

## Synthesising existing knowledge on feasibility of BECCS: Workshop Report

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## Non-technical summary

- Biomass energy with carbon capture and storage (BECCS) is used in most future emission scenarios that do not exceed 2°C warming, to remove carbon dioxide from the atmosphere by providing ‘negative emissions’. The use of BECCS is driven by the need to resolve the emissions gap between current emission trajectories and the cumulative carbon budget that equates to 2°C.
- BECCS is used extensively in many scenarios; for example in the majority of the RCP2.6 scenarios, BECCS deployment starts in 2020 and by 2070 is delivering a net removal of CO<sub>2</sub> from the atmosphere. It is this large scale use of BECCS that raises feasibility concerns, especially in terms of global bioenergy resource potential (including underlying socio-economic assumptions), deployment of carbon capture and storage (CCS) infrastructure and necessary policy and governance structures (including and going beyond a financial enabling environment).
- Our results highlight concerns about uncertainties in the ability of a global BECCS industry to deliver negative emissions at the magnitudes assumed in the models. Specific concerns were raised over the bioenergy component including direct and indirect land use change emissions and regional diversity of governance and regulation regimes.
- We identify the critical dependence of the potential for BECCS to make a significant contribution to climate change mitigation on new policy and governance structures. This goes beyond the requirement for a global financial enabling environment, to include governance and regulation infrastructure necessary to coordinate, monitor and verify the magnitude of negative emissions from BECCS. Future scenarios of BECCS assume global participation in policy frameworks that incentivise and regulate the deployment of CCS infrastructure and BECCS.

Approach: this study focused on a structured examination of issues related to the feasibility of BECCS using a facilitated workshop with 18 participants. The issues considered were drawn from earlier work on BECCS including the AVOID 2 literature review.

## Media interest

This report covers the biophysical and Earth system scientific questions around BECCS in supporting emissions reductions over the 21<sup>st</sup> century. As such it may be of interest to journalists who specialise in this area. Some of the key messages will be of interest to the media (especially at the time of COP21) as BECCS research and its potential for reducing emissions will be drawn in to international mitigation negotiations.

## NERC results

This project did not draw directly on NERC funded work.

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## 1. Introduction

### 1.1 Background

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 100 of the 116 scenarios associated with concentrations between 430–480 ppm CO<sub>2</sub> depend on BECCS to deliver global net negative emissions in the IPCC Fifth Assessment Report (AR5) (Fuss et al., 2014). 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).

BECCS is an emerging technology that combines large scale biomass energy applications (including electricity generation) with the capture and storage of CO<sub>2</sub>. Integrated assessment models (IAMs) construct future emission scenarios and have different assumptions and constraints on the way BECCS is used. For example some include detailed representations of land use (e.g. IMAGE, van Vuuren et al, 2011) whilst others do not explicitly model bioenergy production, using instead an assumed maximum limit from the literature, e.g. 200 EJ yr<sup>-1</sup> (e.g. GET, Azar et al., 2013;). The 200 EJ yr<sup>-1</sup> is generally assumed to be achieved by 100 EJ yr<sup>-1</sup> from residues and 100 EJ yr<sup>-1</sup> from dedicated energy crops. According to a recent review of global bioenergy potential, ~100 EJ yr<sup>-1</sup> equates to ~400-500 mha of dedicated energy crops with yields of 10-15 oven dry ton (odt) ha<sup>-1</sup> yr<sup>-1</sup> (Slade et al., 2014).

In a review of the literature Gough & Vaughan (2015) discuss the explicit and implicit assumptions in BECCS scenarios and uncertainties therein. Global bioenergy resource potential estimates are an issue, comprised of uncertainties in land and water availability, crop yields, residue availability and the socio-economic assumptions upon which these are based. Weak governance and regulation is identified as being a barrier to delivering negative emissions through BECCS as is the need for strong policy incentives and regulation to establish the CCS industry component of BECCS.

For the purpose of our expert workshop we sought to examine the general assumptions in BECCS scenarios in IAMs rather than focus on one single scenario in one single model. Instead we provided contextual information for some key assumptions from three distinct sources. 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 (these constraints vary between models, are generally technical in nature and are by no means exhaustive, e.g. complex socio-political factors are not included); 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 contextual information provided to experts came from three sources; for the top-down perspective, we used the negative emissions scenarios created for AVOID1 (Bernie et al., 2012) and for an IAM scenario we use RCP2.6 (van Vuuren et al., 2011) complemented with information from some initial TIAM model runs for AVOID 2. BECCS in AVOID1 were top-down simple scenarios constrained by an implementation start date (between 2040 and 2070) and a maximum rate of CO<sub>2</sub> removal (11 GtCO<sub>2</sub> yr<sup>-1</sup> or 3 GtC yr<sup>-1</sup>). RCP2.6 is generated by the IMAGE model which includes detailed representations of land use (van Vuuren et al., 2011), and represents BECCS through the use of residues from agriculture, forestry and waste and dedicated sugar cane and woody biomass bioenergy crops (van Vuuren et al., 2010) and the use of this biomass in applications such as electricity generation with CCS. Gough & Vaughan (2015) provide further details about these models and their representations of BECCS.

## 1.2 Rationale

This report presents results from an expert elicitation workshop held in January 2015. The aim of the workshop was to review the key issues and assumptions which underpin the feasibility of BECCS scenarios used in IAMs to ensure global mean temperature does not exceed 2°C by the end of the century (Gough & Vaughan, 2015). The results represent a preliminary process of opening up the discussion around the underlying assumptions – both explicit and implicit – associated with the scale of BECCS deployment represented in many of the stricter climate change mitigation pathways. The expert elicitation process brings together experts from across a variety of disciplines relating to BECCS to come together and share knowledge and understanding in a way that can benefit from published and unpublished wisdom of those experts (Knol et al. 2010). The method has been designed to explore the underlying quality of the assumptions in question in a systematic and structured way with the broad aim of improving transparency and validity to the claims made in relation to BECCS.

## 2. Methods

The workshop was conducted on Tuesday 27<sup>th</sup> January at Imperial College, London and was structured around an expert elicitation method adapted specifically for this workshop. The method, described below, was intended to support an initial scoping of the level of confidence associated with key assumptions relating to the role of BECCS within the three IAMs described above. The method provides a qualitative assessment of uncertainty as a complement to more formal quantitative approaches to uncertainty analysis beyond the scope of this study. The workshop was structured around a deliberative process which provided individual assessments of key assumptions by a variety of professional stakeholders with expertise in fields relevant to the BECCS technology, group feedback on those assessments and a wider discussion on the role of BECCS in climate change mitigation scenarios.

### 2.1 Participants

18 participants attended the one day workshop, representing a diversity of expertise from a variety of sectors including business, policy, NGOs and academia; this number of participants is at the upper end of workshop sizes in previous applications of the methodology (e.g. de

Jong et al. 2012; van der Sluijs et al. 2005). Participants were primarily ‘subject matter’ experts (Knol et al. 2010), selected for their expertise in bioenergy, CCS or BECCS.

