissions via BECCS (or biochar). 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.

1. *A conceptual problem in a cap and trade system*: currently these are set up in terms of allowances of emitted CO_2 and not "credits", as negative emissions might be considered. The problem arises because within a cap and trade regime, a fixed number of emission allowances are issued and this 'right to emit' is traded – whilst negative emissions could contribute to reaching the system 'cap' (total system emissions) there is no facility for incorporating this as a 'credit' in the trading scheme. An uncapped system could be more straightforward with the possibility of trading in two separate 'credits'. In addition whilst emissions of greenhouse gases can be measured, accounting for negative emissions is more challenging (and potentially more subject to witting or unwitting abuse due to the need to protect stocks of vegetation over substantial periods of time – see non-permanence below).
2. *A practical problem within the EU ETS*: BECCS does not 'fit' the current carbon market, the EU emissions trading scheme. At an operational level, the existing system does not recognise a 'BECCS credit' so there is no way of incorporating negative emissions within the EU ETS.
3. *The Kyoto Protocol* – 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 forestry and land use (Articles 3.3 and 3.4)– there is no class of credit that would cover BECCS. (Gronkvist *et al.* 2006) present a discussion of how BECCS could be incorporated into the carbon pool approach currently adopted within the Kyoto Protocol for managing CO_2 "storage" in harvested wood products.
4. *The Clean Development Mechanism* (*CDM)* – 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, a CER (Certified Emission Reduction), is traded. While biomass energy in developing countries is included in the CDM (see, for example (Jürgens *et al.* 2006) for a detailed discussion of this), Carbon capture and storage is not currently recognised within the CDM, although it is under discussion it is proving to be contentious. (Shackley *et al.* 2009) address some of the arguments put forward against inclusion of CCS in the CDM (typically by environmental campaigning organisations and some developing countries); these 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. The authors conclude, however, that once CCS becomes more established there could be significant potential for it within the CDM.
5. *Non-permanence* – should any negative emissions be reversed once a credit has been issued, for example through leakage from the storage site, it would need to be accommodated for in the system. Some experience of possible solutions to this problem has been gained within the forestry sector, for example: 'temporary credits' (although the introduction of temporary CERs for forestry projects within the CDM was not successful, leading to very few projects); '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); mandatory insurance (although this has been discussed within the broader CCS context, there is no experience in this area. There may 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.

5.4 Public perceptions

In terms of public perceptions of using biomass for energy, surveys suggest modest approval by the UK public: Poortinga *et al.* (2006) found that just over half of the British population have mainly or very favourable opinions or impressions – a favourability rating that is comparable to natural gas. Other nationally representative surveys (e.g. TNS Plc 2003) have produced similar findings: opinions of biomass are less favourable than for more 'traditional' renewable energy technologies, such as solar and wind power. However, on balance they are still positive. (Eurobarometer 2007) research shows that support for biomass in the UK is among the lowest in Europe. It is then perhaps not surprising that relatively few people believe that biomass will significantly contribute to reliable and secure supplies of electricity in Britain in the future (Poortinga *et al.*, 2006).

Physical bioenergy infrastructure can be unpopular if perceived as intrusive: Upham and Shackley (2007) found very negative attitudes to the siting of a large-scale biomass gasifier plant in Devon. Local residents living close to the proposed plant expressed a wide range of concerns, including lorry traffic congestion/air pollution, the credibility of the developer, air pollution, odour and appearance of the plant. Further concerns were related to fuel waste, technological reliability, landscape changes and the impact on house prices. A follow-up survey (Upham 2009) showed that the level of concern remained high up to the final withdrawal of the planning application, and the number of people viewing any benefits of the biomass gasifier plant had decreased substantially after planning permission was refused. Furthermore, trust in developers and district councils have been found to be low with regard to similar developments (Sinclair and Lofstedt 2001; Upreti 2004; Upreti and Van der Horst 2004). In McLachlan's (2010) study of a Miscanthus and clean woodchip electricity plant in Staffordshire, local opposition centred on the health implications of burning wood, the potential for other 'dirtier' fuels to be used in future, increases in traffic, the impact on local visual amenity and concerns over the process of consultation (particularly the communication of alterations made to the original plans for the development). There were also some positive assessments from local stakeholders and residents in terms of the development showing the area to be 'green' and 'pioneering'.

