AVOID 2
Can we avoid dangerous climate change?

Synthesising existing knowledge on the feasibility of BECCS

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Key Findings

- Biomass energy with Carbon dioxide Capture and Storage (BECCS) is an emerging technology that combines large scale biomass energy applications (including electricity generation) with the capture and storage of CO_2.
- BECCS has the potential to remove CO_2 from the atmosphere (‘negative emissions’).
- Alternative CO_2 removal approaches do not provide the co-benefit of energy production.
- BECCS technology is entering the demonstration phase; the first large scale (1 $MtCO_2$ yr^{-1}) project is due to start operation in 2015 in Decatur, Illinois, USA. There are around 15 pilot scale BECCS plants globally.
- Most, but not all, IPCC WG3 emission scenarios that, for a mid-range equilibrium climate sensitivity, do not exceed 2°C warming require BECCS at a large scale to reconcile current emission trajectories with cumulative carbon budgets.
- For a given climate target the inclusion of BECCS in emission scenarios allows higher total carbon emissions, and/or a later peak in emissions, by removing carbon dioxide from the atmosphere later in the 21st century.
- Many scenarios consistent with 2°C use BECCS to achieve *global net* negative emissions (when negative emissions from BECCS are greater than total emissions from *all* other sources) by about 2070, with a mean CO_2 removal across IPCC WG3 scenarios of 616 $GtCO_2$ by 2100.
- Integrated Assessment Models (IAMs) are based on different assumptions and constraints; some set a maximum limit of 200 EJ yr^{-1} for BECCS applications, whilst others incorporate explicit land use modelling. IAMs take account of future population, food production and land availability to varying levels of detail.
- The potential global bioenergy resource available for BECCS is a key uncertainty; composed of uncertainties in land and water availability, crop yields and residue availability, each associated with socio-economic assumptions, e.g. future agricultural efficiency gains, population growth, dietary trends and lifestyles.
- Many IAM scenarios assume that BECCS utilises dedicated rain-fed bioenergy crops grown on surplus agricultural land, assuming medium yields and the use of crop and waste residues. This seeks to circumvent issues of competition with food production and other land uses but is strongly dependent on the underlying socio-economic assumptions.
- BECCS may not deliver negative emissions if the biomass energy system is weakly governed and regulated. A poor choice of biomass type and location could lead to a net *release* of carbon to the atmosphere through direct and indirect land use changes.
- Deployment of CCS adds to the costs of energy generation, without strong climate policy incentives, such as suitable carbon pricing, and regulation there is no driver to establish the technology.
- Almost all scenarios compatible with the 2°C target assume full global participation in delivering emissions reductions; at scales sufficient to deliver global net negative emissions, uptake of BECCS in particular will require new global implementation and governance frameworks in the context of a highly complex supply chain.
- The global potential for negative emissions is estimated to be between 0 and 10 $GtCO_2$ yr^{-1} in 2050 and between 0 and 20 $GtCO_2$ yr^{-1} in 2100. Assuming 150 EJ yr^{-1} bioenergy in 2050, 250 EJ yr^{-1} in 2100, a 90% capture rate and emissions of 15 kg CO_2 GJ^{-1} from bioenergy production. If BECCS starts in 2020, the maximum values equate to 900

$GtCO_2$ (245 GtC) removed by 2100. The lower bounds could result from weak or no climate policy; lack of social acceptability; and/or failure of the BECCS system to deliver net negative emissions. The confidence in this estimate is limited as it is based on one expert team using one particular modelling approach.

Media interest

This report covers the biophysical and Earth system scientific questions around BECCS in supporting emissions reductions over the 21st century. As such it will be of interest to science and environment journalists who report in this area. Some of the key messages will be of interest to the media (especially at the time of COP) as BECCS research and its potential for reducing emissions will be drawn in to the international negotiations on emissions reduction.

Contents

1. Introduction

There is a growing and significant dependence on biomass energy with carbon capture and storage (BECCS) in future emission scenarios that do not exceed 2°C warming; over a hundred of the 116 scenarios associated with concentrations between 430–480 ppm CO_2 depend on BECCS to deliver global net negative emissions in the IPCC Fifth Assessment Report (AR5) (Fuss et al., 2014). Wiltshire et al (2015) found a median value of around 168 GtC cumulatively removed by 2100 using BECCS in the IPCC scenarios. The feasibility of this dependence on BECCS is coming under increased scrutiny, given the interconnected issues of food production, energy provision, energy system capacity and environmental impacts of large scale bioenergy coupled with large scale carbon capture and storage (CCS).

1.1 Context

Fossil fuel CCS has consistently featured as a key component of proposed emission reduction strategies for some time, despite limited progress in realising its commercial application. As the climate change mitigation challenge grows, the potential role for coupling CCS with biomass energy (BECCS) to deliver zero or negative emissions increasingly features within this discourse. In the case of BECCS, the negative emissions concept is based on the principle that, since CO_2 is absorbed from the atmosphere during the growth cycle of biomass feedstocks, if the CO_2 produced during combustion of biomass energy is captured and stored indefinitely in geological formations, removal of carbon dioxide from the atmosphere can be achieved (Read and Lermit, 2005; Keith and Rhodes, 2002). Other approaches for negative emissions have also been proposed (for example direct capture of CO_2 from the air, ocean fertilisation *inter alia*) but BECCS is by far the most prominent of these options in climate change mitigation scenarios and so BECCS will be the focus of this report (Fuss et al., 2014; van Vuuren et al., 2013; Azar et al., 2013, Vaughan and Lenton, 2011).

Climate change mitigation policies are focused around a target of limiting the increase in the global average temperature to 2°C (by 2100), a policy goal agreed within the UNFCCC in 2010. Achieving this target is dependent on tight limits to cumulative emissions of CO_2 (and other greenhouse gases) in order to stabilise their atmospheric concentration. As global emissions continue to increase, the cumulative emissions, and consequently atmospheric CO_2 concentration, also continue to rise and the remaining emission ‘budget’ contracts, making the task of reaching the targets ever more challenging. In this context, BECCS appears to be an attractive approach to potentially enabling mitigation costs to be reduced, more ambitious targets to become feasible than would otherwise be possible (although still not avoiding climate change) or allowing a delay in the year in which emissions peak and overshooting long term concentration targets in the near term (‘buying time’) (Friedlingstein et al., 2011, Huntingford et al., 2012; van Vuuren et al., 2013, Bernie and Lowe, 2014).

Working Group 3 (WG3) of the IPCC Fifth Assessment Report (AR5) describe four Representative Concentration Pathways (RCPs). These have been developed to represent the wide range of emission scenarios from different sources published across the literature; the RCPs are presented as cumulative greenhouse gas (GHG) concentrations over time (1850-2100) and are associated with different levels of radiative forcing. The RCPs provide a consistent set of pathways for subsequent analysis in different areas of climate change research – for example by climate modellers to analyse potential climate impacts associated with the pathways (including projected global average temperature rise) and in Integrated Assessment Models (IAMs) to explore alternative mitigation scenarios consistent with achieving the concentration pathways (IPCC, 2014; van Vuuren et al., 2011b).

The pathways are grouped according to the estimated radiative forcing due to GHG emissions in 2100 (i.e. RCP2.6 represents concentration pathways resulting in a radiative forcing of 2.6 W/m^2 etc.). There are two stabilisation pathways, RCP 6 (~850 ppm CO_{2eq}) and RCP4.5 (~650 ppm CO_{2eq}[1]), a high pathway, RCP 8.5 (~1370 ppm CO_{2eq}) and a low pathway RCP 2.6 (~450 ppm CO_{2eq} by 2100). This latter pathway, RCP2.6, includes an 'overshoot' whereby concentrations reach a peak of 490 ppm CO_{2eq} before declining by 2100; this peak and decline profile is achieved by including a negative emission component based on deploying BECCS (Figure 1) and, to a lesser extent, afforestation measures (van Vuuren et al., 2011a) and will provide a focus of our review.

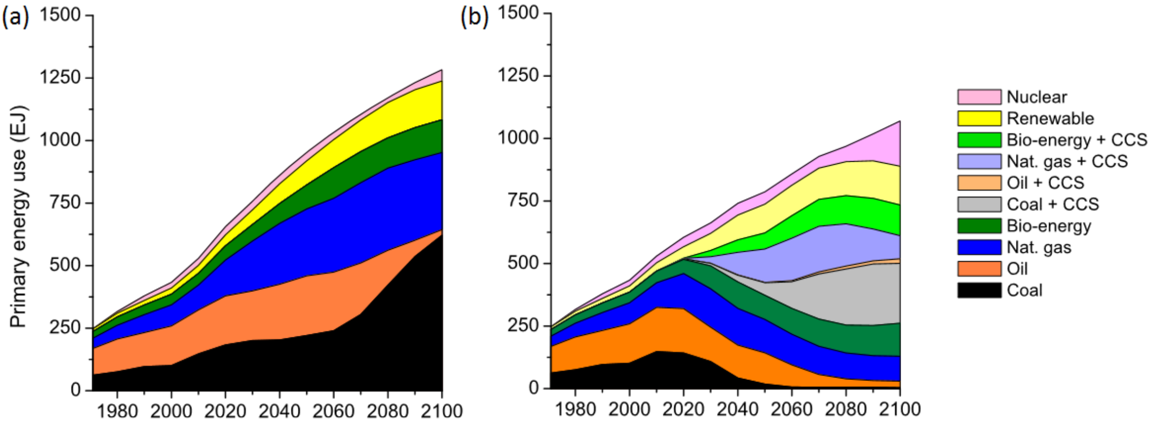

Figure 1. Trends in global energy use for (a) baseline and (b) RCP2.6 scenario. Figure 2 from van Vuuren et al., 2011 (p102). Note BECCS use from 2020, non-CCS bioenergy use and fossil fuel with CCS use.

The process of relating GHG concentrations to projected temperature rise is complex and carried out by models of the Earth's climate system. Global mean surface temperature increase by the end of the century is dependent on cumulative emissions over time. Only scenarios achieving concentration levels within 430-480 ppm by 2100 (and a small number of the scenarios extending to 530 ppm) were associated with a greater than 66% chance of achieving the policy goal of limiting global atmospheric temperature rise to below 2°C (IPCC, 2014).