At the start of the workshop all participants were asked to consent to the proceedings being digitally recorded and were asked to indicate their specific field of expertise as it relates to biomass energy and CCS. The self-stated expertise and institutional affiliations of all participants is detailed in Table 1.

| ID | Organisation                | Expertise (self-stated)  |
|----|-----------------------------|--|
| 1  | Utrecht University          | CCS [carbon capture and storage], system analysis, LCA [life cycle analysis], transport infrastructure, techno-economic analysis |
| 2  | British Geological Survey   | CO <sub>2</sub> storage (underground)  |
| 3  | Met Office                  | Global climate carbon cycle. Levels of negative emissions including land-use change etc necessary to meet carbon budget          |
| 4  | DECC                        | LCA  |
| 5  | Met Office                  | Mitigation advice, scenario analysis, climate processes/modelling  |
| 6  | Virgin Earth Challenge      | Policy, innovation, impact of GGR [greenhouse gas removal] technologies in addressing climate change discourse                   |
| 7  | Met Office                  | Climate science  |
| 8  | Aston University Birmingham | Bioenergy modelling, tech-economics, socio-economics and environmental impacts   |
| 9  | Friends of the Earth        | Bioenergy  |
| 10 | Imperial College London     | CCS, thermodynamics, BECCS, supply chain modelling, dynamic system modelling   |
| 11 | Imperial College London     | GGR, innovation systems experience   |
| 12 | Imperial College London     | CCS, bioenergy   |
| 13 | Imperial College London     | Bioenergy, technology assessment, resource availability  |
| 14 | University of Nottingham    | Agricultural supply chain, farmers attitudes/perception of biofuels and bioenergy, policy analysis                               |
| 15 | E4Tech                      | Techno-economics and status of development, as gained through industry and government consultancy projects                       |
| 16 | University of Exeter        | Earth system science, modelling  |
| 17 | Imperial College London     | Range of technologies including CCS applied to power generation and industry, as well as Biomass CCS.                            |
| 18 | University of Edinburgh     | CCS, carbon systems science and carbon capture, energy and climate policy analysis   |

Table 1. Workshop participants and their self-stated area of expertise. Note, area of expertise is as written by the experts themselves, square brackets denote acronym definitions added by authors.



## 2.2 Elicitation methodology

The workshop methodology draws inspiration from the work of (Kloprogge et al., 2011; van der Sluijs et al., 2005) for analysing the value-ladenness of assumptions based on a pedigree matrix, originally proposed by (Funtowicz and Ravetz, 1990) as part of the NUSAP (Numerical, Unit, Spread, Assessment, Pedigree) method for uncertainty assessment. It is underpinned by the premise that there are different types of uncertainty associated with scientific evidence, particularly as it is used for policy relating to complex environmental problems (van der Sluijs et al., 2005). Uncertainties may relate to different framings of a problem and institutional and societal constraints as well as the knowledge base on which evidence is built; assessing these uncertainties is well served by a deliberative and reflexive approach (van der Sluijs et al., 2005). Qualitative assessment of pedigree entails the evaluation of assumptions against a set of criteria which describe the quality and scientific status of information on which they are based; a pedigree matrix may then be used to map expert judgements of pedigree from weak to strong (van der Sluijs et al., 2005).

Given the time constraints of the project, we were not in a position to conduct a full pedigree assessment of the assumptions for BECCS in IAMs. However, we have adopted a heuristic approach to draw on some of the key principles of the methodology to pursue a specific aim: notably to discuss and characterise the value-ladenness of certain key assumptions in a process of discussion and evaluation (Jong et al., 2012). The method described below draws on the principles that assumptions can be characterised in relation to their influence on model results and their pedigree according to certain quality criteria (Jong et al., 2012). This enabled us, with limited resources and in a short time frame, to obtain a preliminary assessment of the selected assumptions by a particular group of experts, in a form that can be visualised on a matrix plot. We acknowledge that we have adapted and condensed the methodology to suit the constraints of this study. For example, although experts were given the opportunity to propose additional assumptions to include in the assessment, the initial assumption list was drawn up by the research team prior to workshop; a reduced pedigree matrix was presented for scoring, providing limited information on how to interpret each score in relation to the criteria; opportunity for revision and extending the process was limited and could be pursued further in future studies. However, we remain confident that the results provide valuable insights, consistent with adopting “flexibility and creativity” in the application of the methodology (Kloprogge et al., 2011).

The purpose of the process described below was to provide some structure to the analysis, enabling an initial exploration of the different dimensions of uncertainty associated with estimating the potential future role for BECCS, rather than to deliver a quantitative assessment of the assumed values as part of a full calculation chain (Jong et al., 2012). The results presented here are intended to open up and inform an on-going dialogue that delves more deeply into the detailed assumptions underlying the use of BECCS to deliver negative emissions.

The starting point in this analysis is a literature review conducted by the authors (Gough & Vaughan, 2015) and from which a list of key assumptions was identified prior to the workshop (Table 2). These were considered to be the critical assumptions and parameters that govern either the contribution that BECCS makes to final carbon budgets in the IAMs (in terms of magnitude or timescales of CO<sub>2</sub> removal) or the feasibility of establishing BECCS at the

assumed scales. The aim was to expose and discuss implicit as well as explicit assumptions behind the claims made for BECCS, rather than to deliver any quantitative assessment of numerical assumptions used in the models. This enabled us to discuss quantitative and qualitative assumptions together; detailed quantitative values for all assumptions used in the IAMs are not widely published, unpacking the fine details of these models would require an extended and more ambitious research project.

Assumptions are assessed according to their perceived influence on model results and their 'pedigree' according to a set of predefined criteria, chosen to describe different types of uncertainty. The original method presents a diagnostic plot (pedigree matrix) which is based on a strict process through which the criteria scoring process is defined and implemented (Kloprogge et al., 2011). We present plots of individual and combined scores in order to provide a comparative illustration of participants' views on the quality of the selected assumptions and identify those which should be prioritised for further consideration, i.e. those having a strong influence on the model results and high uncertainty ("danger zone").

## 2.2.1 Assumptions

A set of nine assumptions (Table 2) was drawn from a review of the bioenergy, CCS and BECCS literature (Gough & Vaughan, 2015). These were identified by the authors as being key assumptions that could be critical in modelling the contribution of BECCS to achieving climate change mitigation targets. Where available, information on how these assumptions were interpreted in AVOID1, RCP2.6 and TIAM was provided to the workshop participants (see Appendix 1 for a summary of the data was provided with each assumption). However, the assumptions 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 and recognising that many of these assumptions are strongly interconnected and interdependent. 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.

| 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 <sub>2</sub> storage capacity (t CO <sub>2</sub> ) | Total amount of CO <sub>2</sub> 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 2. Assumptions selected for discussion in the expert workshop based on a review of the literature (Gough & Vaughan, 2015).

### 2.2.2 Pedigree criteria

Table 3 details the five criteria against which each assumption was scored and the explanations for scoring as detailed on the score cards (see Appendix 2 for a copy of a generic score card). These criteria were selected by the authors as being the most appropriate for the analysis and are based on those detailed in Kloprogge et al. (2011). The final criterion, ‘expediency’, was the most challenging to explain to participants; it is derived from the criterion in the original methodology “sensitivity to view and interests of the analyst” which is designed to capture the ‘socio-political’ value-ladenness of assumptions (Kloprogge et al. 2011). However, the authors felt that ‘expediency’ better reflected the notion of susceptibility to interpreting the assumption in different ways according to how it is to be used in a model. Time was taken during the workshop to ensure that participants reached a shared understanding of this criterion before commencing scoring. Each criterion was assigned a score between 0 (very low) to 4 (high level of confidence) with guidance on how the scores should be interpreted with respect to each of the criteria; these are intended to reflect how an assumption has been produced and its degree of value-ladenness (Knol et al. 2011).

| Criterion                          | Low score   | High score                                 |
|------------------------------------|---|--|
| Influence on results               | <i>Limited influence</i>                          | <i>Highly influential</i>                  |
| Agreement amongst peers            | <i>Very little consensus</i>                      | <i>High level of consensus</i>             |
| Availability of data / information | <i>Very little data available</i>                 | <i>Plenty of data available</i>            |
| Plausibility                       | <i>First order estimate (speculative)</i>         | <i>Assumption based on strong evidence</i> |
| Expediency                         | <i>Assumption malleable to context or purpose</i> | <i>Assumption robust to context</i>        |

Table 3. Criteria used for pedigree scoring.