While CCS remains an unfamiliar concept to the majority of the lay population, research exploring opinion about CCS suggests that, given sufficient information to enable formation of an opinion, other mitigation options (energy efficiency, renewable energy and to some extent nuclear power) are widely seen as preferable to CCS. However, provisional acceptance of the technology is observed at a general level (i.e. not in the context of specific developments) when it is seen as a bridging technology while the preferred alternatives become more widely established (see for example, (Gough *et al.* 2002; Reiner *et al.* 2006; Tokushige *et al.* 2007; van Alphen, *et al*. 2007; Ha-Duong *et al.* 2009). The primary concerns about the technology relate to the safety and reliability of CCS plants but also to their governance and regulation over the long term (Mander *et al.* 200).

A review of experience in establishing CCS demonstration plants in a variety of locations revealed that local communities are sceptical about the motivations of developers when projects were introduced to them by representatives from large corporations (associated with the oil and gas industry); the importance of engaging local communities at the earliest opportunity; the importance of justifying the project within the wider policy context (i.e. climate change and the need to reduce CO_2 emissions) and providision of access to adequate information about the project (Waldhober, Brunsting et al. 2010). Recently, in the Netherlands, a planned onshore CO_2 storage project at Barendrecht was cancelled (Guardian 2009; Feenstra *et al.* 2010) and in the US, developers pulled out of a project to store CO_2 from an ethanol production plant in Ohio (Dayton Daily News 2009)[7] both in the face of intense local public opposition.

5.5 Avoiding carbon lock-in

The final presentation at the workshop was given by Philip Vergragt (Clark University), in which he used 'Transition Management Theory' to explore the role that BECCS could play in avoiding a potential carbon lock-in that could be associated with Fossil-CCS (FECCS). Transition management theory adopts multi-level perspectives to describe how innovation may occur via three interlocking levels (landscape, socio-technical regimes and niches), resulting in transitions between socio-technical systems (Geels 2002; Geels 2005). An example of how this theory may be applied in the context of decarbonising the UK energy system may be found in (Shackley and Green 2007).

The current socio-technical system is "locked-in" to a carbon intensive fossil fuel energy system whereby the inertia of the associated technological, physical, political, economic and cultural networks which develop around the energy system inhibits change to an alternative energy system (Unruh 2000). Vergragt illustrated how, from a multi-level perspective, modern biomass technologies and CCS occupy technological niches within the fossil energy system - with the key difference being that CCS is driven by incumbents of the current system rather than fringe actors, as is more typical for radical innovation (Vergragt *et al.* 2010). CCS is often presented as a 'bridging technology' that could allow large-scale reduction in CO_2 emissions between a fossil energy system and a decarbonised energy system. Assessing fossil-CCS (FECCS) against a set of criteria[8] developed to assess degree of lock-in, Vergragt suggests that it is more likely to reinforce the technological lock-in of fossil fuels by strengthening the depth of the lock-in.

A Technology Innovation System (TIS) framework has previously been used to explore the relative strengths of a socio-technical regime or niche (Hekkert *et al.*

[7] Anti CCS blog at http://citizensagainstco2sequestration.blogspot.com/

[8] The criteria, based on those proposed by Shackley, S. and M. Thompson (unpublished). Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? supplied by authors.Criteria are: heaviness (scale, infrastructure, capital intensity and lead time); interrelatedness between technologies, legitimation (hyping, closed to criticism); learning effects; expectations and interests.

2007) and Vergragt used this approach to demonstrate the weakness of the BECCS TIS compared to the much stronger FECCS system (see for example (van Alphen *et al.* 2009)). Although much of the knowledge and experience developed through FECCS is applicable to a BECCS system, Vergragt argues that concentrating this knowledge towards fossil applications could risk locking biomass out from the CCS technology. Although biomass co-firing could potentially reduce this risk (and consequently the risk of reinforced lock-in of fossil fuels), the relatively modest level of co-firing in current applications weakens this effect.