Over 1000 emission scenarios fed into the process through which the RCPs were developed (Fifth Assessment Report of the IPCC (WG3)), including emission pathways likely to exceed 1000 ppm CO_{2eq} and, consequently, climate warming up to 5°C and beyond. In an analysis of these pathways, Fuss et al. (2014) found that roughly half of all the scenarios include a significant contribution from BECCS. Furthermore, a large majority of the pathways which deliver atmospheric CO_2 concentrations consistent with the 2°C target (and indeed many of

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[1] CO_2 concentrations may be reported as either CO_2 equivalents (CO_{2eq}) (e.g. RCPs and some IAMs), or as carbon dioxide (CO_2). CO_{2eq} can represent total greenhouse gas forcing or total anthropogenic forcing, e.g. including cooling due to aerosols. Here we quote figures that maintain the format of the original literature under review.

those associated with temperature increases up to 3°C) require *global net* negative emissions by about 2070 (Fuss et al., 2014). Global net negative emissions are achieved when the negative emissions associated with BECCS are greater than total emissions from *all* other sources (i.e. anthropogenic and non-anthropogenic) (Fuss et al., 2014). In other words, the large scale deployment of BECCS in the models is central to the feasibility of not exceeding 2°C of global mean temperature warming above pre-industrial.

The IAMs used to produce emission pathways are driven by economics based decision making approaches – and most deliver cost minimising scenarios (i.e. emission profiles that deliver a particular level of mitigation at the least aggregate cost within the set of constraints defined in the model) (IPCC WG3). Those pathways presented in the IPCC assessment that do not include negative emissions are estimated to be significantly more expensive in the model results (Fuss et al., 2014). However, there are very significant uncertainties associated with the use of BECCS as a carbon dioxide removal approach. CCS used with fossil fuels is in itself a new technology that has not been widely deployed at a commercial scale (there is currently only 1 full chain commercial scale plant in operation, the Boundary Dam project in Canada). Extending this technology to use with biomass introduces further challenges to the approach – both in terms of the technological operation and in establishing a sustainable supply chain for the biomass feedstocks. Emission pathways derived from IAMs all cover a global scale and, although much of the data is regionally disaggregated, the assumptions driving the models are nevertheless developed at a top-down level. The top-down nature of the assumptions vary from model to model; some constrain BECCS by an upper value of energy generated by BECCS drawn from the literature whilst others are more detailed including assumptions about land use, crop yield, crop energy value, percentage of carbon stored in CCS, energy penalty of CCS etc. In the case of both fossil and biomass CCS, there is currently very little actual deployment; extrapolating from what is often data derived from desk-based analyses, or, at best, small scale demonstration plants, the models introduce large scale estimates of globally significant levels of deployment with a vastly expanded biomass energy market. Here, we aim to unpick some of the broader assumptions made around the potential role for BECCS in order to consider how its representation in mitigation pathways could be improved.

1.2 BECCS scenarios

The purpose of this literature review is to provide a synthesis and analysis of the key uncertainties in the assumptions in future scenarios of BECCS. It provides the basis for an expert workshop on the feasibility of BECCS scenarios which was held in London on 27 January 2015 (see Report WPD1b). For the expert workshop, we provided contextual information for our identified key assumptions (Section 5, Table 5) from three distinct sources. For the top-down perspective, we used the negative emissions scenarios created for AVOID 1 (Bernie et al., 2012), for an IAM scenario we use RCP2.6 (van Vuuren et al., 2011a; 2009; 2007) complemented with information from some initial TIAM model runs for AVOID 2. Here, we outline how BECCS scenarios are constructed in general and we pay particular attention to the scenarios we used in the expert workshop, AVOID 1 (Bernie et al., 2012) and RCP2.6 (van Vuuren et al., 2011b).

Future scenarios of BECCS can be constructed using simple top-down approximations or more commonly through the use of Integrated Assessment Models (IAMs) where BECCS is constrained by a set of assumptions. IAMs are constructed in different ways; whilst all attempt to represent the global energy system, different models represent different component aspects to different degrees of complexity, often reflecting the lineage with which an IAM has evolved over time.

IAMs create cost-optimal pathways to reach set targets, e.g. 2°C, constrained by a wide range of assumptions about the global economy and energy systems including future socio-economic assumptions relating to population, diets, and living standards. The upper limits of BECCS potential are set within each model as constraints, based on literature estimates; the amount of BECCS used in any one scenario is an output of the model run, and will not exceed the levels defined by the model assumptions. The way BECCS is used in the models is constrained in different ways, for example some IAMs include detailed representations of land use (e.g. IMAGE, van Vuuren et al, 2011b), and with input from more complex land use models (e.g. LPJml as input to MAgPIE, Humpenöder et al., 2014) whilst many do not explicitly model bioenergy production, using instead an assumed maximum limit, e.g. 200 EJ yr^{-1} (e.g. GET, Azar et al., 2013; ReMIND, Kriegler et al., 2013). Models that represent land use such as IMAGE are not coupled to climate models directly, instead they use simple climate models (e.g. MAGICC) to generate global mean temperature and precipitation and pattern scaling to convert these to regional temperature and precipitation data. IMAGE includes the carbon and nitrogen cycles, but does not include biophysical effects of land use change such as albedo (Bouwman et al., 2006).

The BECCS scenarios used in AVOID 1 were top-down simple scenarios constrained by an implementation start date and a maximum rate of CO_2 removal. BECCS started between 2040 and 2070 and increased linearly over periods of 20 to 50 years to full deployment of 11 $GtCO_2$ yr^{-1} (3 GtC yr^{-1}). This equates to a maximum BECCS deployment of 110 $GtCO_2$ (30 GtC) sequestered (Bernie et al., 2012). Full deployment is based on Committee on Climate Change (CCC) (2011) 'Further Land Conversion' bioenergy land-use scenario which assumes up to 700 Mha of land available for bio-energy globally. This 700 Mha is based on conversion of either current agricultural land or natural habitat. The agricultural land conversion scenario i.e. the growth of energy crops on land where food crops are currently grown, implies either global dietary change or agricultural productivity growth beyond current FAO estimates. The natural habitat conversion scenario assumes energy crops are grown on uncultivated land, leading to the conversion of natural habitats and associated land use change emissions (CCC, 2011).

For the AVOID 1 scenario, the 700 Mha land area available in the model provides a maximum limit on BECCS when combined with the assumed rate of CO_2 sequestration 18 t CO_2 ha^{-1} yr^{-1} (4.9 t C ha^{-1} yr^{-1}) using a 90% capture rate (DECC, 2011). This equates to 154 EJ yr^{-1} assuming half the biomass by weight is carbon and the 1 t of dry matter yields 20 GJ (assumptions from Azar et al., 2013). The AVOID 1 scenarios have a larger land area requirement than other IAMs, due to the use of dedicated energy crops only for BECCS. In contrast, many IAMs use, or assume, a combination of dedicated bioenergy crops and residues from agriculture, forestry and waste (van Vuuren et al., 2013; Azar et al., 2013; Wise et al., 2009).

In the IPCC WG3 database, there are 116 scenarios that reach a radiative forcing of 2.6 W m^{-2} in 2100 and over a hundred of these rely on global net negative emissions (Fuss et al., 2014; Krey et al., 2014). Here we focus on one RCP2.6 IAM scenario that is created using the IMAGE model framework which includes the TIMER global energy model and a detailed land use model (van Vuuren et al., 2011b; 2010; 2007). In this scenario bioenergy is provided by residues from agriculture, forestry and waste and dedicated sugar cane and woody biomass bioenergy crops (van Vuuren et al., 2010).

The RCP2.6 scenario assumes 430-580 Mha is available for energy crop production, this is restricted to abandoned agricultural land and natural grassland systems (e.g. savannah, scrubland, tundra and grasslands) with areas with low potential such as parts of tundra and deserts excluded (Hoogwijk, 2004; van Vuuren et al., 2009). To represent further constraints such as biodiversity protection a land-cover accessibility factor is applied (De Vries et al., 2007). The biophysical potential is calculated using this land area and potential yields of sugar cane and woody biomass bioenergy crops. The technical potential allows for actual yields being lower than potential yields and limited conversion efficiency in the energy extraction process (van Vuuren et al., 2009).

The TIAM model does not constrain bioenergy by land area or crop yield, instead bioenergy is limited by annual maximum production by region and bioenergy type based on literature estimates. Bioenergy types included are solid biomass, bioenergy crops, biogas, bioliquids, industrial wastes and municipal wastes (ETSAP, 2013). There are regional and storage type limits on CO_2 storage capacity. Initial runs with delayed action until 2020 but staying within the 2°C limit see BECCS installed capacity increase from zero to 460 GW in 2030, rising to 3700 GW in 2100 (Napp, *pers. comm.*).

2. Bioenergy

2.1 Modern bioenergy

In 2008 biomass accounted for 50.3 EJ (10.2%) of total primary energy supply, of which 11.3 EJ was for modern bioenergy and the remainder for traditional biomass uses, i.e. firewood for cooking and heating. Modern bioenergy uses biomass as secondary energy carriers to generate electricity, combined heat and power or for transport fuels. Modern bioenergy comprises 4.0 EJ of electricity generation and combined heat and power from biomass, municipal solid waste (MSW) and biogas; 4.2 EJ of heat in buildings from solid biomass and biogas and 3.1 EJ of road transport fuels (Chum et al., 2011). To place this use of biomass for energy in context of other human uses, such as food and fibre, in 2000 the gross energy value of all harvested biomass was approximately 300 EJ (Haberl et al., 2007).

Using bioenergy in combination with carbon capture and storage (CCS) (Section 3) places certain restrictions on the type of biomass and type of energy conversion facilities that are feasible. CCS is more effective at scale, therefore BECCS is better suited for electricity production or use in heat and process heat plants such as pulp mills (Azar et al., 2006). BECCS is not suitable for mobile CO_2 emissions, but could be used in the transportation sector for the production of alternative energy carriers such as electricity, hydrogen or liquid fuels (Humpenöder et al., 2014; Klein et al., 2011; Lindfeldt and Westermark, 2009). Given these constraints, only 4.0 EJ (8%) of the present day 50.3 EJ of total primary energy from bioenergy is currently used in applications that would be suitable for BECCS.

There are a variety of biomass feedstocks currently used and under development (Table 1). In IAM scenarios of BECCS there is some variation in the type of biomass and the use of biomass in the energy system. Almost all assume second generation bioenergy crops, e.g. lignocellulosic biomass and many include residues from a combination of agriculture, forestry and/or municipal waste (van Vuuren et al., 2013; Wise et al., 2009; Azar et al., 2006;

Kriegler et al., 2013). Lignocellulosic biomass crops require low-intensity management and less fossil energy inputs and have less of a negative impact on biodiversity compared to first generation biomass (Chum et al., 2011; Immerzeel et al., 2014). Macro- and micro-algae are generally not considered as feedstocks in IAMs due to insufficient available data (Chum et al., 2011).

