



# Mapping feasibilities of greenhouse gas removal: Key issues, gaps and opening up assessments

Johanna Forster<sup>a,c,\*</sup>, Naomi E. Vaughan<sup>b,c</sup>, Clair Gough<sup>d</sup>, Irene Lorenzoni<sup>b,c</sup>, Jason Chilvers<sup>b</sup>

<sup>a</sup> School of International Development, University of East Anglia, Norwich, NR4 7TJ, UK

<sup>b</sup> School of Environmental Sciences, University of East Anglia, Norwich, UK

<sup>c</sup> Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK

<sup>d</sup> Tyndall Centre for Climate Change Research, University of Manchester, Manchester, UK

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## ABSTRACT

Greenhouse gas removal technologies and practices are essential to bring emissions to net zero and limit global warming to 1.5 °C. To achieve this, the majority of integrated assessment models (IAMs), that generate future emissions scenarios and inform the international policy process, use large-scale afforestation and biomass energy with carbon capture and storage (BECCS). The feasibility of these technologies and practices has only so far been considered from a relatively narrow techno-economic or biophysical perspective. Here, we present one of the first studies to elicit perspectives through an expert mapping process to open up and broaden the discussion around feasibility of afforestation and BECCS. Our stakeholders included business and industry, non-governmental organisations and policy makers, spanning expertise in bioenergy, forestry, CCS and climate change. Perspectives were elicited on (1) issues relating to BECCS with large-scale afforestation, and (2) specific criteria for assessing feasibility. Participants identified 12 main themes with 61 sub-themes around issues, and 11 main themes with 33 sub-themes around feasibility criteria. Our findings show important societal and governance aspects of feasibility that are currently under-represented, specifically issues around real-world complexity, competing human needs, justice and ethics. Unique to the use of these technologies for greenhouse gas removal are issues around temporal and spatial scale, and greenhouse gas accounting. Using these expert insights, we highlight where IAMs currently poorly capture these concerns. These broader, often more qualitative perspectives, issues and uncertainties must be recognised and accounted for, in order to understand the real-world feasibility of large-scale afforestation and BECCS and the role they play in limiting climate change. These considerations enable widening the scope to broader and deeper discussions about possible and desirable futures, beyond a focus on achieving net-zero emissions, attentive to the effects such decisions may have. We outline approaches that can be used to attend to the complex social and political dimensions that IAMs do not render. By complementing IAMs in this way opportunities can be created to open up considerations of future options and alternatives beyond those framings proposed by IAMs, creating opportunities for inclusion of knowledges, reflexivity and responsibility.

## 1. Introduction

The Paris Agreement aims to limit the rise in global mean temperatures to ‘well below 2 °C’ above pre-industrial values and to pursue efforts to limit the warming to 1.5 °C above pre-industrial (UNFCCC, 2015). Present day global mean surface temperatures are 1 °C above pre-industrial (Allen et al., 2018). Meeting these aspirations requires rapid decarbonisation of the energy system, and to bring emissions to net zero, requires deployment of greenhouse gas removal (GGR) technologies and practices. Current scenarios focus on

afforestation/reforestation (AR) and biomass energy with carbon capture and storage (BECCS) (Clarke et al., 2014; Rogelj et al., 2018). It is important to recognise the constructed nature of IAMs and their outputs, for example alternative GGR methods could have a role and/or a much broader range of conceivable futures are possible than those prescribed by IAMs. Despite their central place in future emission scenarios most GGR technologies are in the early stages of development and have not yet been demonstrated at large-scale. Considerable uncertainty and speculation exists over the efficacy of these approaches in tackling climate change as well as their possible future implications for

\* Corresponding author at: School of International Development, University of East Anglia, Norwich, NR4 7TJ, UK.  
E-mail address: [j.forster@uea.ac.uk](mailto:j.forster@uea.ac.uk) (J. Forster).

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environment and society (Anderson and Peters, 2016).