## 2.2.3 Workshop structure

Following a brief introduction to the AVOID 2 project made by Prof Jason Lowe from the Met Office and another by the authors explaining the day's proceedings, the workshop activities began with a breakout session during which assumptions were discussed and scored, followed by report back from the breakouts and a final facilitated group discussion to end the day. The format of each of these sessions is described below.

### **Breakout session**

The workshop participants were split into three smaller groups according to their area of expertise; each facilitated subgroup was allocated three assumptions on bioenergy, CCS and cross cutting issues respectively, as detailed in Table 2. The full list of assumptions was presented in plenary and posted up on the wall, so that groups could see all of the assumptions being considered and could choose to assess one of the other assumptions if they wished to. Taking each assumption in turn, the subgroup discussed the definition of the assumption and refined it to ensure that it provided an accurate description with a clear shared meaning. At this point each participant was given a score card (Appendix 2), based on those presented in (Kloprogge et al., 2005) for the assumption in question. Before scoring, facilitators made sure that all participants understood what was meant by the criteria and how to interpret the scoring system. Each participant was asked to rate their level of expertise on the score card in relation to the specific assumption being scored (Table 4a, 4b & 4c). The overall scoring was based on an assessment of the level of "influence on results" and a "pedigree" assessment for each assumption, made up of the scores for four criteria (Table 3). Blank score cards were provided to allow participants to include additional assumptions not included in the original list. All score cards included a space next to each criterion and participants were encouraged to annotate score cards with comments relating to the use of the assumption and their views on its performance relative to the criteria. The group's scores were then collated on a large group score card, providing a tally of scores for each criterion and allowing discussion and reflection on scoring across the group. Individual comments and group discussion are included in the results presented in Section 3. Only one of the groups (CCS) chose to utilise the blank score cards to create a new assumption to discuss as a group.

### **Plenary 1: Breakout group feedback**

During the lunch break facilitators calculated weighted means based on groups' scores; these composite scores were plotted onto a Matrix (in PowerPoint) and presented back to the group during plenary. Facilitators reported the group score cards during a plenary session, summarising the discussions around the assumptions and describing the basis for the scores. The group score card and position on the matrix were open to comment, question and refinement during this session.

### **Plenary 2: Open questions session**

The final plenary session was designed to allow a more open discussion on the issues relating to the deployment of BECCS as a climate change mitigation option with the aim of giving space for other and more general concerns that may not have been captured by the focus on assumptions. Participants were given A5 post-its on which they were asked to note down answers to the question: '*What are the three things that cause you most concern with the use of BECCS in future scenarios (especially scenarios that meet the two degree target)?*'. All responses were read out and put up on the wall. During this session one facilitator lead the

discussion while the other grouped the issues into clusters; additional points were added as they emerged during the discussions.

## 3. Results and Analysis

### 3.1 Assumption Scoring

#### 3.1.1 Summary

The group mean scores for the ten assumptions are shown in Figure 1, where pedigree is the mean of the scores for peer agreement, data availability, plausibility and expediency (Tables 4a, 4b & 4c). In the methodology (Section 2.2), when plotting influence on the results against pedigree an area of the figure is denoted the 'danger zone', where scores have a high (> 2.5) influence on results and a low (< 2.5) pedigree. Seven of the ten assumptions are within the 'danger zone', including all the bioenergy and cross cutting assumptions. The newly created CCS assumption of net negative emissions (Section 3.1.7) is the only one scored by the CCS group that falls within the danger zone. The spread of scores and experts' self-stated expertise are detailed in Tables 4a, 4b & 4c.

These results would suggest that the CCS component of the BECCS scenarios are better constrained. The three key assumptions relating to CCS all broadly relate to technical aspects of the technology and the scoring reflects that there are not considered to be significant technical barriers to delivering CCS as a mitigation approach. However, challenges to delivering CCS at large scale do remain and these are captured under the cross cutting assumptions which performed less well in the scoring process.

Key areas of uncertainty lie in global scale bioenergy resource potential (land availability and future yields) and future energy mix (proportion of bioenergy); overarching policy and social acceptability of large scale BECCS and its constituent parts; and uncertainty as to the magnitude of net negative emissions of a full BECCS system (e.g. taking into account emissions from all components, including for example emissions from direct and indirect land use change) which is central to BECCS as a form of carbon dioxide removal. The more detailed scoring and responses are described in the following sections.

It is important to note that these results may differ if the same exercise was conducted with a different set of experts, as the scorings are individual expert judgements which will be influenced by participants' particular specialism and perspective. The assumptions presented in the elicitation exercise do not represent an exhaustive list of components of the representations of BECCS in IAMs but were identified as potentially critical through a review of the literature (Gough & Vaughan, 2015), this explains to some extent the high proportion that fall within the 'danger zone'.

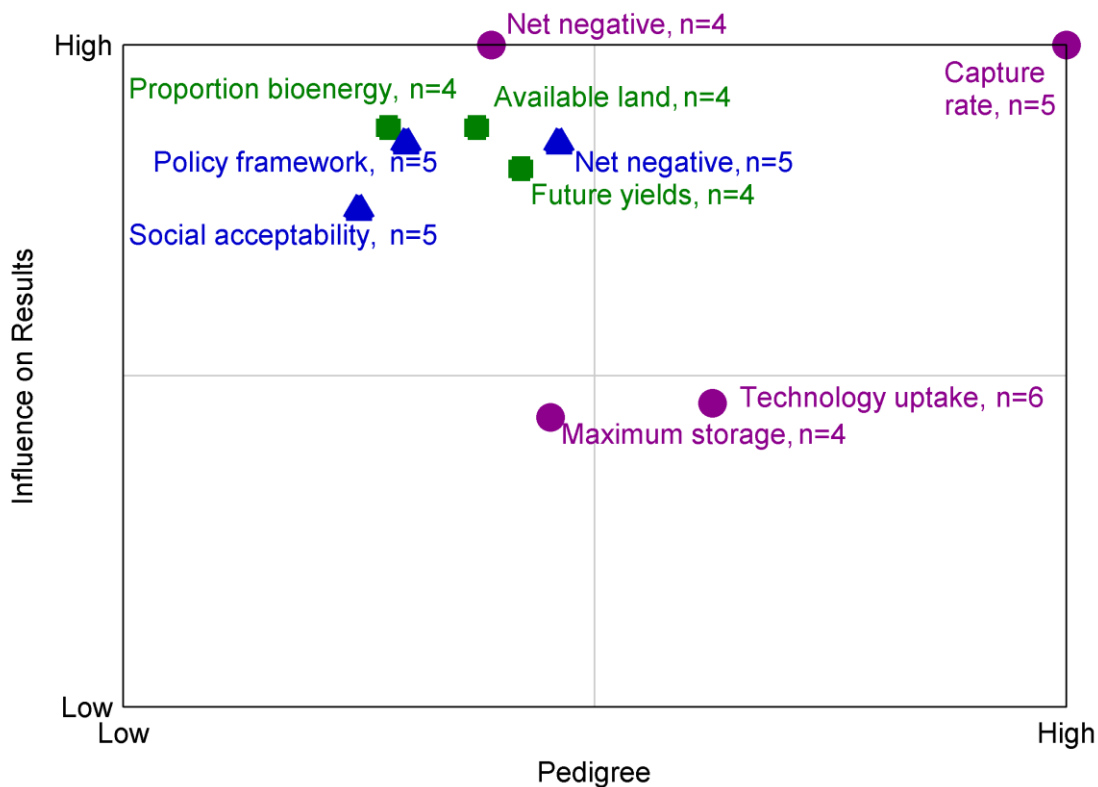


Figure 1. Summary of influence on results vs pedigree scoring. Pedigree is the mean score of the four criteria: data availability, peer agreement, plausibility and expediency (see Tables 4a, 4b & 4c). Data points are colour coded to show how the three different assumption groups are represented on the matrix: green are the bioenergy assumptions, purple are the CCS assumptions, blue are the cross cutting assumptions. Number of participants who scored the assumption, n=x.