Feedstock		**Examples**
First generation	Oil crops	Rapeseed, sunflower, soya, waste oils and animal fats.
	Sugar and starch crops	Maize and sugarcane.
Second generation	Lignocellulosic biomass	Wood, straw, energy crops e.g. *Miscanthus*, switchgrass, and municipal solid waste.
	Biodegradable MSW	Sewage sludge, manure, wet wastes (farm and food waste) and macroalgae.
	Photosynthetic microorganisms	Microalgae.

Table 1 Bioenergy feedstocks. Modified from Figure 2.2 in Chum et al. (2011).

2.2 Bioenergy potential

The potential global bioenergy resource available for BECCS is a key uncertainty, composed of uncertainties in land availability, crop yields and the supply of residues and wastes alongside their underlying socio-economic and environmental assumptions (Slade et al., 2014). Land available for dedicated energy crops depends upon assumptions about future population and dietary trends, agricultural yield increases and specific constraints on the type of land available for dedicated energy crop production (Slade et al., 2014; Powell and Lenton, 2012; Chum et al., 2011). The many interconnected issues include other land uses, food production, water resources, direct and indirect land use change, biodiversity, social acceptability and policy frameworks (Azar et al., 2010; Bonsch et al., 2014; van Vuuren et al., 2009; 2010; van Vuuren and Riahi, 2011).

A recent review of the bioenergy literature concludes that estimates are highly variable with order of magnitude uncertainties (Table 2) (Slade et al., 2014). The *theoretical* potential of biomass supply is constrained only by biophysical conditions, here we focus on the *technical* potential which incorporates limitations due to biomass production practices and other land area and biomass demands, i.e. food and fibre production (further restrictions to this potential may also be expressed as the *economic* potential) (Chum et al., 2011).

Biomass sources		**EJ**
Energy crops		22 – 1272
Residues	Agricultural	10 – 66
	Forestry	3 – 35
	Wastes	12 – 120
	Total	*25 - 221*
Forestry		60 – 230

Table 2 Bioenergy potential estimates for 2050.
Data from Slade et al (2014). Only 12 of the 22 studies include biomass extraction from primary forest, others exclude this source due to concerns about impacts on biodiversity and carbon stock.[2]

2.2.1 Residue availability

The uncertainty in estimates of residue availability relate to assumptions about types of future economic activity. A number of future scenarios of BECCS in IAMs include an upper annual limit of 100 EJ from residues (e.g. van Vuuren et al., 2013; Azar et al., 2013). A recent review of the global bioenergy resource potential identified 22 original analyses, of which 12 studies include residues in their estimates (Slade et al., 2014).

2.2.2 Land availability

The future availability of land for dedicated bioenergy crops is an important driver of variations in bioenergy potential estimates. Competition with other land uses and attendant ecosystem services can have detrimental impacts on food production and prices, water resources, biodiversity and greenhouse gas emissions from direct and indirect land use change (Rosegrant and Msangi 2014; Tilman et al., 2009; Searchinger et al., 2008). Growing dedicated energy crops on abandoned agricultural land seeks to circumvent some of these issues (Tilman et al., 2009).

Most IAMs scenarios assume land currently used for food production and undisturbed forests are not available for bioenergy crop production. Some focus solely on ‘abandoned agricultural land’ (e.g. Kriegler et al., 2013) and others allow expansion of bioenergy crops into natural vegetation types, e.g. grasslands (e.g. van Vuuren et al., 2013). If constraints that prioritise food production and the value of carbon in primary forests are not in place (Figure 2), economic drivers can cause deforestation of primary forests (Wise et al., 2009).

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[2] Slade et al (2014) state 28 original analyses, but 6 are excluded from the supplementary tables as they were not bottom-up estimates (Slade, *pers. comms.*; Slade et al., 2011; Slade et al., 2014).

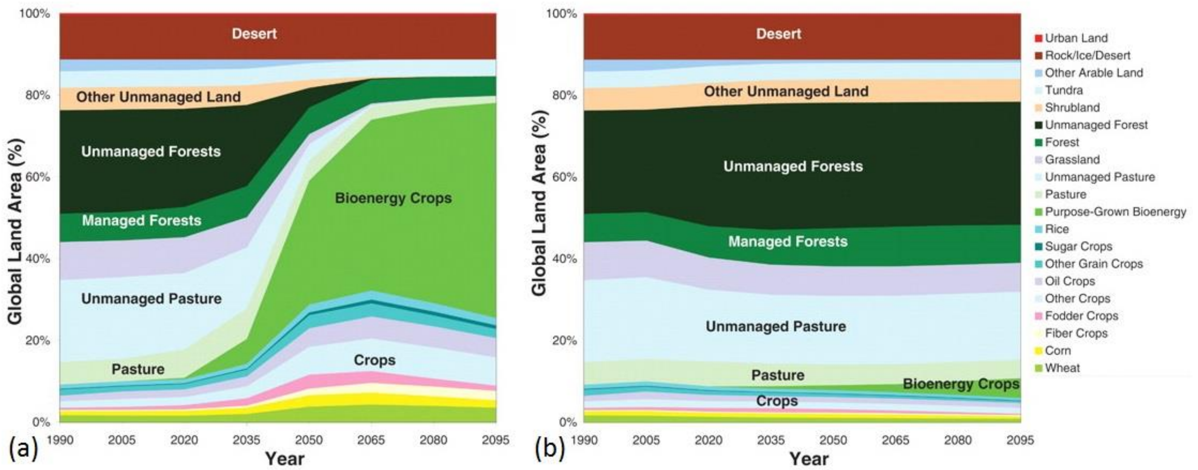

Figure 2. Comparison of global land use for two scenarios achieving 450 ppm CO_2 concentration assuming (a) a carbon tax on emissions from fossil fuel and industrial emissions and (b) a common carbon tax on emission from fossil fuel, industrial and terrestrial carbon emissions. Adapted from Figure 2 in Wise et al., 2009 (p1184).

Abandoned (or surplus) agricultural land arises due to improvements in agricultural productivity, but also abandonment due to changing climate and/or land degradation (Chum et al., 2011). Some studies assume bioenergy production potential on marginal or degraded land, and others include rest land, i.e. non-productive land that could be used for bioenergy crop production, e.g. grassland, shrubland and savannah (Hoogwijk et al., 2009; Chum et al., 2011; Slade et al., 2014). There is some ambiguity and overlap between the definitions of abandoned land and marginal land between different studies (Shortall, 2013). Estimates of present day abandoned agricultural land are from 385-438 Mha (Campbell et al., 2008) to 500 Mha (CCC, 2011). This is one third of current arable agriculture (1550 Mha) which is assumed to increase by approximately 70 Mha by 2050 (CCC, 2011). Abandoned agricultural land is predominately located in developed countries such as USA, Europe and Australia (Campbell et al., 2008). Estimates of future abandoned agricultural land depend strongly on future trends in agriculture (van Vuuren et al., 2009).

The RCP2.6 using the IMAGE model assumes 430-580 Mha are available for energy crop production (Hoogwijk, 2004) and the land use scenario for RCP2.6 has a trend of agriculture moving from high income areas to low income areas (Hurtt et al., 2011). This land is mostly abandoned agricultural land with some conversion of grassland (van Vuuren et al., 2009) Land availability estimates by Berndes et al. (2003) and Hoogwijk (2004) underpin a number of IAM future bioenergy assumptions (van Vuuren et al., 2009, Kriegler et al., 2013, Azar et al., 2006).

Studies using the IMAGE model estimate the technical potential of bioenergy crops on abandoned (surplus) agricultural land and grassland for 2050 of 271 EJ to 129 EJ for SRES A1 and A2 respectively, with a mid-range cut-off cost of 2.3 $US\$_{2005}$ GJ^{-1} of biomass harvested including transport. The upper estimate of 438 EJ (high cut-off cost, A1) is 30 times greater than the lowest estimate of 14.6 EJ (low cut-off cost, A2) (Hoogwijk et al., 2009).

2.2.3 Crop yields

There is a trade-off between assumptions about yields and available land area, with higher yields requiring less land area to achieve the same bioenergy potential (Bonsch et al., 2014). Future increases in agricultural crop yields have an impact on bioenergy potential by making more land available for bioenergy (van Vuuren et al., 2009; Slade et al., 2014). Lignocellulosic biomass yields on good land are currently 9-12 (oven dry ton) odt ha^{-1} and expected to increase by 2030 to 13-20 odt ha^{-1} (Table 3) (Fischer et al., 2009). Productivity on some abandoned agricultural land can be lower due to degraded soil quality. A review of literature on global biomass potential identified crop yields from <5 odt ha^{-1} yr^{-1} on marginal or degraded lands to >15 odt ha^{-1} yr^{-1} (Slade et al., 2014). Highest yields are found in the tropics (Wiltshire et al., 2015). Very high end estimate yields of 60 odt ha yr^{-1} are for sugarcane in the tropics (Moreira, 2006). Hoogwijk et al. (2005) assume a low productivity area has a crop yield of 3 odt ha^{-1} yr^{-1} with more productive abandoned agricultural land achieving average yields of 11-13 odt ha^{-1} yr^{-1} (Slade et al., 2014). Assumed yield improvements over time can have a significant impact on bioenergy potential. Van Vuuren et al (2009) calculate that a 12.5% increase in global yields could increase bioenergy potential by 50%. Assumed nitrogen fertiliser use and irrigation have a significant impact on modelled yields, as discussed below. A further uncertainty in crop yields is introduced by changes in future climate (Hoogwijk et al., 2005; Wiltshire et al., 2015).

Feedstock	Current yields (odt ha^{-1})	Expected yields by 2030 (odt ha^{-1})
Miscanthus	10	20
Switchgrass	12	16
Short rotation willow	10	15
Short rotation popular	9	13

Table 3 Typical yields of second generation (lignocellulosic) biofuel feedstocks. These yields refer to good land and will be substantially lower under marginal conditions. Data from Table 3.6-6 in Fischer et al. (2009) (p171) using the source Worldwatch Institute (2007).