Most existing anticipatory assessments of GGR focus on relatively narrow techno-economic or biophysical dimensions of feasibility (e.g., EASAC, 2018; Smith et al., 2016). Yet, experience has repeatedly shown that attempts to introduce emerging technologies in contexts of climate change and beyond are never governed by technical issues alone but are always shaped by and effect a range of social, political, cultural and ethical dimensions (Jasanoff, 2003; Kearnes et al., 2006; Stilgoe et al., 2013; Macnaghten and Chilvers, 2014; Bellamy and Healey, 2018). In order to understand the potential and limits of emerging technologies like GGR in general, and AR and BECCS in particular, it is crucial to open up widespread deliberation and anticipation of the future worlds they will bring forward socially and politically, not only in physical and techno-economic terms. As earlier work on climate geoengineering has shown, such upstream engagement is crucial to the responsible development of emerging technologies, not only through including wider publics (Macnaghten and Szerszynski, 2013) but also expert and stakeholder communities as well (Bellamy et al., 2013).

There is an extensive literature exploring both CCS and biomass energy technologies from the perspectives of both lay publics and wider stakeholders but very little relating to the use of biomass energy with CCS (Dowd et al., 2015; Feldpausch-Parker et al., 2015). Literature specifically describing expert assessments of CCS is sparse (see for example, Gough, 2008; Evar, 2011; Sala and Oltra, 2011; Shackley et al., 2007; Bellamy and Healey, 2018) particularly in recent years; similar research on bioenergy has focused on biofuels (Ribeiro and Quintanilla (2015); Upham and Dendler (2015); Röder, 2016). While there is literature available which reflects the importance of specific contexts on the social implications of afforestation (see for example, Shiva et al., 1985; Lin et al., 2012; Marey-Pérez and Rodríguez-Vicente, 2009) the primary focus of the existing literature on afforestation for greenhouse gas removal is the biophysical efficacy of the approach.

Minx et al. (2017) reports on the accelerating pace of research into GGR, featuring both BECCS and afforestation; and the recent publication of the IPCC special report on 1.5 °C presents the current state of knowledge in this field (IPCC, 2018). With a lack of actual or proposed BECCS projects, much of the social science research on the technology has focused around more abstract issues such as the ethical aspects (e.g., Burns and Nicholson, 2017; Gough et al., 2018a; Lenzi, 2018; Mabon and Shackley, 2015), sustainability (e.g., Fajardy and MacDowell, 2017), technology upscaling (Buck, 2016; Gregory et al., 2018), and a growing literature exploring the political and governance challenges (e.g., Gough et al., 2018b; Meadowcroft, 2013; Gamborg et al., 2014; Bellamy and Healey, 2018; Geden et al., 2018; Honegger and Reiner, 2018; Thornley and Mohr, 2018; Torvanger, 2019).

With specific reference to BECCS, Vaughan and Gough (2016) present an expert elicitation process to assess the quality of assumptions relating to BECCS within integrated assessment models (IAMs). Assessing the pedigree (based on expert assessment of the combined score of each assumption against four pedigree criteria: agreement amongst peers; availability of data; plausibility; expediency), this study identified generally poor pedigree but high influence on model results of assumptions relating to both biomass energy and cross-cutting issues (such as policy frameworks and social acceptability) (ibid). A recent survey of UN climate conference delegates revealed a large variation in perspectives about the potential for and prioritisation of BECCS technologies according to actor type and region, reporting the most important constraints to be socio-political (lack of policy incentives and social acceptance) (Fridahl and Lehtveer, 2018; Fridahl, 2017). Dooley and Gupta (2017) discuss the role of expert knowledge in the context of accounting for land-based mitigation, emphasising the importance of political, socioeconomic and equity aspects, which go beyond the typically technical focus, given the importance of developing nations in this context. More recently, several studies use interviews and surveys

to elicit perspectives amongst the IAM and other expert communities, in order to open up assessment processes and address the issue of feasibility of negative emissions technologies (NETS) such as BECCS (Haikola et al., 2019; Rickels et al., 2019; Low and Schäfer, 2020). By mapping experts' views and perspectives, Haikola et al. (2019) and Low and Schäfer (2020) highlight concerns relating to differing and competing judgements of BECCS feasibility, within the IAM community and wider disciplinary and policy experts; while Rickels et al. (2019) is more tightly focused on the biophysical and techno-economic feasibility constraints associated with these technologies (including BECCS).

Thus, whether the focus is on CCS, biomass, BECCS, or land-based mitigation in general, a clear message comes through the literature that many of the critical challenges and major uncertainties lie in the non-technical aspects of delivering these approaches and the importance of understanding not only the technical parameters but also the social, political and ethical feasibility.