Details of the assumption scoring are presented in Tables 4a, 4b & 4c, including self-stated expertise and the mean group score for each assumption. Following Kloprogge et al (2011) a nominal mean is calculated for the ordinal data. In the following subsections, the scoring of each assumption is discussed including; the original assumption as detailed on the score cards (see Appendix 2) and the groups' discussed understanding and/or refinement; the main patterns in scoring and key issues that arose in discussions within the group. In the final subsection, a summary figure of assumption pedigree scores plotted against influence on results scores.

### 3.1.2 Bioenergy 1 Land area used for biomass production (ha)

The first bioenergy assumption discussed was land area used for biomass production, described as the total land area used for biomass production, i.e. not including land use for food production. Note that this applies to a variety of biomass types: bioenergy crops (first and second generation), forestry residues, waste etc. Four participants scored this assumption, all stating some expertise.

Land availability assumptions were considered to have a high influence on results, with comments noting the differences in the quality of land, dependency on energy crops and forestry and the role of residues. Agreement amongst peers was given a low score, with comments that models are normative in that they are driven towards a specific policy goal (i.e.

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2°C), drawing on very different input assumptions to create alternative scenarios that reach the stated policy goal, they do not provide predictions of the future. Data availability was given a medium score with participants noting the quality of present and historical data in contrast to the more speculative future information based on assumptions and extrapolations. Plausibility was given a low score with lower estimates and residues better constrained than dedicated bioenergy crops and higher estimates. Expediency was scored mid-to-low with many commenting that the models are normative (i.e. constrained by specific policy framings such as staying within 2°C) and driven by assumptions which are malleable, albeit explicitly so.

The discussions on this assumption were wide ranging given the interconnected nature of land availability and its effect on yields and biomass type. Issues raised included yield improvements through bioengineering, other sources of biomass including residues and aquatic biomass, variation in land quality, the large range in estimates of land availability, the difference between current data and more speculative future assumptions.

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|  | Influence on results |   |   |   |   |    | Agreement amongst peers |   |   |   |   |          | Availability of data |   |   |   |                |                      | Plausibility   |    |   |   |   |                | Expediency     |                |    |   |   |    |  |  |
|--|----------------------|---|---|---|---|----|-------------------------|---|---|---|---|----------|----------------------|---|---|---|----------------|----------------------|----------------|----|---|---|---|----------------|----------------|----------------|----|---|---|----|--|--|
|  | 0                    | 1 | 2 | 3 | 4 | Mn | 0                       | 1 | 2 | 3 | 4 | Mn       | 0                    | 1 | 2 | 3 | 4              | Mn                   | 0              | 1  | 2 | 3 | 4 | Mn             | 0              | 1              | 2  | 3 | 4 | Mn |  |  |
| Bioenergy 1<br><b>Available land</b>       |                      |   |   |   |   |    | 03<br>13<br>15<br>16    |   |   |   |   |          |                      |   |   |   |                |                      | 03<br>13<br>16 | 15 |   |   |   |                |                | 03<br>13<br>16 | 15 |   |   |    |  |  |
| Bioenergy 2<br><b>Future yields</b>        |                      |   |   |   |   |    |                         |   |   |   |   | 15<br>03 | 13                   |   |   |   |                | 03<br>13<br>15<br>16 |                |    |   |   |   |                | 03<br>15<br>13 | 16             |    |   |   |    |  |  |
| Bioenergy 3<br><b>Proportion of energy</b> |                      |   |   |   |   |    |                         |   |   |   |   |          |                      |   |   |   | 03<br>15<br>16 | 13                   |                |    |   |   |   | 03<br>15<br>13 | 16             |                |    |   |   |    |  |  |

Table 4a. Bioenergy assumption scores.

Participant identification numbers (see Table 1) are entered in each column according to how each participant scored the criteria; the ID font reflects the self-stated expertise expressed as little (italics), some (normal) and considerable (underlined). For each criterion, mean (Mn) group score is presented.



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|                                 | Influence on results  |   |   |                                   |           |             | Agreement amongst peers |   |                      |                                     |            |             | Availability of data |                      |                 |                                   |                              |          | Plausibility |   |   |                                   |                      |  | Expediency  |                      |                      |  |            |             |
|---------------------------------|-----------------------|---|---|-----------------------------------|-----------|-------------|-------------------------|---|----------------------|-------------------------------------|------------|-------------|----------------------|----------------------|-----------------|-----------------------------------|------------------------------|----------|--------------|---|---|-----------------------------------|----------------------|--|-------------|----------------------|----------------------|--|------------|-------------|
|                                 | 0                     | 1 | 2 | 3                                 | 4         | Mn          | 0                       | 1 | 2                    | 3                                   | 4          | Mn          | 0                    | 1                    | 2               | 3                                 | 4                            | Mn       | 0            | 1 | 2 | 3                                 | 4                    | Mn   | 0           | 1                    | 2                    | 3  | 4          | Mn          |
| CCS 1<br>Storage capacity       | 01<br><u>02</u><br>18 |   |   |                                   | 10        | <b>1.75</b> |                         |   | 01<br>10<br>18       | <u>02</u>                           |            | <b>2.25</b> |                      |                      | 01<br>18        |                                   | <u>02</u><br>10              |          | <b>1.75</b>  |   |   | 01<br>18                          |                      | <u>02</u><br>10                                  |             | <b>1.75</b>          | 01<br>18             | <u>02</u><br>10                                  |            | <b>1.5</b>  |
| CCS 2<br>Technology uptake      | 02<br>05<br><u>12</u> |   |   | <u>01</u><br>18                   | <u>10</u> | <b>1.83</b> |                         |   | 05<br>18             | <u>01</u><br><u>02</u><br><u>10</u> | <u>12</u>  | <b>3</b>    |                      |                      | <u>01</u><br>18 |                                   | <u>02</u><br>05<br><u>10</u> |          | <b>2</b>     |   |   | 05<br>18                          |                      | <u>01</u><br><u>02</u><br><u>10</u><br><u>12</u> |             | <b>2.83</b>          | 05<br>18             | <u>01</u><br><u>02</u><br><u>10</u><br><u>12</u> |            | <b>2.17</b> |
| CCS 3<br>Capture rate           |                       |   |   | 01<br>02<br><u>10</u><br>12<br>18 |           | <b>4</b>    |                         |   |                      | 01<br>02<br><u>10</u><br>12<br>18   |            | <b>4</b>    |                      |                      |                 | 01<br>02<br><u>10</u><br>12<br>18 |                              | <b>4</b> |              |   |   | 01<br>02<br><u>10</u><br>12<br>18 |                      | <b>4</b>   |             |                      |                      | 01<br>02<br><u>10</u><br>12<br>18                |            | <b>4</b>    |
| CCS 4<br>Net negative emissions |                       |   |   | 01<br>02<br>05<br>18              |           | <b>4</b>    |                         |   | 01<br>02<br>05<br>18 |                                     | <b>2.5</b> |             |                      | 01<br>02<br>05<br>18 |                 |                                   | 01<br>02<br>05<br>18         |          | <b>1</b>     |   |   |                                   | 01<br>02<br>05<br>18 |  | <b>2.25</b> | 01<br>02<br>05<br>18 | 02<br>01<br>18<br>05 |  | <b>0.5</b> |             |

Table 4b. Carbon capture and storage assumption scores.