Vergragt concluded that CCS is becoming locked-in to fossil fuels and as current CCS R&D and demonstration projects progress, this is likely to be perpetuated. For BECCS to take over from the FECCS system it would need to offer very clear advantages (*such as negative emissions?*) and would probably require government intervention with a coordinated effort to improve the R&D, market opportunities, collaboration (between CCS, biomass and BECCS stakeholders) and legitimation of BECCS,

(Shackley and Thompson unpublished) explore in detail the possible influence of CCS on carbon lock-in, concluding that the development of fossil-CCS does not inevitably lead to carbon lock-in. For example, different types of CCS technology hold different implications to the energy system – from the limited changes associated with post-combustion capture on existing types of fossil plant (with potential to reinforce the existing regime) through to precombustion capture processes (such as flexible gasification technologies) which could link in to a hydrogen-based energy system. Shackley and Thompson present various strategies to reduce the risk of other (low-carbon) technologies effectively being 'locked out'; the key being to avoid *deep* lock-in by maximising flexibility. In the case of CCS, the features identified as giving the greatest flexibility (and hence potentially shallowest lock in) include adopting the least capital intensive capture options (e.g. Natural gas combined cycle, or pulverised fluid bed combustion in the case of coal plant); avoiding extensive transport networks by locating capture facilities as close as possible to storage locations, enabling the use of dedicated pipelines; early storage projects exploit well-understood HC fields where existing infrastructure can be used. By pursuing such strategies to avoid the reinforced lock-in that concerns Vergragt, Shackley and Thompson argue that by striving for the most flexible CCS technologies the system will be more responsive to factors such as depletion of coal reserves or improved economics of renewable energy that could make FECCS less viable- thus avoiding carbon lock-in in the shorter term without reinforcing fossil lock-in in the longer term.

6. Conditions for BECCS

This report has presented an overview of the technologies and issues associated with combing 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, these challenges are dominated by the non-technical, as 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 and where their exploitation will be most effective.

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 (Azar *et al.* 2006). 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 community. 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. BECCS is not cheap and without a clear mandate for large scale emissions reductions there is no reason for it to be implemented. However, 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 must be made of the potential impacts on communities in developing countries that have been well-rehearsed in the context of biomass energy.

Broader perceptions. As with any novel technology or approach, its success depends upon how 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. A key argument for introducing BECCS is the urgency of achieving a CO_2 concentration target of 350ppmv, but is the need for and the scale of this challenge widely understood? Research on the acceptability of fossil-CCS suggests this could be a critical element of the acceptability of BECCS.

7. 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). However, the suitability of BECCS is not 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 (Mollerstein *et al.* 2003; Gronkvist *et al.* 2006). In UK, there is a relatively small bioenergy resource, so the focus in terms of BECCS is here perhaps best directed to co-firing rather than dedicated biomass plant; once a CO_2 transport and storage infrastructure is established there may be opportunity to establish smaller scale biofuel 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 other energy sources, due in part to land use factors that affect greenhouse gas emissions, are difficult to measure and which are frequently remote from the end use application. 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, extreme 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) ((Azar *et al.* 2010); at the very least this would hold deleterious implications for long term problems associated with ocean acidification. Using BECCS or bioenergy/biofuels generally 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 sustainable decarbonised energy systems. BECCS / FECCS 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 (Azar *et al.* 2010).

Rhodes and Keith (2008) recommend that, due to the uncertainties and complexities associated with achieving sustainability, bioenergy policy should be developed through a process of adaptive management. This ensures an open, inclusive and iterative process that accommodates uncertainty. In the context of BECCS in UK, this could be realised through the introduction of BECCS within a co-fired system – 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 establish fossil plants, and potentially rendering any fossil fuel lock-in associated with CCS more shallow. 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.

Thus we have described how, while not a panacea to solve global climate change, or even the UK's national emission reduction challenge, BECCS could contribute to the acceleration emissions reductions in the medium term.

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