

Expert assessment concludes negative emissions scenarios may not deliver

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Many integrated assessment models (IAMs) rely on the availability and extensive use of biomass energy with carbon capture and storage (BECCS) to deliver emissions scenarios consistent with limiting climate change to below 2 °C average temperature rise. BECCS has the potential to remove carbon dioxide (CO₂) from the atmosphere, delivering ‘negative emissions’. The deployment of BECCS at the scale assumed in IAM scenarios is highly uncertain: biomass energy is commonly used but not at such a scale, and CCS technologies have been demonstrated but not commercially established. Here we present the results of an expert elicitation process that explores the explicit and implicit assumptions underpinning the feasibility of BECCS in IAM scenarios. Our results show that the assumptions are considered realistic regarding technical aspects of CCS but unrealistic regarding the extent of bioenergy deployment, and development of adequate societal support and governance structures for BECCS. The results highlight concerns about the assumed magnitude of carbon dioxide removal achieved across a full BECCS supply chain, with the greatest uncertainty in bioenergy production. Unrealistically optimistic assumptions regarding the future availability of BECCS in IAM scenarios could lead to the overshoot of critical warming limits and have significant impacts on near-term mitigation options.

Introduction

With the long term trend of rising global CO₂ emissions (Le Quéré *et al* 2015), BECCS increasingly features in future IAM scenarios (Fuss *et al* 2014). In the context of integrated assessment modelling, BECCS enables mitigation costs to be reduced; more ambitious targets to become feasible (Rogelj *et al* 2015); or a delay in the year of peak emissions and overspending of the cumulative carbon budget in the near term (‘buying time’) (van Vuuren *et al* 2007). In light of Article 2 of the UNFCCC Paris Agreement which aims to ‘Hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels’ (United Nations 2015), closer scrutiny of the feasibility of BECCS becomes increasingly pertinent (Anderson 2015a). BECCS achieves negative emissions

if the CO₂ produced during combustion of biomass energy is captured and stored indefinitely in geological formations, since CO₂ is absorbed from the atmosphere during the growth cycle of biomass feedstocks (Obersteiner *et al* 2001, Kemper 2015, Smith *et al* 2015a). BECCS is used in 101 of the 116 (86%) IPCC Fifth Assessment Report (AR5) scenarios associated with limiting climate change to below 2 °C (Fuss *et al* 2014). Although BECCS is the most widely used in the IAMs, other approaches for removing carbon dioxide have been proposed, including afforestation which is also represented in IAM scenarios (Vaughan and Lenton 2011, Fuss *et al* 2014). The majority of the scenarios assume BECCS is deployed from 2020 onwards, with the rate of CO₂ removal in 2050 ranging from 2 to 10 GtCO₂ yr⁻¹, reaching global net negative emissions by 2070 at a maximum rate of 20 GtCO₂ yr⁻¹ (equivalent to half of present day fossil fuel emissions)

(*ibid*). Wiltshire *et al* (2015) found a median value of around 166 GtC cumulatively removed (13.5 GtCO₂/yr) by 2100 using BECCS in the IPCC scenarios associated with limiting climate change to below 2 °C. The feasibility of this dependence on BECCS must be considered in the context of the interconnected and interdependent issues of food production and energy provision for a growing population and their attendant environmental impacts. The use of significant amounts of both biomass energy and CCS feature across IPCC mitigation scenarios (Clarke *et al* 2014) and we note that the issues associated with the large scale supply of biomass energy are not dependent on its deployment as part of a BECCS system and, indeed, are not solely restricted to 2 °C scenarios.

Here we seek to open up the feasibility debate by unpacking some of the issues that govern the potential role of BECCS in climate change mitigation. We utilise an expert elicitation method designed to investigate the quality of IAM assumptions in a systematic and structured way (de Jong *et al* 2012). The assumptions assessed here were drawn from the literature where they are either explicitly described, referred to but not quantified, or implicit. Improving the transparency of assumptions would support the ability of model users and wider policy and academic communities to better understand and respond to conclusions drawn from model outputs (Smith *et al* 2015b), in terms of both establishing their role in defining the policy landscape and improving the credibility of model results (Saltelli and Funtowicz 2014).