Participant identification numbers (see Table 1) are entered in each column according to how each participant scored the criteria; the ID font reflects the self-stated expertise expressed as little (italics), some (normal) and considerable (underlined). For each criterion, mean (Mn) group score is presented.

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|  | Influence on results |   |   |                 |                 |            | Agreement amongst peers |   |   |   |                              |            | Availability of data |   |                              |                |            |             | Plausibility |   |   |                              |            |          | Expediency |   |   |                       |                |            |
|--|----------------------|---|---|-----------------|-----------------|------------|-------------------------|---|---|---|------------------------------|------------|----------------------|---|------------------------------|----------------|------------|-------------|--------------|---|---|------------------------------|------------|----------|------------|---|---|-----------------------|----------------|------------|
|  | 0                    | 1 | 2 | 3               | 4               | Mn         | 0                       | 1 | 2 | 3 | 4                            | Mn         | 0                    | 1 | 2                            | 3              | 4          | Mn          | 0            | 1 | 2 | 3                            | 4          | Mn       | 0          | 1 | 2 | 3                     | 4              | Mn         |
| Cross-cut 1<br><b>Policy framework</b>       |                      |   |   |                 | 04<br>14        | <b>3.4</b> |                         |   |   |   | 07<br>14                     | <b>1.4</b> |                      |   |                              |                | 04<br>07   | <b>1.75</b> |              |   |   |                              | 09<br>14   | <b>1</b> |            |   |   |                       | 04<br>07<br>09 | <b>0.8</b> |
| Cross-cut 2<br><b>Social Acceptability</b>   |                      |   |   | 07<br>04        | 14<br>09        | <b>3</b>   |                         |   |   |   | 07<br>09<br>04               | <b>2.4</b> |                      |   | 04<br>09                     | 17<br>14<br>07 | <b>0.8</b> |             |              |   |   | 07<br>09                     | <b>0.6</b> |          |            |   |   | 04<br>09<br>14        | <b>0.2</b>     |            |
| Cross-cut 3<br><b>Net negative emissions</b> |                      |   |   | <u>07</u><br>14 | <u>04</u><br>17 | <b>3.4</b> |                         |   |   |   | <u>04</u><br><u>07</u><br>09 | <b>2.2</b> |                      |   | <u>04</u><br><u>07</u><br>09 | 14<br>17       | <b>2.2</b> |             |              |   |   | <u>07</u><br><u>04</u><br>09 | <b>1.6</b> |          |            |   |   | 09<br><u>04</u><br>14 | <b>1.4</b>     |            |

Table 4c. Cross-cutting assumption scores.

Participant identification numbers (see Table 1) are entered in each column according to how each participant scored the criteria; the ID font reflects the self-stated expertise expressed as little (italics), some (normal) and considerable (underlined). For each criterion, mean (Mn) group score is presented

### 3.1.3 Bioenergy 2 Future yields (T/ha/yr)

The second bioenergy assumption discussed was future yields, described as yield assumptions for BECCS in IAMs. Note that this incorporated a variety of biomass types and difference assumptions for agricultural factors such as fertiliser and irrigation. Four participants scored this assumption, all stating some expertise.

Future yields scored highly for influence on results with comments that there are yield differences between trial plots and farms/forestry and uncertainties due to differences in land quality, land management, fertiliser use and multi-year crops. Agreement amongst peers was given low scores with participants noting more agreement at in certain regions than others, that future climate change and land quality impacts on yields are not well known but that current plot level experimentation provides some insights on where future trends may go. Availability of data and plausibility were given a medium scores with all participants commenting on the good availability of trial plot data, but a lack of data on future climate impacts on yields, the scalability of trial plot data and limited real experience. Concerns around plausibility include lack of studies on climate change impacts on yield with water availability and nutrients noted as big questions by one participant. Expediency was given low to medium scores with most participants commenting that models tend to ignore water and nutrient limitations, with one participants noting a lack of consideration of developments such as bioengineering more efficient photosynthesis.

### 3.1.4 Bioenergy 3 Proportion of energy supply from biomass (% or EJ)

The third bioenergy assumption discussed was proportion of energy supply from biomass, described as total contribution to the energy system that is from biomass whether used for electricity, biofuels or heat. Four participants scored this assumption, two stating little expertise and two stating some expertise.

This assumption was scored as having a high influence on results with comments that BECCS is chosen because of the negative emissions it provides and that it is needed to meet climate targets. Agreement amongst peers was given a medium score with two participants commenting that there is a consensus that a 'magic bullet' is needed to meet 2°C target and that BECCS is the favoured option to deliver this. Generally there are wide ranges in the proportion of energy supply from biomass in models and for those with large amounts of bioenergy some would contest there are more efficient energy supply options. There was a spread of scores for availability of data (Table 4a), with comments that there are many scenarios but a lack of experience of BECCS deployed at large scale. Plausibility was given low scores with comments that BECCS emerges from the models as a way to reach targets and integrating multiple immature technologies is risky. Two participants noted that the components of BECCS exist but are not operational at scale, with concerns over how quickly BECCS can be scaled up and the necessity of policy to enable this. Expediency was given the lowest scores with BECCS seen as magic bullet that enables targets to be met.

### 3.1.5 CCS 1 Maximum CO<sub>2</sub> storage capacity (T CO<sub>2</sub>)

Maximum CO<sub>2</sub> storage capacity (T CO<sub>2</sub>) describes the total amount of CO<sub>2</sub> that can be stored in geological formations – including onshore, offshore storage in hydrocarbon fields or saline aquifers. Four participants scored this assumption, three of whom declared some expertise and one expert, a specialist in CO<sub>2</sub> storage with considerable expertise.

Although this assumption was clearly understood, and it was recognised that this is how the storage element is represented and constrained in the models, it was suggested that it would be better to consider the minimum storage required within the scenario. It was noted that it is not just total storage capacity but the rate at which it is to be used that is important – i.e. the time frame over which capacity can be accessed. The limiting factor in relation to storage is surveying and exploration of potential reservoirs in order to verify their suitability for CO<sub>2</sub> storage, one participant noting that there is significant global uncertainty with respect to all criteria.

A range of scores were allocated for the influence on results attributed to CO<sub>2</sub> storage, some of the variation attributed to geographical factors; the low score was awarded in the context that, if regional capacity could be guaranteed, this assumption would not influence results. In some locations CO<sub>2</sub> storage is not considered to be a constraining factor (e.g. UK.) whereas in others it is a key parameter (e.g. South Africa, Middle East, China). Moderate to high scores (Table 4b) were given for agreement among peers, with the caveats that there remains limited practical experience and that debate about storage efficiencies, in open or closed formations, remains unresolved. Availability of data, plausibility and expedience were scored either low or moderate – again noting the effect of high geographical variation such that in some areas storage reservoirs are well characterised (e.g. US, UK) whereas in others the data based on early (static) estimates is more speculative (e.g. S Africa, China).