Bioenergy production at the scale required in many scenarios will put significant pressure on water resources. This is characterised by a trade-off between achieving higher yields through irrigation and accepting lower yields with rain-fed agriculture. Irrigation may lead to conflict with other potential users and degradation of freshwater ecosystems but requires less land area, while rain-fed agriculture will require larger land areas for bioenergy production and may create issues of competition for other land uses (Bonsch et al., 2014). A modelling study, that includes changing water demands due to population (following the shared socio-economic pathway, SSP2 (O'Neill et al., 2013)) but not climate change, found that without irrigation there was a 40% increase in land requirement, leading to a loss of pasture areas and tropical forests (Bonsch et al., 2014). In the study dedicated lignocellulosic bioenergy crop production reached 300 EJ yr^{-1} by 2075 which is three time the amount in most future BECCS scenarios (van Vuuren et al., 2013; Azar et al., 2010; Kriegler et al., 2013). A study of the resource demand for producing 2.1 GtC yr^{-1} of switchgrass estimated a water demand of 750 L m^2 yr^{-1} with an additional demand of 0.6 m^3 kg^{-1} of switchgrass used in the BECCS process (Smith and Torn, 2013). A study using the IMAGE model and water scarcity data from the WaterGap model (Doll et al., 2003) both using OECD (2008) reference scenario for population and economic development, suggests that 17.5% of bioenergy potential may not be available due to water scarcity (van Vuuren et al., 2009).

Assumptions about crop yield and agricultural productivity improvements also rely upon the use of fertilisers to improve yields, which impact on greenhouse gas balances. A number of IAMs include direct and indirect N_2O emissions from fertilisers (van Vuuren et al., 2009; Azar et al., 2013, Humpenöder et al., 2014). In one study, the increase in bioenergy crop yield due to increased fertiliser use was associated with an increase in N_2O emissions over the century which reduced the net CO_2 equivalent removed by 45 $GtCO_{2eq}$ (Humpenöder et al., 2014). Smith and Torn (2013) calculated the fertiliser requirement for 1 GtC yr^{-1} sequestered through a switchgrass based BECCS system to be 20 Tg yr^{-1} of nitrogen, which equates to 20% of global nitrogen fertiliser production.

Improvements in agricultural productivity that determine both the availability of abandoned land in the future and bioenergy crop yield are not only constrained by irrigation or fertiliser use, technological learning and shifts in labour-to-capital systems in developing regions also play an important role.

Factor	**Common assumptions in IAMs**
Land area	Most scenarios assume abandoned agricultural land for dedicated bioenergy crops, to avoid issues of food production, biodiversity and land use change carbon emissions.
Bioenergy type	Most scenarios assume dedicated bioenergy crops, such as switchgrass, *Miscanthus* and short rotation poplar or willow. Those that include residues depend upon socio-economic activity.
Crop yields	Crop yields assumptions affect: agricultural production and therefore future land availability; yields of dedicated bioenergy crops; and availability of residues from crops. Improvements are achieved through use of irrigation and/or fertiliser use and technological developments.
Water source	Most scenarios assume rain-fed agricultural, reflected in lower crop yields, yield improvements are made when irrigation is assumed.
Fertiliser	Yields improvements can be made through use of fertiliser although there is a trade-off with N_2O emissions and embed carbon emissions.

Table 4 Summary of assumptions affecting estimates of large scale bioenergy use.

In conclusion, there are some very high estimates of global biomass resource potential, >600 EJ (Slade et al., 2014), but the assumptions made in IAMs (Table 4) such as IMAGE (RCP2.6) are generally are in the order of 200 EJ yr^{-1} (van Vuuren et al., 2011a). This nevertheless presents a significant change in land use of a vast area (~500 Mha). Less than

10% of the present day total primary energy from biomass is suitable for use in a BECCS system, and would be required to be scaled up forty fold by 2050 to reach 200 EJ yr^{-1}.

2.3 Socio-economic and environmental impacts of large scale bioenergy

The feasibility of the bioenergy requirement in future BECCS scenarios, and the assumed levels of land availability and crop yields can be significantly impeded by various, often interconnected, socio-economic and environmental factors. The so called 'food energy environment trilemma' encapsulates the potential conflicts between bioenergy production and food supply on biodiversity, water resources, and fertiliser use (Tilman et al., 2009; Slade et al., 2014; Powell and Lenton, 2012).

Land use change arising from bioenergy production can increase greenhouse gas emission either through direct (at the location of biomass production) or indirect (displacement of other activities) land use change (Searchinger et al., 2008; van Vuuren et al., 2010; 2013). Wiltshire et al (2015) show the net CO_2 removal from BECCS using dedicated energy crops on abandoned agricultural land is lower when soil carbon losses are taken into account. Van Vuuren et al (2009; 2013) assume a land use change emission factor of 15 kg CO_2 per GJ of bioenergy produced. Land use changes can also have an impact on other climate relevant factors, such as albedo. If large scale deforestation occurs to enable bioenergy crop production, the cooling effect of the deforestation due to changes in albedo dominate the resulting temperature change (Wiltshire et al., 2015; Davies-Bernard et al., 2014).

In addition to the direct biodiversity impacts of deforestation, indirect biodiversity impacts may also occur if bioenergy crops replace food crops in one area but lead to food crop expansion in undisturbed areas, for example (van Vuuren et al., 2009; Immerzeel et al., 2014). A recent review of the biodiversity impacts of bioenergy production concludes that land-use change is a key driver leading to habitat loss and changes in species richness and abundance (Immerzeel et al., 2014).

Global available land area is not all equally available for bioenergy production with socio-economic structures affecting the regions that will likely develop bioenergy. Bioenergy production has a reliance on transport infrastructure due to its distributed spatial extent, this in turn can effect where bioenergy production will take place with preference for regions with more sophisticated transport infrastructure (Humpenöder et al., 2014). These factors can also constrain the upper estimates of bioenergy potential.

There are numerous, often implicit, social assumptions about bioenergy in IAMs such as societal tolerance of large scale bioenergy (~500 Mha) and its associated impacts on biodiversity and food supply in addition to landscape, culture and lifestyle implications. Global policy frameworks and institutions are commonly assumed. Most modelling studies assume that all regions take part in emissions mitigation thus implying a suitable policy framework exists and is adhered to, with a limited number of studies investigating partial participation of regions (Clarke et al., 2009; van Vuuren and Riahi, 2011). Assumed protection of food production areas and undisturbed forests from bioenergy exploitation imply significant global policy and institutional frameworks are in place and effective (Tilman et al., 2009). However, there may also be positive social and economic effects (Domac et al. 2005). A review of the sustainability implications of bioenergy options can be found in Thornley et al. (2009).

3. CCS

Carbon dioxide Capture and Storage (CCS) describes a family of technologies designed to extract CO_2 from combustion processes, the CO_2 is subsequently transported and stored indefinitely in a suitable geological repository. At each stage a variety of technology options are available – plants may be retrofit or new build; the technology may be applied to power generation or other energy intensive industrial processes (such as in the iron and steel industry, cement manufacturing, chemical processing and refineries); it may deploy a variety of combustion and capture approaches (pre- or post-combustion or oxyfuel); storage may be in hydrocarbon fields (as straight storage in depleted reservoirs or as part of an enhanced oil or gas recovery process) or saline aquifers, located on- or off-shore (for an overview see e.g. (Leung et al., 2014). Indeed this variety of technology options presents on element of uncertainty in terms of investment decisions and policy support (Markusson et al., 2012) and each technology variant is characterised by different technical and performance parameters and potential suitability dependent on deployment context.

A review of literature on life cycle emissions of different CCS technologies reports emissions estimated in the range of 75 – 275 g CO_2 KWh^{-1}, depending on the technology (comparing integrated gasification combined cycle (IGCC), pulverised coal and natural gas combined cycle plants (NGCC), and oxyfuel technologies), suggesting ranges of 47% - 97% reduction in lifecycle global warming potential from power plants (with oxyfuel giving the lowest emissions) (Corsten et al., 2013). Furthermore, this study highlights the importance of the non CO_2 impacts of CCS, both upstream (i.e. coal extraction and transport, and production of amines for the capture process) and downstream (CO_2 transport and storage) (ibid). For example, reducing the distance over which coal (i.e. solid fuel) is transported has a greater impact on GHG emissions than reducing the distance over which CO_2 is transported by pipeline; MEA (monoethanolamine) based solvents improve capture efficiency but have a greater impact on other air pollutants (e.g. NO_x and NH_3) than other approaches (Odeh and Cockerill, 2008).

3.1 Moving from demonstration to commercialisation

While the use of biomass is established for a variety of energy applications, the use of BECCS (at any scale) depends on the implementation of carbon capture and storage (CCS) technology, which is itself not widely established at a commercial scale. Although the individual components which make up the CCS system are in industrial use, its full chain integrated application is not widespread. The first commercial scale full chain CCS electricity plant, the Boundary Dam project in Saskatchewan in Canada, recently commenced operation in October 2014. This project is a 110 MW post-combustion coal-fired CCS plant, transporting 1 $MtCO_2$ yr^{-1} via pipeline for use at an Enhanced Oil Recovery site and for storage in a deep saline formation (both onshore) (Saskpower, 2014). A further two CCS electricity plant are planned to commence operation in the next two years (Texas and Mississippi in the USA) and another is under construction in the iron and steel sector (in Abu Dhabi, United Arab Emirates) (GCCSI, 2014). However, government funding for a further project (Futuregen, Illinois, USA) has just been withdrawn, making it unlikely that the project will proceed (Tollefson, 2015). In total, there are 13 large scale plants in operation globally and a further 9 under construction (large scale plant is defined as one which captures and stores at least 0.8 $MtCO_2$ per year for coal-fired power generation, or at least 0.4 $MtCO_2$ in the case of other applications, such gas fired electricity or other industrial processes) (GCCSI, 2014).

Despite high expectations on the promise of CCS to deliver significant emission reductions for more than a decade (see for example IPCC, 2005) it remains at a stage of modest demonstration. The key technical uncertainties associated with expanding global CCS capacity lie primarily in the challenge of scaling up CCS technologies to deliver large scale mitigation (moving from current storage rates in the order of Mt per year up to the Gt scale storage represented in IAMs and long-range mitigation pathways) (Herzog, 2011). Herzog *et al*. (2011) examine the challenge of scaling up in terms of the key issues of cost, transportation infrastructure, subsurface uncertainty (safe storage) and regulatory and legal issues. To this list of uncertainties can be added public perceptions, system integration and variety of technology pathways (Markusson et al., 2012; Watson et al., 2014). An expert elicitation study exploring views on the potential for CCS deployment identified costs and the lack of long term policy and regulatory frameworks as critical barriers (potential showstoppers) to establishing the technology (Gough, 2008).