Methods

We have adopted a heuristic approach designed to unpack and characterise the value-ladenness of certain key assumptions, drawing on the principle that assumptions can be characterised in relation to their influence on model results and their pedigree according to certain quality criteria (de Jong *et al* 2012). The methodology was conducted in two stages: (i) a literature review to identify key assumptions (Gough and Vaughan 2015) followed by (ii) an expert elicitation exercise designed to explore the underlying quality of the assumptions in question in a systematic and structured way. The expert elicitation process brought together experts from academia, business, policy, and NGOs to share knowledge and understanding in a way that can benefit from published and unpublished wisdom of those experts (Knol *et al* 2010). The one day workshop involved 18 experts with relevant knowledge in areas including CCS, bioenergy, policy, climate, earth systems, and modelling (supplementary data table 2). All but one of the experts represented UK institutions, the exception being an academic from the Netherlands. While recognising that the small number of participants drawn from a narrow geographical area introduces a

certain bias to the results, the diversity of expertise and knowledge that the participants bring to this qualitative assessment is nevertheless considered to provide a useful assessment of uncertainty as a complement to more formal quantitative approaches to uncertainty analysis. Furthermore, this number of participants is at the upper end of workshop sizes in previous applications of the methodology (van der Sluijs *et al* 2005, de Jong *et al* 2012).

Nine key assumptions (table 1) were selected by the authors from 20 identified in the literature review (supplementary data table 1) (Gough and Vaughan 2015); 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 CO₂ removal) or the feasibility of establishing BECCS at the assumed scales. Experts were split into three groups according to expertise and evaluated assumptions related to: bioenergy including (1) available land area, (2) future yield, and (3) proportion of energy; CCS including (4) storage capacity, (5) technology uptake, and (6) capture rate; cross-cutting issues including (7) policy framework, (8) social acceptability, and (9) net negative emissions (table 1). Although the present analysis is explicitly interested in how these assumptions come together in the way that BECCS is represented in IAMs, note that the assumptions identified in the bioenergy and CCS groups are not specific to BECCS applications *per se*, but are equally relevant when considering how those technologies are modelled as separate technologies. Groups were given the opportunity to suggest additional assumptions, the CCS group chose to score (10) 'How negative is BECCS?' (table 1); thus ten assumptions were scored in total.

Experts individually scored each assumption allocated to their group against five criteria, these were: influence on results, agreement amongst peers, availability of data or information, plausibility, expediency (table 2). These criteria were selected by the authors as being the most appropriate for the analysis and were chosen to describe different types of uncertainty (Kloprogge *et al* 2011). Criteria were scored between 0 (very low) and 4 (high level of confidence) with guidance on how the scores should be interpreted with respect to each of the criteria. The number of participants scoring any one assumption ranged from 4 to 6 depending on group size and non-completion of score cards. A final session was designed to allow a more open discussion on the issues relating to the deployment of BECCS (see supplementary data).

Results and discussion

The assumption scores can be mapped onto a pedigree matrix, plotting mean pedigree scores against 'influence on results' (van der Sluijs *et al* 2005) (figure 1). A nominal mean was calculated for the ordinal data

Table 1. Assumptions scored and deliberated by experts.

Group	No.	Assumption	Description
Bioenergy	1	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.
	2	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.
	3	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	4	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.
	5	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.
	6	Capture rate (%)	How much carbon in the fuel does the capture process remove for storage?
	10	How negative is BECCS? (group defined)	How negative is BECCS? Assumption proposed independently by this group, aimed at getting to the heart of the basic premise behind the use of BECCS to deliver negative emissions.
Cross-cutting	7	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?
	8	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).
	9	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. Criteria used for pedigree scoring.