### 3.1.6 CCS 2 Technology uptake (GW / yr)

This assumption describes the rate at which BECCS technology can be rolled out, it depends upon technological innovation rates, capacity and knowledge base, upscaling etc. but also capital turnover rates of existing stock. Of the six members of the CCS breakout group, three identified as having considerable expertise in this area, one with some and the remaining two as having only little expertise. There was some discussion over whether this assumption would be better described as technology readiness (within the next 40 years). This assumption was considered to have a moderate to low influence on results (scores between 1 and 3) with a comment that the technology is mature enough now that deployment should not present a problem. It was seen to perform well against the peer agreement criterion – that although research and development remains necessary, there should be no technological show stoppers but that the rate at which plant can be built would be likely to be a limiting factor. A greater spread of scores was seen for the availability of data; at the time of the meeting, participants were awaiting results from a major techno-economic assessment of biomass CCS in the UK to be released and this clearly influenced how this assumption was scored. However, one participant did comment that experimental validation was necessary to support theoretical models. Plausibility was scored moderate to high with comments that assumptions for CCS technologies could draw on experience of other energy technologies' development pathways, data availability was considered to be good although not always in the public domain. The assumption also scored highly for expediency, suggesting that its evaluation is robust. During the broader discussions around this assumption, there was agreement that the limit in deployment was more over the will to deliver and the availability of finance rather than any limitations with the technology *per se*.

### 3.1.7 CCS 3 Capture rate

This assumption is widely used in all quantitative analyses of CCS technologies and describes how much carbon in the fuel the capture process removes for storage. The group considered

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this to be a straightforward and well understood parameter; it was scored very quickly with only a short discussion, participants mostly omitted to declare their expertise on the score sheets but all were confident in their scoring. There was consensus in the group that capture rate, although influential on the results, scored highest marks on all pedigree criteria. One participant, an expert in this area, remarking that the rate is a question of optimisation – that capture rate is essentially a function of costs, once it exceeds 90% the costs become high.

### 3.1.8 CCS 4 How negative is BECCS (g/KWh)

The CCS group added a fourth assumption to their scoring which they felt was critical in the analysis of BECCS scenarios, namely, is the assumption of carbon neutral biomass possible - how negative is BECCS? Although this is similar to the assumption presented to the cross cutting issues subgroup (Section 3.1.11), it was proposed independently by the CCS subgroup and is presented separately here since it was conceived and scored slightly differently. All four participants gave this the highest score for influence on results. While it is considered to perform reasonably well on peer agreement (noting that agreement lay in terms of its importance despite large uncertainties on the calculation of negative emissions) and plausibility (identified as the plausibility that BECCS could deliver negative emissions) it was scored less highly for data availability. Limitations to data availability for this assumption were attributed to variable results on location, future climate and the types of crops in question. This assumption performed poorly against the expediency criterion – since it depends on the economic context and life cycle performance involving multiple variables across the value chain, such as land use, transport etc. It was also noted that, because of its potential to deliver negative emissions, BECCS is subject to a higher level of scrutiny across the life cycle than other fuels or mitigation measures and it was questioned whether it was possible to get robust data on negative emissions within models. This assumption gets to the heart of the basic premise behind the use of BECCS to deliver negative emissions – the scoring reflects both views on the validity of that premise as well as the challenges in its quantification within models. The notion of negative emissions from BECCS needs to be unpacked much further than is possible in this exercise.

### 3.1.9 Cross-cutting 1 Policy Framework

The first cross cutting assumption discussed was policy frameworks, described as the possibility of institutional frameworks to deliver global carbon tax/price/incentive to enable BECCS to become commercially viable. All participants stated some expertise in this area. Participants queried the focus on carbon price in the description and the common use of a carbon price or incentive in most IAMs the use was discussed. Most participants (3 of 5) scored policy framework as having a high influence on results, commenting that such pricing will be very influential on uptake and noting the implicit assumption of effective markets. Peer agreement and data viability were both allocated medium to low scores, with concerns about the availability of data on scaling up, uncertainties in the interactions between components of the technology and underlying cost assumptions for bioenergy at scale regarding available land and yields. Plausibility was scored low with concerns about the multiple assumptions and contingencies involved and the difficulty of predicting policy in the future. For the expediency criterion, both the scoring and comments reflect a sense of high malleability with participants commenting that it was a very flexible assumption strongly dependent on technology mix and constraints and diversity of the political economies within which it may be deployed, although one participant commented that it is likely to be overridden by physical constraints.

In the group discussion key issues included the implied assumption of a market system; the interaction with land use policy and feedbacks on land availability; and policy surrounding CCS infrastructure and technology transfer. One participant noted that there are many more actors involved in reality and carbon pricing or incentives as modelled are generally focused solely on industrial actors, for example what do these assumptions mean for the prices paid to farmers? Participants commented that it is likely that countries that grow biomass may well not be the countries where the power generation with CCS occurs and given this, would the assumed policy framework be successful across such a breadth of localised differences?

### 3.1.10 Cross-cutting 2 Social acceptability

The second cross cutting assumption discussed was social acceptability, described as 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). One participant claimed little expertise whilst the remaining participants stated some expertise in this area. Within the description the use of the phrase 'abandoned' was discussed, querying whether such land is really unused or not. Given the limited representation of social acceptability in IAMs, there was some variability between participants in the interpretation of social acceptability assumptions in the model and in the real world. The group discussed their interpretation specifically around some of the criterion; agreement amongst peers was clarified as how big an issue is social acceptability in the feasibility of scenarios and; plausibility was clarified as how plausible are the assumptions about social acceptability from now until 2100.

Four participants regarding social acceptability as highly influential on results but one participant noted that societal acceptability is only represented in a limited capacity within models. Most participants noted social acceptability will likely differ between countries. Agreement amongst peers was given a mid-range score with comments that this is likely to be a barrier to BECCS but there is little consensus on the magnitude of the barrier. Availability of information was given low scores with questions raised as to the capability of such qualitative data being represented in a model. Plausibility was given low scores with one participant commenting that it is impossible to work out the acceptability of a technology to a diverse global society, in the future, against the backdrop of a changing climate and associated damages (Table 4c). Social acceptability assumptions were scored as highly malleable to context by the group, with one participant suggesting that this was very time dependent, suggesting this would be more robust to context in the future. Discussions included issues around timescale; climate change narrative; the scale up rate of BECCS and how people change their perspectives over time. It was noted that regional differences may lead to differing perspectives and that social tolerance or intolerance would be very specific to different actors. With respect to large scale biomass participants suggested that different biomass sources would have different issues for social acceptability.

### 3.1.11 Cross-cutting 3 Net negative emissions

The third cross cutting assumption discussed was net negative emissions, described as 'can adequate accounting and verification frameworks be put in place to verify that BECCS results in net negative emissions during the full life cycle'. Whereas the new assumption discussed by the CCS subgroup (Section 3.1.8) focused on the conceptual assumption that net negative emissions can be achieved, the scoring for this assumption places a greater emphasis on accounting and quantifying negative emissions. Two participants stated little expertise, one



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stated some and two stated considerable expertise in this area. Discussions about the description presented questioned a perceived implicit focus on carbon, with participants commenting on the importance of broader metrics, e.g. the full impact on climate, such as albedo, and other environmental impacts. Net negative emissions assumptions were scored as highly influential on results with comments that the ability to achieve and correctly quantify negative emissions is central to the use of BECCS. Issues of accounting, verification including direct and indirect land use change was commented on by three participants, whilst one noted that the magnitude of negative emission depends on the type of biomass used. Agreement amongst peers was given medium scores with notes that there is agreement this issue is important for BECCS role in mitigation but that there is a lack of agreement around carbon accounting at many stages, particularly land use change. Data availability was given medium scores with comments regarding data quality around certain components. Plausibility was given medium to low scores with issues around carbon impacts on land, noting the difficulty of quantifying indirect land use change impacts cycle impacts. Expediency was given a broad range of scores (Table 4c), with a diversity of opinions around the capability to improve estimates of direct and particularly indirect land use change.