Nevertheless, small scale demonstration projects do provide valuable experience from technical and non-technical perspectives; Russell et al (2012) outline research and practical questions associated with moving from demonstration to large scale deployment. These include the extent to which specific contexts shape demonstrations; the role of unexpected outcomes and what is learnt from them; managing the dissemination and exchange of results between companies and countries, the role of demonstrations in the innovation and ongoing development and implementation of CCS across the industrial chain (ibid.). Even given successful results from demonstration plants, however, the challenges of delivering large scale deployment remain significant (Scott, 2013).

3.2 Key uncertainties

The only driver for introducing CCS technology is climate change mitigation, its deployment is entirely dependent on either stringent regulation and/or the application of economic incentives, such as a sufficiently high carbon price. The greatest costs in the CCS chain lie with the capture of CO_2. In addition to capital costs associated with CO_2 capture, the energy penalty associated with the process reduces the net output of a plant by between 15 and 25%, depending on the plant type (Rubin et al., 2007); adding CO_2 capture to a power plant increases the costs of electricity delivered by 25-50% (in the case of supercritical pulverised coal plant, data on costs not available for IGCC) (Herzog et al, 2012). Flexible plant operation can reduce the operational costs of CO_2 capture (by shutting down the capture process when electricity prices are high) (Chalmers et al., 2009) but this results in higher capital costs calculated over the plant lifetime per unit CO_2 removed (Patino-Echeverri and Hoppock, 2012). Recent estimates of the carbon price required for (post combustion coal) CCS to be economically viable are typically in the region of US $60-65 /t$CO_2$ (Hamilton et al., 2009; Herzog, 2011) or UK £30–50 /tCO_2 (Akgul et al., 2014). Estimates for future costs of CCS depend not only on the type of CCS technology but also assumptions around fuel and electricity prices, fuel characteristics and operating specifications *inter alia* (see e.g. Rubin et al., 2007).

Deployment of CCS will require development of a new infrastructure to transport CO_2 between capture and storage locations – the most efficient mode is by pipeline but there may also be the potential for CO_2 transport over larger distances by ship (IPCC, 2005).

Although CO_2 is currently transported by pipeline (notably in the US), large scale CO_2 storage would require a new pipeline infrastructure to be developed with a potential capacity to transport up to 10 GtC yr^{-1} – the current gas pipeline infrastructure transports the equivalent of around 1.5 GtC (van Vuuren et al. 2010). The costs of CO_2 transport by pipeline have been estimated to be between €1.5-6 /tCO_2 (depending on the mode and distance of transport and whether on or offshore) (ZEP, 2011).

Uncertainties around CO_2 storage hinge on the capacity of formations suitable for use in long term storage and the integrity of the storage locations (a function of both geological characteristics and well integrity) (Herzog, 2010). Although there is extensive data describing the locations of sites which may potentially be suitable for CO_2 storage, and published figures suggest that potential capacity may be in the region of hundreds or thousands of Gt (e.g. (Bradshaw et al., 2007; IPCC, 2005)), detailed assessment on a site by site basis is required to ascertain with confidence a more precise figure for potential storage capacity (Bachu et al., 2007; Bradshaw et al., 2007). Estimates for potential capacity using well-studied hydrocarbon fields can be made with a reasonable degree of confidence, since the locations and characteristics of potential storage sites are well mapped, the key uncertainties lie in the proportion of the field that is available for storage and the geological integrity of depleted reservoirs (Bachu et al., 2007). Hydrocarbon fields alone are unlikely to provide sufficent capacity for large scale CO_2, estimated to provide 675-900 $GtCO_2$ potential capacity (IPCC, 2005). Estimates for capacity using saline aquifers are less reliable, with estimates quoted within a large range of 1-$10^4$$GtCO_2$ (IPCC, 2005). Moreover, ensuring long term safe storage will require the establishment of reliable monitoring regimes, governed by strong regulatory frameworks and which provide for long-term liability management. CO_2 storage costs are also highly site specific and have been estimated at US$ 2-30/ tCO_2, depending on the location and specific geological characteristics of the storage site, although initial deployment will exploit the more accessible sites and likely entail costs at the lower end (below US $ 2 /tCO_2) of this range (IPCC, 2005).

Thus, any large scale expansion of CCS technology is dependent on regulatory and policy measures to incentivise and manage its deployment, such as strict emission limits or a high carbon price alongside an adequate regulatory framework to govern both short- and long-term liabilities and responsibilities (IPCC, 2014). Investment requires certainty in long term funding for a technology that essentially reduces the cost effectiveness of an existing power generation technology – CCS technology is entirely dependent on a strict climate mitigation policy.

3.3 Societal responses

Awareness of CCS is not high amongst lay publics; in a recent Eurobarometer survey on CCS, 67% of the EU population had not heard of CCS (and of the 28% which had heard of it, only 10% claimed to know what the technology is) (European Commission, 2011). These figures are broadly representative across all Member States, with the exception of the Netherlands, where awareness of CCS is significantly higher (52% claiming to know what CCS is) (ibid). Demonstration plants have received a mixed response so far (Russell et al., 2012) – ranging, for example, from a well-studied example in the Netherlands in which a project at Barendrecht was ultimately abandoned in the face of strong local opposition (Brunsting et al., 2011a; Feenstra et al., 2010; Terwel et al., 2012), to community tolerance of the Otway project in Australia (Anderson et al., 2012) and the Lacq project in France (Ha-Duong et al., 2013).

Concerns about the safety of CCS typically focus on CO_2 storage (see e.g. Hammond and Shackley, 2010; Upham and Roberts, 2011), and the likelihood and consequences of CO_2 leakage (Mander et al., 2010). In total, 61% of respondents to the Eurobarometer survey expressed concern over the safety of CO_2 storage in underground formations, with concerns relating primarily to environmental and health impacts and risks associated with leakage during operation (Eurobarometer 2011). Very little research has explicitly looked at how different storage locations/types might be differently received. A recent study, however, conducted an online survey in Germany to compare reactions to potential storage in deep saline aquifers, depleted gas fields and as part of enhanced gas recovery, finding that linking storage to perceived benefits associated with enhanced gas recovery was viewed more favourably than the alternatives (Duetschke et al., 2014); however, care has to be taken in interpreting or extrapolating from survey results on public opinions with respect to such an unfamiliar technology (Malone et al., 2010). Furthermore, preliminary research exploring community responses to an experimental CO_2 release designed to study the potential marine impacts of leakage associated with offshore storage, suggests that issues around the governance of a storage facility may be more influential than the physical remoteness of the storage site – it cannot necessarily be assumed that publics will more favourably disposed to offshore than onshore storage (Mabon et al., 2014). Previous experience of projects successfully storing CO_2 (e.g. Sleipner, off the coast of Norway) and analogues that include natural accumulations of CO_2 and natural gas storage (both on and offshore) provide physical evidence of secure geological storage as well understanding of the impacts on affected communities (IEAGHG, 2009).

At a project level, the community response is critically influenced by how the community and stakeholder engagement process is managed (Ashworth et al., 2012) and plays an essential role in the formation of trust between stakeholders. Trust has been identified as a crucial factor in how CCS (and other new technologies) is received by lay publics (Midden and Huijts, 2009; Terwel et al., 2011; Terwel et al., 2012). However, establishing a ‘social license to operate’ (see for e.g. Rooney et al., 2014) depends on many factors including: communicating technical and scientific knowledge of risks and benefits, reputation of the proponents and previous relationships with communities (or other stakeholders), transparency of process and trust in the developers – and at a project level will be highly context specific (Brunsting et al., 2011b; de Coninck et al., 2009; Oltra et al., 2012). In addition to the specific social context of the project site (Ashworth et al., 2012; Bradbury et al., 2009), other factors influencing how CCS is received by both local communities and wider society include the media framing of the technology (Boyd et al., 2013; Boyd and Paveglio, 2014; Nerlich and Jaspal, 2013) and ethical aspects (Gough and Boucher, 2013; Mabon, 2012; Medvecky et al., 2014). A review of research into public perceptions of CCS can be found in (L′Orange Seigo et al., 2014).

4. BECCS

BECCS can be considered to be a type of climate intervention known as carbon dioxide removal (CDR), where CO_2 is removed from the atmosphere and stored, thus delivering ‘negative emissions’, whilst others consider it a form of climate change mitigation (Boucher et al., 2013; Royal Society, 2009; Vaughan and Lenton, 2011; McLaren, 2012). CDR approaches seek to enhance existing carbon sinks or, like BECCS, create novel carbon sinks e.g. direct air capture (using chemicals) and storage (Vaughan and Lenton, 2011). It has advantages compared to other carbon dioxide removal or negative emissions approaches that electricity (or liquid biofuels) is generated during the process and it is broadly compatible with current energy and social infrastructures (McGlashan et al., 2012). Although it is often described as being the most mature or least costly of the alternative negative emissions approaches (Kriegler et al., 2013; McGlashan et al., 2012) and, given its prominence in the mitigation pathways described above, there is relatively little research into the challenges and viability of bringing BECCS into mainstream commercial deployment. There are around 15 pilot scale BECCS plants across the world and the first large scale BECCS project, due to start operation in 2015, is a corn-to-ethanol plant in Decatur, Illinois, storing 1 $MtCO_2$ yr^{-1} in an onshore saline aquifer; an overview of the status of these projects may be found in GCCSI (2013).

Over and above the specific issues associated with large scale biomass energy production and the use of fossil CCS described above, bringing the two distinct supply chains together will introduce certain specific uncertainties and challenges. A review of the literature relating to BECCS as a negative emissions approach published in 2011 (Gough and Upham, 2011) cautioned against making exaggerated claims for the deployment of the technology and suggested a relatively modest approach to establishing a sustainable role for it. The review identified the key challenges to BECCS implementation as: 1) biomass resource strategy (managing competing needs for the resource across transport, electricity, and heat applications, as well as ecosystem and livelihood concerns); 2) assuring carbon neutral biomass (life cycle emissions accounting); 3) locational factors across the combined supply chains; 4) establishing BECCS actor networks; 5) incentives and policy mechanisms (including new regulatory frameworks) and 6) broader perceptions of the BECCS system. A new report by ETI reviews some of the issues relating to the use of Biomass energy with CCS in the UK (ETI, 2015).

Drawing on the uncertainties and challenges identified by Fuss et al (2014) we describe below five broad areas of uncertainty associated with large scale deployment of BECCS, namely biophysical constraints; technical and engineering issues; costs and financing; performance characteristics and socio-institutional factors.