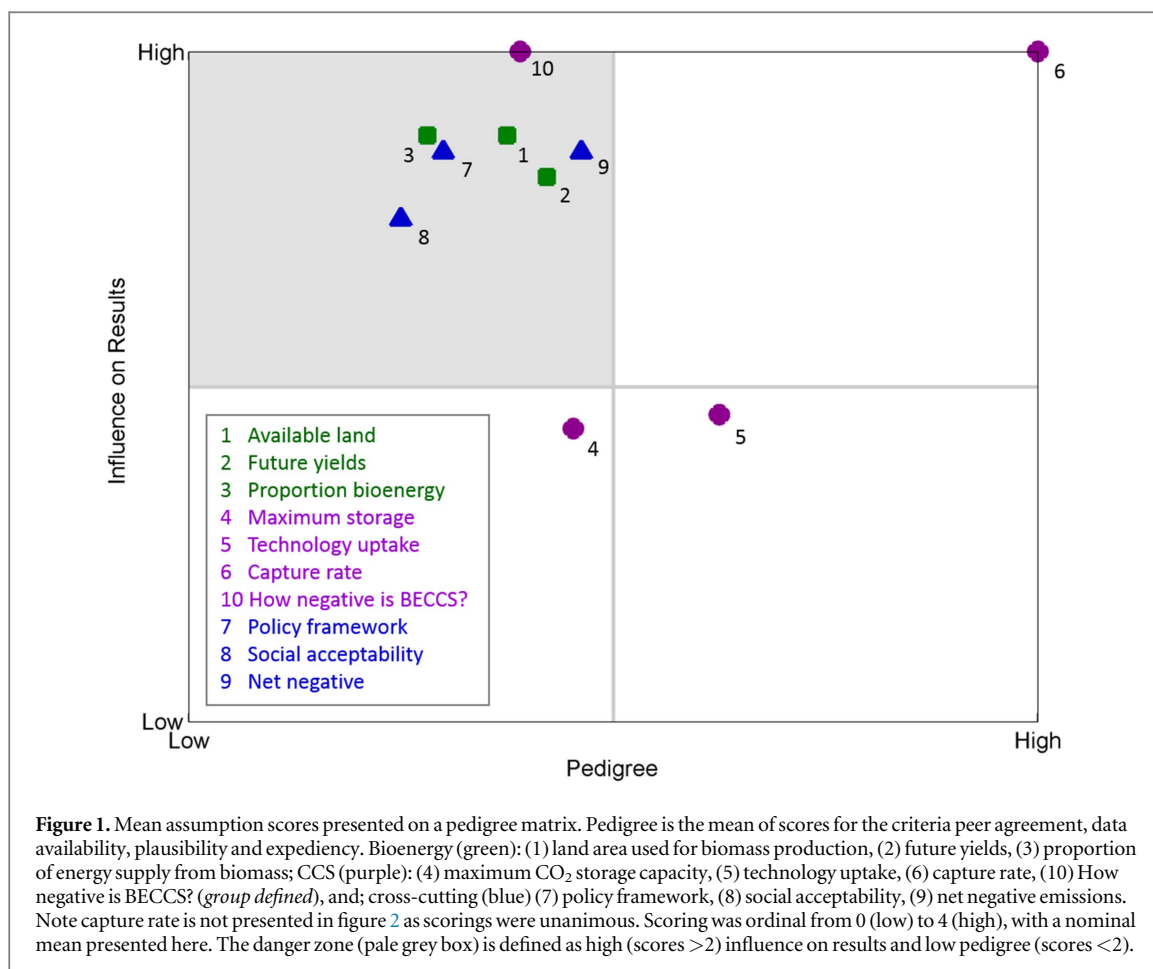
Criterion	Low score	0	1	2	3	4	High score
Influence on results	Limited influence	—————▶					Highly influential
Agreement amongst peers	Very little consensus	—————▶					High level of consensus
Availability of data/information	Very little data available	—————▶					Plenty of data available
Plausibility	First order estimate (speculative)	—————▶					Assumption based on strong evidence
Expediency	Assumption malleable to context or purpose	—————▶					Assumption robust to context

(Klopprogge *et al* 2011). Detailed breakdown of the scoring of criteria are presented in figure 2. Figures 1 and 2 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’) (figure 1). We use the results of the scoring (figures 1 and 2) and the associated deliberation to summarise concerns that emerged, supported by additional evidence from the wider literature.