In response, and with clear distinction from recent survey-based studies (see Haikola et al., 2019; Rickels et al., 2019; Low and Schäfer, 2020), here we use a novel elicitation process to explore the range of perceptions from experts and practitioners working across technologies and practices relevant to BECCS, forestry and broader climate change policy and governance, and non-governmental organisations in the UK. This serves to open up and expand the discussion around uncertainties associated with, and the feasibility of, BECCS and large-scale afforestation. It is critical to understand the issues and implications associated with large-scale deployment of these technologies given the key role that greenhouse gas removal may play in reaching net-zero emissions and limiting climate change. We discuss also the importance of opening up conversations about desired futures with a range of possibilities, which may include reaching next-zero emissions with BECCS and afforestation.

## 2. Methods

A one day workshop was held in July 2017 involving 19 participants across policy, non-governmental organisations (NGO), and business and industry. Participants self-stated their sector from three choices (business & industry, policy or NGO) and were allocated to one of three 'dominant expertise' groups (carbon capture and storage (CCS), bioenergy or climate change) accordingly (Table 1). In order to prioritise perspectives outside academic literature, workshop invitations preferred participants from business and industry, policy and NGO over academics. The aim was to bring together relevant expertise ranging from key elements of a variety of potential BECCS or afforestation approaches (including Miscanthus farmers, energy conversion and UK forestry practitioners) through to global climate policy, including NGOs with a strong development remit.

A variety of expert elicitation approaches were used to address the two workshop aims: (1) explore issues around large-scale afforestation and BECCS for greenhouse gas removal; and (2) explore the criteria by which the feasibility of these alternative approaches should be assessed. A further activity took place during the workshop where participants provided feedback on BECCS and afforestation supply chains used elsewhere in the project. Following a brief introduction to the research project, an explanation of the wider context (i.e., the role of greenhouse gas removal through large-scale afforestation and BECCS in low emission scenarios (i.e., Fuss et al., 2014)) and the specific aims of the workshop including the opportunity to raise questions and consider alternatives (e.g., to BECCS and afforestation, including alternative forms of mitigation), activities were designed to address the two aims respectively, as follows:

- (1) In four breakout groups, each comprising a mix of sectors and expertise, and each with a facilitator and a note-taker, participants captured on post-it notes their responses to the following question: "What are the key issues related to using large-scale afforestation and

**Table 1.**

The 19 respondents who took part in the research workshop. Their anonymous ID, self-stated sector and expertise, and the dominant sector (Business & industry = 9; Policy = 5; NGO = 5) and expertise (Bioenergy & forestry = 8; CCS = 6; Climate change = 5) categories as used in the analysis.

ID	Self-stated sector and expertise	Dominant sector	Dominant expertise
01	BECCS business modeller	Business & industry	CCS
02	BECCS techno-economics; innovation needs in bioH <sub>2</sub> , bio SNG and biopower; supply chain LCA; CO <sub>2</sub> capture technology	Business & industry	CCS
03	Land use (alternatives) GGR, bioenergy and CCS (broad but shallow)	Policy	Bioenergy & forestry
04	Environmental and social considerations	NGO	Climate change
05	Carbon capture; biomass conversion to gaseous fuels (with CCS) by gasification (SN <sub>4</sub> , hydrogen)	Business & industry	CCS
06	Biomass, whole chain producers and organization of biomass chain	Business & industry	Bioenergy & forestry
07	Manager of Forestry Commission England (FCE) Woodland Creative Programme, responsible for collating forestry scenarios for GHG projects. Climate Change Policy Lead for FCE England.	Policy	Bioenergy & forestry
08	CO <sub>2</sub> capture; CO <sub>2</sub> transport; CO <sub>2</sub> storage; biomass, marine biomass; industrial decarbonisation; Energy system	NGO	CCS
09	Previously forestry contractor; currently, environmental impacts of bioenergy and biomass production (specifically <i>miscanthus</i> ). <i>Miscanthus</i> breeding and modelling; land-use change, carbon and GHG exchange.	Business & industry	Bioenergy & forestry
10	Impacts and implications of climate change (and to some extent associated mitigation and adaptation policies) on human development, broadly with emphasis on the poorest people in 'developing' countries.	NGO	Climate change
11	Working with other NGOs at the UNFCCC on NETs – especially BECCS and afforestation, and chair the Climate Action Network International on land use, land use change and forestry.	NGO	Bioenergy & forestry
12	Sustainable energy, climate change	Policy	Climate change
13	BECCS, CCS, CO <sub>2</sub> utilization	Policy	CCS
14	Biomass feedstocks, biomass energy and biomass sustainability	Business & industry	Bioenergy & forestry
15	Research Scientist - environmental chemistry and policy issues.	NGO	Climate change
16	GGR, climate, safe and just future for humanity; innovation	Business & industry	Climate change
17	Geoengineering, GGR	Policy	CCS
18	Professional forester with 20 years' experience in global forestry. 10 years' experience in biomass sector.	Business & industry	Bioenergy & forestry
19	Tropical forest recovery and protection, carbon standards, carbon markets, community engagement and safeguards, impact measurement and reporting.	Business & industry	Bioenergy & forestry