4.1 Biophysical constraints

4.1.1 Sustainability of biomass resource

The issues relating to sustainability of large scale expansion of the biomass energy sector are described in Section 2. Bringing together bioenergy energy and CCS does not introduce additional challenges to these constraints specifically, beyond the potentially ambitious expansion of the scale of resource requirements. Furthermore, the location of the feedstock, the end use and CO_2 capture location, and the storage destination may be geographically separated – which, in addition to the challenges of transporting large quantities of biomass and/or CO_2, could further challenge sustainability in terms of economic viability, distributive justice, regulatory and emissions accounting and the efficacy of the full chain BECCS system for example.

4.1.2 Available storage capacity

The availability of safe and secure CO_2 storage capacity is independent of the source of the CO_2 and is described in Section 3. Estimates of maximum storage capacity relate to *total* potential storage; much of the discourse relating the fossil CCS, whether explicitly or implicitly stated, relates to the role of CCS as a bridging approach towards a long term goal of decarbonisation and the move away from fossil fuels. The discourse around BECCS is different: it is already associated with renewable rather than fossil fuels and brings the potential for delivering negative emissions - potentially enabling the offsetting of emissions from sectors such as agriculture and aviation which are harder to abate. Thus, BECCS is not typically framed in such time-limited terms and the total usable storage capacity becomes important in terms of how long a significant reliance on BECCS can be sustained. In a study exploring the global land use implications of BECCS (using the MAgPIE model), Humpenöder et al. (2014) estimate that the potential for BECCS is limited by the rate at which storage can be exploited (which they cap at a rate of 20 $GtCO_2$ yr^{-1}) and which would be associated with 237 EJ yr^{-1} from biomass by 2100. Caps on annual available storage in IAMs are typically based on assumed maximum storage capacity (e.g. 3960 Gt CO_2, Bradshaw et al. 2007) divided by a number of years over which storage is assumed to be used - e.g. 200 years (e.g. Humpenöder et al. 2014).

4.2 Technical and engineering issues

There are a variety of options for combining biomass energy with CCS, of which dedicated biomass electricity generation offers the greatest potential for delivering negative emissions (Schakel et al., 2014). In the context of BECCS applied to power generation, systems may be either co-fired (with conventional fossil fuels) or dedicated biomass; however, to achieve net negative emissions, co-firing applications above 20%-30% are required (Schakel et al. 2014). Research suggests that while modest levels of co-firing (i.e. up to about 20%) offer the advantages of retrofitting existing plant, and may be achieved without boiler modification or additional treatment of the flue gases, as the proportion of biomass increases, the boiler design may require modification and pre-treatment of the feedstock may be required (Koornneef et al., 2012; Schakel et al., 2014). Co-firing levels of up to 50% are considered feasible in the near term (ibid.).

All of the CO_2 capture approaches described earlier are compatible with the use of biomass energy. Post-combustion capture methods with biomass feedstocks operate at lower conversion efficiencies (30-35%) compared to fossil fuel plant (operating in the range of 35-45%) with a greater energy penalty during the capture process – this is a result of energy required for pre-treatment of the fuel (e.g. drying) and lower calorific values with the feedstock (Akgul et al., 2014; Koornneef et al., 2012). There may also be concerns around emissions of other pollutants (such as cadmium or mercury) associated with introducing biomass feedstocks (Akgul et al., 2014). Optimum efficiencies for BECCS are achieved with IGCC, and most IAM scenarios assume IGCC use (e.g. Kriegler et al., 2013). However, IGCC is a less advanced technology than post-combustion and there is limited experience of its use with biomass feedstocks. Co-gasification is anticipated to be feasible at 20-30% biomass feedstock and a dedicated biomass IGCC plant has been demonstrated at a small scale (10s of MW). It is expected that plants up to 500 MW size will be technically feasible in the future - the technological challenge rests with establishing large scale biomass IGCC rather than with pre-combustion capture itself (Koornneef et al., 2012; Minguez et al., 2013).

Oxyfuel processes are in only early stages of development but initial research suggest that the technology will be suitable for use with biomass feedstocks (Toftegaard et al., 2010).

Biofuel (ethanol) production from biomass (mature and commercially available using food crops such as sugar cane, maize or cereals or in the demonstration phase with lignocellulosic biomass such as straw or wood) may also be suitable for BECCS. In such applications, the proportion of carbon converted CO_2 during the process may be captured and the remainder will be emitted downstream during end use of the ethanol, resulting in a capture rate of about 11-13% of the original carbon content of the feedstock (Faaij, 2006; Koornneef et al., 2012). Finally, pre-combustion capture within the Fischer-Tropff process (a commercially viable means of producing bio-diesel or other transport fuels) could operate at capture levels up to 54% (most of the remaining carbon remains in the fuel product and will be emitted as CO_2 during its end use) (Koornneef et al., 2012).

Although it is broadly compatible with existing energy systems, large scale roll out of BECCS has two major infrastructure implications relating to: 1) the biomass supply chain and; 2) transporting large volumes of biomass energy to the end use locations and establishing a CO_2 transport network.

4.3 Costs and financing

Studies modelling the cost-effectiveness of alternative mitigation pathways suggest that BECCS can significantly reduce the cost of achieving ambitious emissions targets at both global (Azar et al., 2006; Kriegler et al., 2013) and regional scales of analysis (e.g. Climate Institute, 2014) as illustrated in Figure 3; the wider AVOID 2 study will be exploring this further. This raises two issues: 1) how uncertain are the costs modelled for BECCS, in absolute terms and relative to other mitigation options and given the lack of empirical experience of implementing the technology and 2) what level of incentivisation or financing will be required to establish the technology?

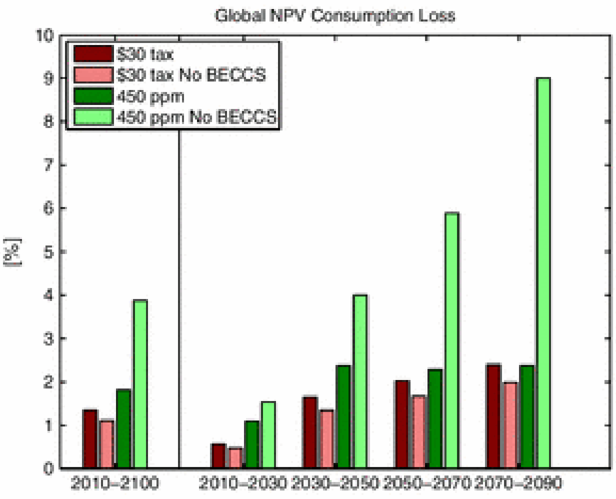

Figure 3 General mitigation costs (consumption loss) as percentage of consumption (NPV at 5% discount rate) (Kriegler et al. 2013).

Fuel treatment requirements and lower conversion efficiencies lead to greater costs associated with dedicated biomass plants compared to their fossil fuel equivalents, which must be added to the investment costs required for capturing, transporting and storing CO_2. Reliable estimates of overall costs of CCS, with or without biomass, at commercialisation are difficult to derive - there are many alternative configurations of technology types and project specific characteristics (such as storage type and location etc.). Estimates are dependent on many assumptions including future fuel and electricity prices. Analysis of plant cost for biomass and fossil CCS can be found in Koornneef et al. (2012), McGlashan et al. (2012) and Klein et al. (2014) and explore the impact of carbon taxes on emissions from the land-use sector on supply of purpose grown lignocellulosic biomass.

Typically, IAMs assume a financial mechanism such as a carbon tax or carbon price (e.g. Humpenöder et al., 2014; van Vuuren 2011a) and there are various estimates of the level carbon tax that might be necessary for BECCS to become economically viable. Using a systems model of power generation in the UK, Akgul et al (2014) suggest that a carbon price of 120–175 UK£ /t CO_2 in the UK would be required for deployment of BECCS - this is based on retrofitting existing stock with CCS technology, co-firing using indigenous biomass and including operating costs only (Akgul et al., 2014). A preliminary high level analysis, based on amine based post-combustion CCS and using capital costs drawn from the literature (subject to a 5% discount rate) suggest BECCS systems cost in the range 59-111 US$ /t CO_2 (McGlashan et al., 2012). Humpenöder et al (2014) estimate that BECCS would require a global carbon price of 165 US$ /t CO_{2eq} (although this estimate assumes that revenue from the carbon tax is the key driver of the technology deployment and does not allocate an economic value to the energy produced). A major limiting factor in the modelled cost performance of BECCS systems is the availability of biomass (Akgul et al., 2014; Humpenöder et al., 2014; McGlashan et al., 2012). There are also uncertainties surrounding the interplay between bioenergy and land-use change emissions for given greenhouse gas (GHG) price regimes (Klein et al., 2014). Incorporating capital costs in long-range modelling involves the use of discount rates and the choice of discount rate has a large influence on relative performance of capital intensive technologies in model results (low discount rates favouring near-term reductions relative to investments made in the longer term and vice versa). Discount rates of 5-7% are typically assumed in the IAMs (Azar et al., 2010; Kriegler et al., 2013; van Vuuren et al., 2013; Humpenöder et al., 2014). An example of cost estimates for different CCS technologies (including fossil and biomass feedstocks) is shown in Figure 4 (Koornneef et al., 2012).

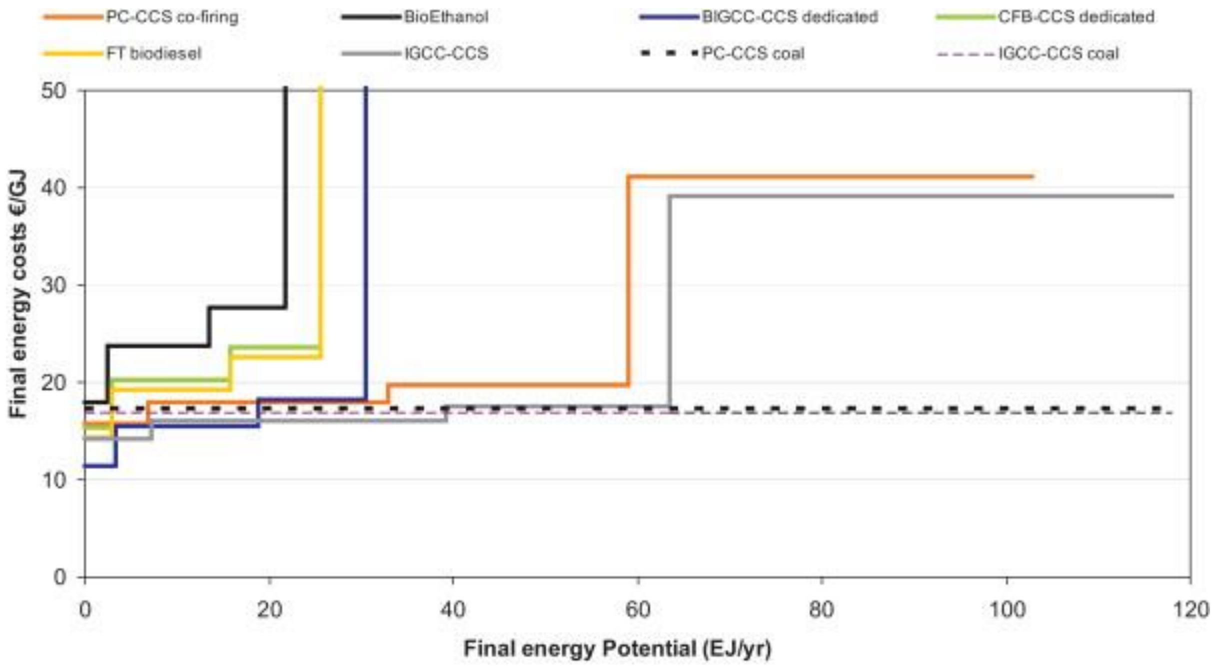

Figure 4. Global supply curve for the six bio-CCS technology routes and coal reference technologies for the year 2050 with a CO_2 price of 50 €/tonne (Koornneef et al. 2012).