Seven of the ten assumptions fall within a ‘danger zone’, with a high influence on results but low pedigree, including all the bioenergy and cross-cutting assumptions (figure 1). Figure 2 presents individual

scores for assumptions on radar plots, in which lines on the plot represent individuals’ scores against each criterion; plots show variation in the scoring by individual experts.

The experts considered all three of the bioenergy assumptions to be strongly interconnected and influenced by uncertain impacts such as future socio-economic trends and the effects of climate change on systems, such as food production, water resources, biodiversity, and land use change (van Vuuren *et al* 2009, Bonsch *et al* 2014, Slade *et al* 2014). Land availability is highly interdependent upon future crop yields and focuses on the fraction (usually up to half) of bioenergy produced by dedicated energy crops; the remaining bioenergy is assumed to come from forestry

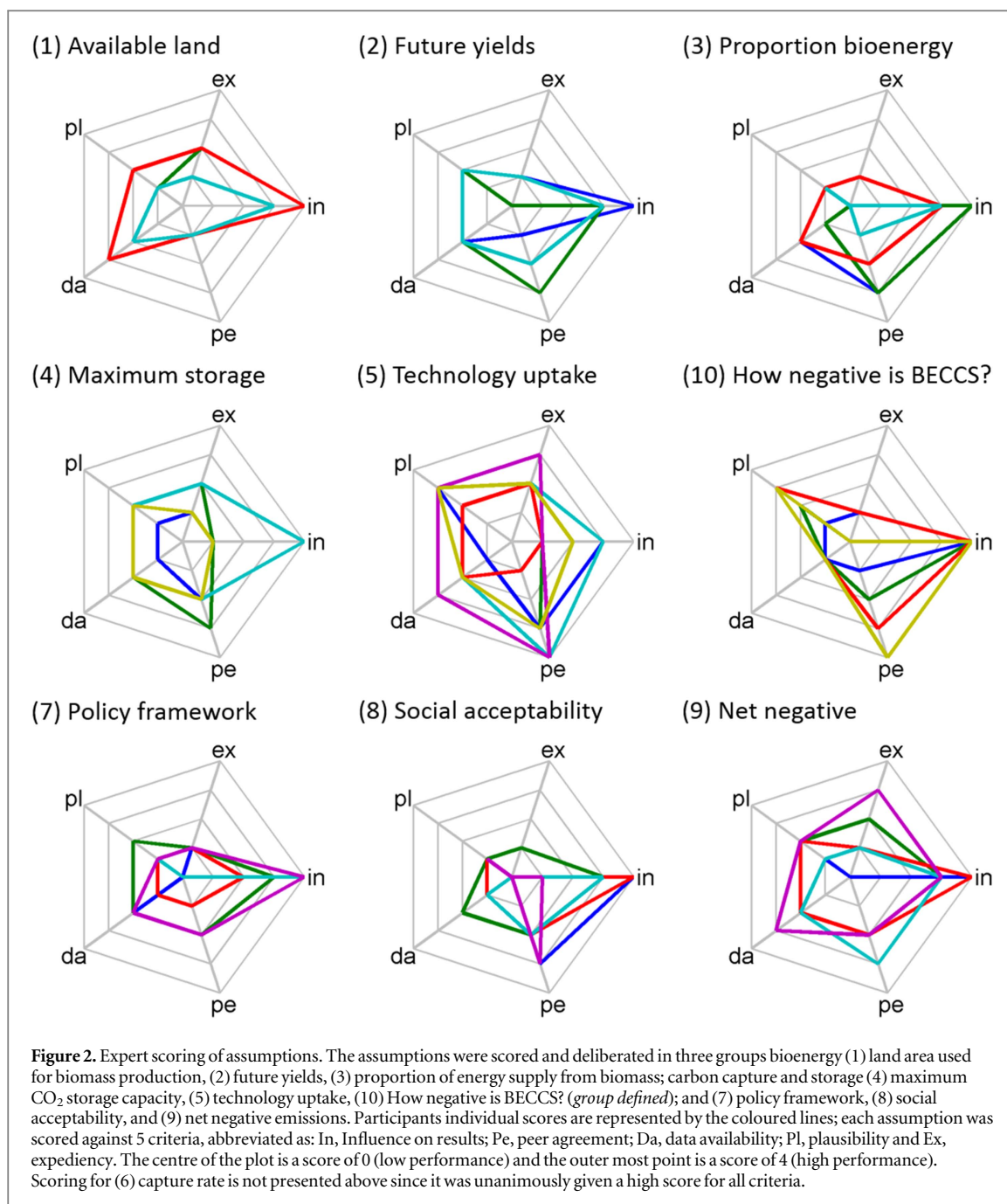


and waste residues (Azar *et al* 2013, van Vuuren *et al* 2013). The experts also noted novel approaches, such as bioengineering and/or algal sources could have a significant impact (Walsh *et al* 2015). The proportion of total energy supply provided by bioenergy scored low for expediency (being malleable to context) and plausibility in particular (figure 2(3)), with concerns expressed about scale up timescales and the prospects for adequate policy measures to enable it. It is worth noting that, as with the CCS assumptions, concerns relating to the bioenergy assumptions apply regardless of whether or not the assumed levels of biomass are destined to be used as part of a BECCS system to deliver negative emissions.

The results imply that the CCS components of the BECCS scenarios are better constrained (figure 1) and that there are presumed to be no significant technical barriers to delivering CCS, although the geographical heterogeneity of the quality of storage data on a global scale was noted (IPCC 2005); individual scores for these assumptions are shown in figures 2(4) and (5). Experts considered that technology uptake, which should be based on precedented technology uptake rates, depend instead on the rate at which storage can be identified and utilised and at which infrastructure, governance and policy frameworks can be put in place. Experts suggested that the speed of adoption will affect the cost of deployment and may influence social