## 3.2 Structured discussion

This section summarises the results of the final plenary session which followed on from the earlier session in which assumptions were scored, discussed and plotted on the matrix (Fig 1) respectively. Participants were asked '*What are three key issues around the use of BECCS in climate change mitigation?*'. Responses were affixed to the wall and grouped by a facilitator with the guidance of the participants; more points were added as the discussion evolved. Table 5 presents the key issues, grouped under three headings and edited to remove repetition and improve clarity (Appendix 3 is the unedited version). Four themes emerge from this structured discussion; (1) the role of BECCS in IAM scenarios of future emissions pathways, (2) assessment of carbon, climate and environmental impacts of BECCS, (3) BECCS technology development and deployment and (4) opportunities and barriers to BECCS arising from policy and socio-economic factors.

|   |                               |  |
|---|-------------------------------|--|
| Role of BECCS in IAM scenarios            | BECCS and 2°C                 | <ul style="list-style-type: none"> <li>• Pursuit of large scale BECCS is tied in to the 2° target</li> <li>• This may divert attention away from its role in real world climate risk management</li> <li>• A slightly lighter target could reduce necessary scale of BECCS and increase feasibility</li> <li>• The 2° framing could embed poor technological choices and perverse outcomes e.g. “too late now for CCS”</li> <li>• Invention of “to the rescue” wedges, having failed delivery of mitigation wedges</li> <li>• At what scale is BECCS feasible?</li> </ul>  |
|   | Carbon dioxide removal (CDR)  | <ul style="list-style-type: none"> <li>• Alternative negative emissions approaches neglected in IAMs and pathways literature</li> <li>• BECCS could be situated within a broader suite of GHG removal &amp; mitigation options</li> <li>• Other technology and non-technology options could achieve the same goal</li> </ul>   |
|   | Integrated Assessment Models  | <ul style="list-style-type: none"> <li>• BECCS is an artificial “get out of jail” card in IAMs forced into a 2°C world</li> <li>• More transparency needed in IAM assumptions about availability of BECCS with time</li> <li>• Improve model consistency and validation</li> </ul>   |
| Carbon, climate and environmental impacts | Net climate effects           | <ul style="list-style-type: none"> <li>• Indirect emissions (e.g. from land use change) are important with large scale BECCS: quantification needs improving to ensure net climate benefit</li> <li>• Can take a very long time for BECCS to become carbon neutral (payback time).</li> <li>• Monitoring / certification is required to guarantee negative emissions</li> </ul>  |
|   | Technical Issues / Assessment | <ul style="list-style-type: none"> <li>• Biomass availability and use of pristine biomass / wastes</li> <li>• Storage space validation (varies with location)</li> <li>• Technical issues around CCS element (storage availability, capture technology) do not impact materially on the <u>bio</u> elements</li> <li>• More robust / better estimates of sequestered carbon / TWh needed</li> <li>• Competing demands for biomass: availability constraints?</li> <li>• LCA equivalence and carbon impacts: across energy sector; in food production</li> <li>• Water and associated energy implications of BECCS</li> <li>• Land use changes should also be accounted for in food production</li> </ul> |

|                                       |                                   |   |
|---------------------------------------|-----------------------------------|---|
| Technology development and deployment | Rate of deployment                | <ul style="list-style-type: none"> <li>• Role of BECCS as part of a suite of mitigation options – using precedented technology diffusion rates</li> <li>• How much can BECCS ‘piggy back’ on ‘conventional’ CCS, e.g. in terms of infrastructure costs, social acceptance and storage technology learning - this has a big impact on policy decisions and feasible ramp up rates</li> <li>• Ramp up time to deploy rates of the technology and the biomass (esp. dedicated energy crops) should not be underestimated.</li> <li>• Starting from zero means deployment needs to start yesterday</li> </ul> |
|                                       | Integration of the BECCS system   | <ul style="list-style-type: none"> <li>• Lack of integration of different research areas in study of BECCS and its life cycles – also reflected in funding opportunities</li> <li>• Supply networks (location) of biomass vs. CO<sub>2</sub> storage sites - how well do these match up?</li> <li>• The development of two large and complex infrastructures / logistics systems is not straightforward and tends to be overlooked</li> </ul>   |
| Policy and socio-economic factors     | Incentivisation                   | <ul style="list-style-type: none"> <li>• Expansion of ‘carbon price’ framework to reward carbon dioxide removal (net negative) and not just a lack of emissions – this is a prerequisite for BECCS</li> <li>• This depends on accounting and verification of carbon removed for negative emissions in carbon trading</li> </ul>   |
|                                       | Institutional & policy frameworks | <ul style="list-style-type: none"> <li>• BECCS depends on large number of global, national and local policies and economic conditions to ensure benefits outweigh damage.</li> <li>• Many of these political and socio economic factors are very difficult to influence</li> <li>• Changes to the policy ecosystem and institutional framework required to realise CDR/BECCS at scale safely</li> </ul>   |
|                                       | Societal responses                | <ul style="list-style-type: none"> <li>• BECCS continues in failing to address land use issues at the heart of the dissatisfaction with bioenergy</li> <li>• Availability and social acceptance of CO<sub>2</sub> storage sites?</li> <li>• Need a constructive dialogue amongst key stakeholders on the role of BECCS in climate mitigation</li> <li>• Narrative must be developed to facilitate social acceptability and deployment at scale</li> </ul>   |

Table 5. Further key issues surrounding the use of BECCS in the mitigation of climate change.

## 4. Discussion

### 4.1 Feasibility of BECCs scenarios

The aim of the expert workshop was to explore the explicit and implicit assumptions which underpin the feasibility of BECCS scenarios used in IAMs to prevent global mean temperature exceeding 2°C by the end of the century. Following a review of the literature (Gough & Vaughan, 2015) nine assumptions (Table 2) were selected for scrutiny by 18 experts in bioenergy and CCS from academia, business, policy, and NGOs (Table 1). The workshop drew inspiration from a methodology for analysing the value-ladenness of assumptions based on a pedigree matrix (Kloprogge et al., 2011; van der Sluijs et al., 2005). A notable amendment to the methodology is that we did not focus on one ‘calculation chain’ or one future scenarios of BECCS, instead experts were presented with information from a number of sources (Section 1.1) and were asked to consider BECCS scenarios, that do not exceed 2°C by the end of the century, in general. During the workshop one group chose to consider an additional assumption, taking the total to ten.

The ten assumptions were evaluated for their influence on results and against four pedigree criteria, comprised of agreement amongst peers, availability of data, plausibility and expediency. Of the ten, seven were considered to have high influence on results but a low pedigree (Figure 1). This indicates key areas of uncertainty lie in global scale bioenergy resource potential (land availability and future yields) and future energy mix (proportion of bioenergy); overarching policy and social acceptability of large scale BECCS and its constituent parts; and uncertainty as to the magnitude of net negative emissions of a full BECCS system. The three remaining assumptions all related to more technical aspects of CCS; maximums storage, capture rate and technology uptake although the policy framework to enable technology uptake was highlighted as a concern.