4.4 Performance characteristics

The CO_2 balance of the CCS elements of the BECCS chain is relatively straightforward to quantify, the greatest uncertainties in ensuring the process delivers genuine net ‘negative’ emissions are associated with the biomass energy system prior to combustion. Adams et al (2013) identify three key challenges with estimates of GHG balances for bioenergy:

1. Accurate and realistic analysis of emissions budgets - this is challenged by both limitations in knowledge and uncertainties in measurement and taking account of the influence of specific characteristics of the system including temporal and geographical factors;
2. Interactions between bioenergy and other sectors and ecosystem services (including land, food, energy, water) in order to fairly present reductions;
3. Establishing policy mechanisms to incentivise GHG reductions in the context of fragmented ownership or responsibility across the supply chain.

Most IAM scenarios calculate BECCS in some combination of energy (EJ), carbon (t CO_2) and price (US \$/t CO_2) and for some, other greenhouse gases (tCO_{2eq}), aggregated to EJ yr^{-1} (Azar et al., 2006; Wise et al., 2009; Kriegler et al., 2013). Those that include land-use explicitly or implicitly, will aggregate to EJ ha^{-1} yr^{-1} over a specified area (ha) assuming particular crop yields (e.g. van Vuuren et al., 2013). These scenarios do not fully account for the range of interconnected carbon, water, energy and other greenhouse gas impacts of the full lifecycle of a BECCS process. Establishing a true net negative emissions value for BECCS is particularly difficult for certain facets, such as indirect land use change (Rosegrant and Msangi 2014; Tilman et al., 2009). Lifecycle analysis for BECCS using switchgrass

(Smith and Thorn, 2013) and biomass co-firing with CCS (Schakel et al., 2014) provide a more comprehensive assessment of the net negative emissions from BECCS.

Within the CCS literature the ‘capture rate’ refers specifically to the efficiency of the capture process at the plant – i.e. the proportion of CO_2 in the flue gas; capture rates of 85-90% are typically assumed on this basis (e.g. Akgul et al., 2014; McGlashan et al., 2012). However as can be seen in Figure 5 there can be significant losses during gasification and conditioning, these will differ for different plant designs and feedstocks, so it is important to distinguish between CO_2 stored and negative emissions, which are not equivalent. It is not clear from the IAM model description literature the extent to which these details are accounted for by different models.

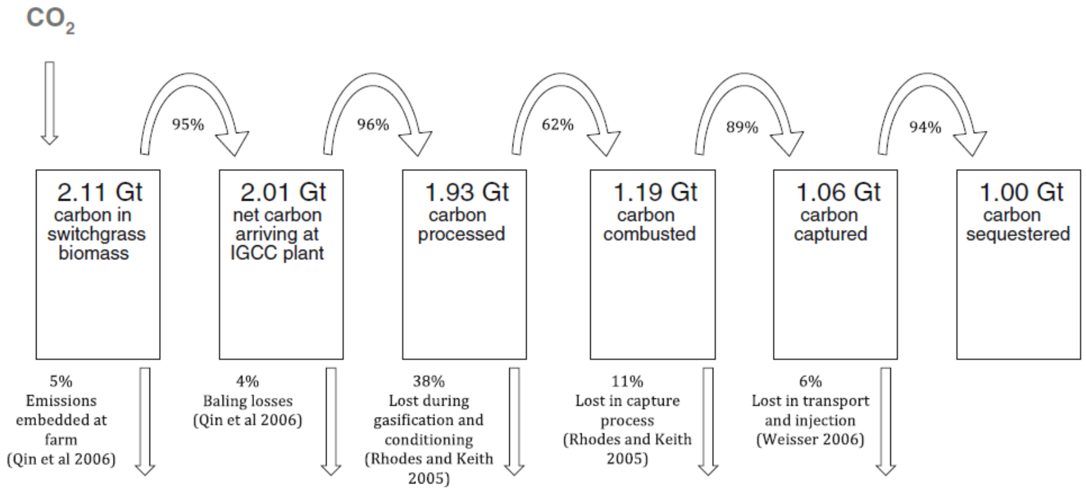

Figure 5. Schematic of carbon flow, life cycle emissions, and carbon losses during temperate switchgrass production and processing with carbon capture and storage from Smith and Torn (2013). The percentage values are carbon losses calculated from literature values (Qin et al., 2006; Rhodes and Keith, 2005; Weisser, 2007) for an IGCC facility retrofitted to burn biomass only. Emissions embedded at farm include machinery involved in soil preparation and seed sowing; production, application and transport of agricultural chemicals; harvest and baling or pelletizing; and transport to the processing plant (5 to 8.5 %). Storage dry biomass losses (4%) (Smith and Torn, 2013). Note this does not include direct or indirect LUC emissions.

4.5 Social and institutional factors

Although there is a substantial body of research forming around the possible societal responses to CCS, there is very little research exploring the impact, if any, that introducing a biomass energy element to the technology might have. Among the issues that CCS opponents cite are: its role in prolonging the use of fossil fuels; diverting financial resources away from developing alternative forms of low carbon energy and risking extending ‘carbon lock-in’ (e.g. Bäckstrand et al., 2011). In short, it is not perceived as a progressive technology for the long term (Parkhill et al., 2013). There is currently limited evidence for how the introduction of biomass to the CCS system could change public responses to the technology. Parkhill et al (2013) found that perceptions of biomass energy are more complex than for other renewables suggesting that responses may be contingent on the fuel type, application and context of their use. However, one study looking at CCS specifically, did find that CCS is perceived less positively in the context of fossil fuel applications, than if it included biomass (Dütschke et al. 2014). Furthermore, it has been suggested that deploying CCS in conjunction with biomass energy could avoid a fossil fuel lock-in effect associated with CCS (Vergragt et al., 2011).

CCS activities to date have been concentrated in certain key regions but interest in the technology extends beyond these areas (see for example Roman, 2011). Introducing BECCS on the large scales suggested in IAMs will necessarily expand the number of contributing nations and regions, particularly those with the greatest potential biomass resource (including many developing countries). This in turn holds implications in terms of climate and energy policies, regulation and international regulatory frameworks that can accommodate the international diversity across the BECCS supply chain – there is very little research on the global governance of CCS (Bäckstrand et al., 2011), let alone BECCS. Lomax et al. (2015) identify four policy principles based on analysis of BECCS to initiate the use of negative emissions technologies in climate policy: (i) support further research, development and demonstration; (ii) support near-term opportunities through modifying existing policy mechanisms; (iii) commit to full greenhouse gas removal (GGR, another term for CDR) integration in carbon accreditation and broader climate policy frameworks in future; (iv) develop sector-specific steps that lay the groundwork for future opportunities and avoid lock-out.

Furthermore, establishing *rapid* deployment of BECCS on a large scale would require government investment that goes beyond a carbon pricing mechanism to support it as an emerging technology. The choice of mitigation options, many at very different stages of development and offering different scales of potential emission reductions, is inflenced by a host of economic factors (including investment in innovation and cost reduction, impact of different technology learning rates etc) in addition to other factors including existing inertia within the energy system, a complex political economy and societal contingencies. Meeting society's energy needs while delivering strict climate constraints in this complex context suggests policy intervention at state level will be required; these challenges are described in detail and explored with explicit reference to CCS by Torvanger and Meadowcroft (2011). McGlashan et al. (2012) explore the precedents from power generation in China and the UK to suggest it could take between 14 and 600 years to achieve BECCS capacity to remove 1 ppm of CO_2 from the atmosphere.

In terms of the feasibility of achieving the levels of BECCS suggested by IAMs, it is important to consider the implicit assumptions regarding societal toleration and political feasibility (van Vuuren et al., 2010). Most IAMs assume full global participation of emissions reductions, in order to achieve strict atmospheric concentration targets, with only a handful investigating the impacts of regions not engaging (Clarke et al., 2009, van Vuuren and Riahi, 2011). Furthermore, the assumed protection of primary forest and/or agricultural land for food production are easily enforced in an IAM, would require significant robust governance and regulation to ensure the undesirable negative impacts of bioenergy do not materialise (Rosegrant and Msangi, 2014).

In conclusion, there is a vast range in the estimates of the potential for negative emissions from BECCS. Van Vuuren et al (2013) suggest the limit is between 0 and 10 $GtCO_2\ yr^{-1}$ in 2050 and 0 to 20 $GtCO_2\ yr^{-1}$ in 2100. Key uncertainties surround the prior requirements of an established CCS infrastructure, the full lifecycle net negative emissions with particularly large uncertainties in the production of biomass energy as well as sufficient and effective policy frameworks and governance to develop and roll out the technology, ensure global participation in emissions reductions and avoid the potential negative impacts of large scale bioenergy, “done wrong” (Tilman et al., 2009).