acceptance and assumptions about societal responses. The workshop highlighted that challenges to CCS delivery at large scale remain around social acceptability and policy frameworks, as reflected by the poorer performance of these assumptions across the criteria (figures 1(7) and (8)). BECCS is predicated on the existence of a CCS infrastructure, which is in turn dependent on policy and institutional support, which are by no means assured (Scott *et al* 2013, Lomax *et al* 2015) and are much more challenging to parameterise than the technical aspects of establishing the technology.

The experts considered policy framework assumptions, such as fiscal carbon incentives, to be influential on the results (figure 2(7)), highlighting concerns about uncertainties due to effectiveness of markets, complexity of interactions with land use policy and feedbacks on land availability, and support for CCS infrastructure and technology transfer. IAM scenarios typically assume robust policy frameworks deliver global participation and collaboration in climate mitigation actions (van Vuuren and Riahi 2011). Experts within the cross-cutting group identified concerns over social tolerance for bioenergy, especially at such a large scale and given its interconnected pressures on food production and water availability, and localised social tolerance concerns relating to CCS storage sites (L'Orange Seigo *et al* 2014, Halder *et al* 2015, Radics



et al 2015); these concerns for social acceptability across the BECCS system are reflected in low scores shown in figure 2(8).

In both sub- and whole group discussions, experts questioned the assumed amount of negative emissions a BECCS system would deliver when considering the whole lifecycle impact. They judged the main sources of uncertainty to lie within the bioenergy contribution to net negative emissions, including direct and indirect land use change effects on carbon, nutrients and water, and robust regulatory frameworks to ensure best practice (Tilman *et al* 2009). Given the dependence on BECCS in IAM scenarios to remove large amounts of CO₂ from the atmosphere (Fuss *et al* 2014), it was stressed that there is a requirement for close

monitoring and robust regulatory frameworks to ensure the BECCS supply chain is genuinely net negative across its whole lifecycle. In the whole group discussions, the scale and timescale at which BECCS is assumed to be deployed in the models was seen by the experts as being extremely ambitious and, to a great extent, a product of working within the constraints of a 2 °C target.