Building on the conclusions relating to specific assumptions described above, certain key concerns cut across a number of assumptions and help to build up a better picture of the challenges associated with the way in which BECCS is represented in lower concentration pathways in IAMs. These are summarised below:

- The **scale** at which BECCS is assumed to be deployed in the models is extremely ambitious; assumptions representing a more modest realisation of BECCS might be more realistic and consequently better represent BECCS as a feasible climate change mitigation option. (Sections 3.1.2, 3.1.3, 3.1.9 & 3.2).
- The **timescale** at which BECCS is assumed to be deployed **at very large scale** is equally optimistic in the models. Assumptions about the rate of deployment, which should be based on precedent technology uptake rates, depend on the rate at which storage can be identified and utilised and at which infrastructure, governance and policy frameworks can be put in place; furthermore it will affect the cost of deployment and may influence social acceptance and the societal responses. (Sections 3.1.6, 3.1.9, 3.1.10 & 3.2).
- To some extent the issues of scale and timing are a product of **constraining IAMs to a 2° target**. Given the dwindling carbon budget, the models depend on negative emission technologies to achieve atmospheric CO<sub>2</sub> concentrations compatible with the target. (Sections 3.1.2, 3.1.4 & 3.2).
- This potential to deliver negative emissions changes the status of BECCS relative to other mitigation technologies – additional checks are necessary to **ensure genuine**

**net negativity** and that the net effect of its deployment is a reduced atmospheric CO<sub>2</sub> concentration. The corollary to this is that BECCS may be subject to higher levels of scrutiny across its life cycle than other approaches – suggesting that other approaches should be equally thoroughly accounted. (Sections 3.1.8, 3.1.11 & 3.2).

- Embedded in figures for global net negative emission is a rich and diverse **spatial and regional heterogeneity** which is represented to different levels between and within models and applies across many assumptions including storage availability, crop yields, political and social context, policy frameworks that must work globally and locally. (Sections 3.1.3, 3.1.5, 3.1.9, 3.1.10).
- The **influence of future climate change** could be significant and impact on many elements of the BECCS chain, including the production of biomass and social acceptability. (Sections 3.1.2 & 3.1.10).
- The **complexity** of systems involved in BECCS approaches should not be underestimated and is characteristic across the component systems and integrating between technologies, between different actor networks and supply chains. (Sections 3.1.2 & 3.2).
- The urgency suggested by the modelled assumptions for BECCS deployment is not currently being translated into action. There remains a **gap between modelled or theoretical perspectives and real world experience** of building and demonstrating the BECCS process as a whole and across the supply chain. (Sections 3.1.6, 3.1.9, 3.1.10 & 3.2).
- There is a widespread assumption that BECCS will be driven by carbon markets or other fiscal incentives but other equally important **governance and policy structures** are implicitly assumed in models and without which a carbon market alone will not be sufficient. (Sections 3.1.6, 3.1.9 & 3.2).

## 4.2 Limitations and further work

This report presents results from a modestly funded study initiated to unpack the assumptions made in relation to BECCS deployment as modelled in IAMs. The results should be seen as a first attempt to explore how estimates for the contribution of BECCS climate change mitigation are represented in models as well as to expose some of the deeper issues associated with the use of BECCS to deliver global net negative emissions, aiming to flag up some of the critical assumptions and concerns. However, certain caveats should be borne in mind when considering the results and conclusions presented in this report:

- Without access to original data and detailed analysis of the models it has not been possible to scrutinise or quantify specific assumptions in all cases. This would require a much more ambitious study that enabled at the very least direct discussion with key individuals from the IAM teams but preferably research secondment to IAM host institutions
- Given this, and the time and resource limitations, we have not carried out an analysis of a full calculation chain as recommended by the uncertainty evaluation methodology
- The expert elicitation process has been significantly contracted compared to the established method associated with devising a pedigree matrix. We are confident that the reduced process which we have adopted nevertheless provides valuable insights

but it should be clear that the results do not substitute a thorough pedigree matrix analysis

- The results presented reflect the views and opinions of a particular group of expert individuals; an extended study bringing in additional expertise and representatives from different institutions would add further robustness to the results
- Areas of expertise that were under-represented in the workshop include biologists or agronomists working in the bioenergy field, experts in the field of international governance and policy frameworks, *inter alia*.
- Finally, the diverse nature of the assumptions discussed in this report, and consequently the varying potential to improve their representation in IAMs should be noted. While some of the more technical parameters, such as storage availability, crop yields etc, are susceptible to improvement in such a way that uncertainty in model outputs could be reduced, others, such as social acceptability, global land use and policy interventions are much more wide-ranging, interdependent and inherently uncertain. It is thus particularly important that these more difficult to characterise uncertainties are not ignored, improving our understanding of these assumptions is critical to our understanding of any potential for benefiting from a BECCS system.

## 5. Conclusions

Even with sizeable reductions in current rates of emissions, there remains a large possibility of exceeding the total global carbon budget associated with 2°C of warming above pre-industrial levels. In order to resolve this, integrated assessment models that construct future emission scenarios have had to include the capacity to remove carbon dioxide from the atmosphere. The least expensive way to achieve this carbon reduction is likely to be by using BECCS (other CDR methods do not generate electricity). Over one hundred of the 116 IPCC WG3 scenarios that do not exceed 2°C assume BECCS deployment (Fuss et al., 2015). This was a key issue identified by our participants and is captured by the following remarks “A lot of modelling relies heavily on BECCS as the silver bullet” and “BECCS is the least expensive fantasy technology”, implying that introducing negative emissions to IAMs is critical to ‘solving’ the cumulative emission constraints and that of the potential negative emissions technologies, BECCS appears to be the most advanced or cost effective.

A feature of this use of BECCS is the *scale* of negative emissions required, for example RCP2.6 has BECCS starting in 2020 and an analysis of the IPCC WG3 scenarios (based on reported primary energy outputs) found a median emissions removal of 166 GtC by 2100 (van Vuuren et al., 2011; Wiltshire et al., 2015). The implied scale at which BECCS is deployed in these scenarios presents a key challenge to the credibility of the assumptions that underpin this for both the required biomass energy, e.g. global resource potential, and CCS, e.g. storage access rate, infrastructure deployment rate.

A crucial premise therefore to the use of BECCS is the delivery of a net removal of carbon dioxide from the atmosphere. There is uncertainty over the quantification of negative emissions from a full BECCS system with particular uncertainty arising from the biomass energy component. For example, variation in biomass type and location, which have strong socio-economic drivers, can lead to different carbon emissions from direct and indirect land use change. When considering BECCS at the scale implied in future scenarios, uncertainty in



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the realisation of negative emissions is important to achieving global net negative emissions, i.e. for BECCS to compensate residual fossil fuel emissions and deliver the reductions in atmospheric CO<sub>2</sub> concentrations modelled.

The implementation of BECCS at scale in future scenarios relies on significant policy and governance assumptions. As one participant expressed it “policy is a prerequisite (to scaling up BECCS)”. There is a path dependency of BECCS on the existence of a CCS infrastructure, which is not currently in place and will not be deployed without incentivisation. In the absence of a policy framework, e.g. carbon price/incentive, BECCS is unlikely to occur. Beyond policy, ensuring the delivery of the assumed magnitude of negative emissions requires strong governance that spans multiple industries and regions.

In conclusion, the four critical issues aligned with the feasibility of BECCS scenarios that do not exceed 2°C above pre-industrial by 2100 are;

1. the use of BECCS is driven by the need to stay within cumulative carbon budgets consistent with a 2°C target;
2. the scale of BECCS implied in most scenarios;
3. uncertainty as to the magnitude of carbon dioxide removal achieved by BECCS and;
4. the critical dependence on policy and governance assumptions.

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