5. Key Assumptions

The main aim of this review of the use of BECCS in IAMs was to identify the key assumptions that could be critical in modelling the contribution of BECCS to achieving climate change mitigation targets (Table 4). Some assumptions are made explicitly in published papers, whilst others are implicit – either not published or tacitly made in constructing the models; here we attempt to unpack the implicit assumptions which could be very influential on the feasibility of BECCS. The IAMs used to create scenarios all construct their models differently, with the inclusion, and more detailed representations, of different components of the global energy system and its contributing factors, as such they have different assumptions and representations of BECCS (Section 1.2). Certain assumptions are easy to identify whilst others can be hard to decipher, especially with the evolution of models over time. Major differences include the explicit modelling of land use (van Vuuren et al., 2013; Humpenöder et al., 2014) compared to a stated upper limit (Azar et al., 2006; Kriegler et al., 2013). In Table 4 we describe explicit and implicit key assumptions, it is important to note that many of these assumptions are strongly interconnected and interdependent.

Assumptions	**Details**
Future climate change	The earth system response to future climate change, and the impact on the carbon cycle, is implicitly assumed in the cumulative emission budgets used in the IAM.
Bioenergy potential	
Agricultural efficiency gains	Assumed trends in agricultural efficiency gains impact the amount of available land as well as future bioenergy crop yields.
Land area requirement for BECCS	For models that explicitly represent land use, the land area available for energy crops is crucial. Whilst IAMs without this, make an implicit assumption given by total bioenergy potential.
Crop yields	Most scenarios focus on dedicated lignocellulosic crops and assume productivity levels in keeping with abandoned agricultural land (i.e. associated with lower yields than agricultural land). Scenarios have differing fertiliser and irrigation assumptions: most assume rain-fed land.
Residue availability	Many scenarios include residues as well as dedicated lignocellulosic crops. Residue availability is dependent upon the types and levels of socio-economic activity.
Infrastructure	Transport infrastructure for biomass and purpose built biomass energy generation plants. Some negative emissions can be achieved through co-firing, but most IAMs assume purpose built biomass energy generation plants.
CCS capability	
Maximum annual rate of	This figure refers to amount of CO_2 stored annually in geological

CO_2 stored	formations. To equate to CO_2 removal, or project level negative emissions, this assumes that CO_2 is captured only from dedicated biomass plant.
CCS infrastructure	A strong implicit assumption is that CCS infrastructure is established and available to capture, transport and store CO_2.
CO_2 storage capacity	Total storage capacity in suitable ‘de-risked’ reservoirs. Estimates of technical potential capacity in appropriate geological formations cover a very large range; IAMs typically incorporate an assumption of how much of this will be suitable for secure storage.
BECCS	
BECCS as a % of primary energy	IAMs in WG3 cluster around 20-30% of total primary energy from BECCS, whilst there are extreme outliers.
Cost of BECCS per t CO_2 stored	Because IAMs typically optimise on cost, the relative costs of different mitigation options is an important driver. Assumptions lie in the range of 60 to 250 US$/t CO_2 (IPCC, 2014).
Policy support	Policy and incentives to develop and establish BECCS technology.
Net negative emissions	Assumed net negative emissions across the full life cycle of the BECCS system; includes large uncertainties in bioenergy production, e.g. direct and indirect land use change, fertiliser use and water availability.
Political and socio-economic	
Population, lifestyle, diets	This is a key overarching set of assumptions that feed into the agricultural assumptions that underpin the bioenergy potential as well as establishing global energy demand.
Sustainable land use	IAMs that strive for sustainable bioenergy production, include assumptions about land areas that are not available for bioenergy such as primary forest and food production.
Social acceptability	Most IAMs do not consider social acceptability, although some express this in terms of a scaling down of technical potential. This is relevant across the entire BECCS supply chain.
Global participation	Most scenarios assume global participation in emission reductions.
Carbon price (or equivalent)	IAMs assume that an effective (global) carbon mechanism exists.
Global governance system	A BECCS supply chain will incorporate a diverse mix of nations, regions, technologies and actors which will require a coordinated regulatory framework in order to deliver, verify and account for negative emissions.

Table 4. Summary of the key uncertainties in future scenarios of BECCS

The list of assumptions used in the expert workshop (AVOID 2 WPD1b) are given in Table 5. Where available, information on the assumptions made in AVOID 1, RCP2.6 and TIAM (see Section 1.2) were provided to the workshop participants. Assumptions selected were worded in an expansive rather than specific manner to enable participants to explore the breadth of issues rather than critique a single model or individual approach. Participants were given the opportunity to discuss and amend the definitions and wording of the assumptions and select additional assumptions to discuss in the workshop, for further details see AVOID 2 Report WPD1b.

Area	Assumption	Description
Bioenergy	Land area used for biomass production (ha)	Total land area used for biomass production, i.e. not including land use for food production. Note variety of biomass types; bioenergy crops (first and second generation), forestry residues, waste etc.
	Future yields (t/ha/year)	Yield assumptions for BECCS in IAMs. Note variety of biomass types and different assumptions for agricultural factors such as fertiliser and irrigation.
	Proportion of energy supply from biomass (% or EJ)	Total contribution to the energy system that is from biomass whether used for electricity, biofuels or heat.
CCS	Maximum CO_2 storage capacity (t CO_2)	Total amount of CO_2 that can be stored in geological formations – includes onshore, offshore storage in hydrocarbon fields or saline aquifers
	Technology uptake (GW/year)	Rate at which BECCS technology can be rolled out – depends upon technological innovation rates, capacity and knowledge base, upscaling etc. but also capital turnover rates of existing stock
	Capture rate (%)	How much carbon in the fuel does the capture process remove for storage?
Cross-cutting	Policy framework	Possibility of institutional frameworks to deliver global carbon tax/price/incentive to enable BECCS to become commercially viable – i.e. can this technology be brought to market?
	Social acceptability	Societal tolerance of large changes in land use (e.g. converting natural grassland and use of ‘abandoned’ agricultural land), location of storage sites, environmental impacts (e.g. biodiversity).
	Net negative emissions	Can adequate accounting and verification frameworks be put in place to verify that BECCS results in net negative emissions during the full life cycle?

Table 5. Assumptions selected for discussion in the expert workshop (WPD1b).

6. Summary and conclusions

This report presents an overview of the literature relevant to the representation of negative emissions in long-range global emission scenarios using Biomass energy with Carbon dioxide Capture and Storage (BECCS), with a view to starting to unpack some of the key assumptions behind these estimates. This draws on literature from Integrated Assessment Modelling, Representative Concentration Pathways, bioenergy, CCS and BECCS. Each of these literatures adopts its own specific terminology and conventions and draws on expertise from a wide variety of disciplinary and interdisciplinary studies. The heterogeneity of the literatures provides an apposite reflection of the complexity of realising BECCS as a climate change mitigation option.

Deployment of BECCS would be driven primarily by concentration / temperature targets and the constraints of staying within very tight carbon budgets. BECCS has featured highly in suggested pathways that do not exceed 2°C of global mean temperature warming above pre-industrial levels; introducing a global net negative emissions component allows an ‘overshoot’ in the year in which emissions can peak while staying within a carbon budget. Crossing this threshold from negative emissions at a project level to delivering global net negative emissions to achieve concentration targets shifts the negative emissions discourse from ‘offsetting hard to abate sectors’ to a more fundamental pillar of managing the future climate by removing CO_2 from the atmosphere.

We describe some of the assumptions made both explicitly and implicitly, in the assessment of BECCS potential, noting that many of these assumptions are strongly interconnected and interdependent. Modelling BECCS systems brings together assumptions about earth system responses and cumulative emission budgets; bioenergy potential; CCS capability; achieving negative emissions through BECCS as well as significant political and socio-economic factors.

Variations in biomass energy potential are due to assumptions about available land area and implications for food production of any restrictions, and preservation of primary forest. The potential global bioenergy resource available for BECCS is a key uncertainty, comprising uncertainties in land availability, crop yields and residue availability and their underlying socio-economic and environmental assumptions. There are many interconnected issues involved including other land uses, food production, water resources, direct and indirect land use change, biodiversity, social acceptability and policy frameworks (Azar et al., 2010; Bonsch et al., 2014; van Vuuren et al., 2009; 2010; van Vuuren and Riahi, 2011). Most IAMs account for these constraints by using an upper limit of 200 EJ yr^{-1} energy from biomass, based on half from residues and half from dedicated energy crops based on literature estimates, whilst others attempt to address some of the interconnected issues by explicitly modelling land use.

CCS technology is currently entering the demonstration phase, dominated by fossil fuel applications; although some projects feature biomass co-firing, there is very limited practical and research experience of dedicated BECCS technologies. While opportunities for secure storage in hydrocarbon fields are relatively well-quantified, the size of the potential for large scale, long term storage in saline aquifers remains uncertain. Although the CO_2 balance of the CCS elements of the BECCS chain is relatively straightforward to quantify, the greatest uncertainties in ensuring the process delivers genuine net ‘negative’ emissions are associated with the biomass energy system prior to combustion. Key uncertainties surround the prior requirements of an established CCS infrastructure, the full lifecycle net negative emissions, with particularly large uncertainties in the production of biomass energy as well as sufficient and effective policy frameworks and governance to develop and roll out the technology, ensure global participation in emissions reductions and avoid the potential negative impacts of large scale bioenergy “done wrong” (Tilman et al., 2009).

Non-technical uncertainties are significant and difficult to represent – particularly societal impacts and responses and governance and regulatory issues. Most IAMs assume full global participation in delivering emissions reductions - a situation which has thus far remained elusive within the UNFCCC negotiations. Furthermore, introducing BECCS on a large scale inevitably requires an expansion in the number of contributing nations and regions, particularly those with the greatest potential biomass resource (including many developing countries). This in turn holds implications in terms of climate and energy policies and regulation and international regulatory frameworks that can accommodate the international diversity across the BECCS supply chain.

Any large scale expansion of CCS technology is dependent on regulatory and policy measures to incentivise and manage its deployment, such as strict emission limits or a high carbon price alongside an adequate regulatory framework to govern both short- and long-term liabilities and responsibilities to manage and monitor storage sites during active injection and provide for post-injection liability respectively. Investment requires certainty in long term funding for a technology that essentially reduces the cost effectiveness of an existing power generation technology – CCS technology is entirely dependent on a strict climate mitigation policy. Furthermore, establishing rapid deployment of BECCS on a large scale would require government investment that goes beyond a carbon pricing mechanism to support it as an emerging technology to deliver policy intervention, which combines strict climate constraints with meeting society’s energy needs.

Much of the research appears to suggest that existing targets for climate change mitigation may not be feasible without the negative emissions benefits of BECCS – even with ambitious emission reduction measures in place across the board. So while there are clearly concerns relating to claims made for BECCS, there is also a strong imperative to better understand the conditions and consequences of pursuing the technology – exposing the uncertainties should be seen as a wake-up call.

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