Other factors noted during the workshop were the diverse spatial and regional heterogeneity embedded within the assumptions underpinning global net negative emissions, including land use policy, political economies, and networks of multiple actors. Furthermore, the influence of future climate change on the potential for negative emissions could be significant

and impact on many elements of the BECCS supply chain, with the potential for this situation to be exacerbated if temperature rises are greater than anticipated, i.e. a high climate sensitivity. The workshop revealed that the complexity of systems involved in BECCS approaches should not be underestimated and are characteristic across both the component systems (bioenergy and CCS) as well as the integration of technologies and their different actor networks and supply chains. Representing a more modest realisation of BECCS might be more realistic and consequently better represent BECCS as a feasible climate change mitigation option.

Conclusion

Overall, our results suggest that IAM scenarios use unrealistic assumptions regarding the extent of bioenergy deployment that is possible and unrealistic assumptions about the development of adequate societal support structures (e.g. cohesive policy frameworks and societal acceptability) needed to enable large-scale negative emissions. In contrast, the technology assumptions for CCS were judged to be realistic, suggesting that CCS assumptions do not confront its physical or technical limits in the same way as those for the use of biomass do. The risk that bioenergy production offsets some of the total negative emissions potential of the BECCS system through direct and indirect land use change emerged as a key concern. While these concerns equally apply to modelled emission reductions from biomass energy use alone, an issue here is whether that would compromise the net negativity assumed within a BECCS system. Without robust regulatory frameworks to guard against this risk, the scale of removal of carbon dioxide achieved through BECCS in future scenarios may be significantly overestimated. The majority of our experts viewed the use of negative emissions in IAM scenarios as driven by the constraint to stay within cumulative carbon budgets consistent with a 2 °C target. The implication of an unrealistically ambitious reliance on BECCS in scenarios is that an overspend of the cumulative carbon budgets in the near term will result in the failure to limit temperature rise to below 2 °C, should the realisation of BECCS at the assumed scale not be achieved.

Policy discourses typically assume that BECCS will be driven by carbon markets or other fiscal incentives, but other equally important governance and policy structures, such as binding global emission reduction agreements, and accounting and monitoring frameworks are implicitly assumed in models. Given these challenges, combined with a current lack of progress in commercial rollout of CCS technologies and limited experience of implementing full chain BECCS systems, it is apparent that the necessary requirements for embarking on a negative emissions

pathway are not in place. Although some IAM runs do present scenarios compatible with 2 °C without BECCS (e.g. Luderer *et al* 2013), the modelling widely suggests that keeping climate change well below two degrees may not be feasible without BECCS, even with ambitious emission reductions in all sectors (Rogelj *et al* 2013, van Vuuren *et al* 2013, Krey *et al* 2014, Anderson 2015b).

One of the primary purposes of this paper was to open up the debate to deliver a better understanding of the relationship between assumptions relating to BECCS and the feasibility of reaching the 2 °C target. While acknowledging that there will always be limitations to the accuracy of large integrated models such as IAMs, the critical nature of how negative emissions from BECCS technologies is represented and the inherent uncertainties identified here warrant further attention. The ultimate aim is thus to not only improve the representation of BECCS within the models but also to clarify the basis of evidence underpinning the policy discourse relating to two degrees. Here we have identified assumptions located within a 'danger zone'; future work would seek to improve their pedigree and further unpack the boundaries and feasibilities of these aspects of BECCS. This could be achieved by parallel approaches of detailed sensitivity analyses to formally identify critical constraints which drive the model results, alongside a thorough socio-techno-economic analysis of BECCS supply chains, including an exploration of possible regulatory and governance frameworks that accommodate the complexities and challenges of negative emissions and in particular BECCS. So while our research shows that there are clearly questions relating to the potential for BECCS to deliver global net negative emissions, there is also a strong imperative to better understand the conditions for and consequences of pursuing the technology.

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