*BECCS to remove greenhouse gases from the atmosphere?*”. Beyond this opening question participants were not constrained by facilitators over the topics to be discussed. Completed post-it notes were then read out, meanings clarified as necessary, and placed into related clusters by the group in an iterative process forming an ‘issue map’ of each group’s responses. Each note included the participant’s initials, enabling comments to be analysed by group (expertise and sector). The issue maps were fed back in plenary, with facilitators reporting key points of discussion from each group, while note-takers captured key points. This was the first session of the workshop.

(2) A second activity, undertaken in plenary, posed the following question to the participants: “*What criteria should we use to judge feasibility of large-scale afforestation and BECCS for greenhouse gas removal?*”. Participants wrote their criteria onto post-it notes individually, these were then read out, clarified as necessary and contributed to a single combined mapping of feasibility criteria ideas, clustered into similar themes by the lead facilitator. This final session was held at the end of the workshop, following a session relating to alternative supply chains. Due to the tightly focused nature of the second session on specific UK supply chains (for use elsewhere in the research project) the researchers have confidence that the information provided and associated discussions did not significantly influence responses in this session.

All materials from the day (issue maps, notes, feasibility criteria and weighting) were photographed, digitised into text and checked for accuracy by three members of the research team.

## 2.1. Data analysis

Data collected during the workshop was transcribed verbatim and coded using NVivo 11 (Q.S.R. NVivo, 2017). One researcher [JF] led the initial coding process, which was subsequently followed-up with iterative crosschecks and discussion with the four other researchers [NV, CG, IL and JC] who facilitated the workshop. This process ensured that the coding was accurate and thorough, but also unbiased by individual perception or opinion. The coding framework was developed iteratively for both research questions. For the issues mapping question (first aim), the first phase used inductive coding to identify all of the

different themes mentioned by the participants. All statements or words in the transcribed data that revealed an issue relating to BECCS with large-scale afforestation were coded (some under one theme only, other comments were coded under more than one theme), resulting in an extensive and diverse set of themes. The second coding phase used a more deductive approach, based on a review of the issues described in the BECCS and afforestation scientific literature and deliberation among the research team, to group the issues identified by the participants into a smaller group of main themes. This approach reduced the number of themes, which is an important analytical step to enable identification of patterns in perceptions across themes. However, finer level detail remains through the sub-themes grouped within each of the main themes.

For the feasibility question (second aim), analysis relied more heavily on the categorisation of themes that emerged from the workshop itself. During the workshop, the participants were asked to group their statements and comments around key feasibility criteria themes, and it was this framework the coding phase is based. While some comments were reassigned themes, or additional themes emerged during the inductive coding of the feasibility criteria data, the majority of the coding framework for this analysis remained consistent with that developed in the workshop. Similarly, to the issues mapping question, finer level detail was retained through a larger number of sub-themes embedded within each feasibility theme.

For both the issue mapping and feasibility data, an NVivo coding matrix query was used to extract the number of participants that mentioned each theme across the three dominant expertise (bioenergy & forestry, CCS, and climate change) and three sector (business & industry, NGO, and policy) categories.

This primary analysis was extended further to identify how the issues raised by our expert group are typically represented in the Integrated Assessment Models (IAMs) that generate future emissions scenarios. IAMs include many assumptions on the development of future energy systems and related processes that influence greenhouse gas emissions and, although this was not one of the explicit aims of the workshop, the authors considered that an exploration of the extent to which the issues generated by participants are included in these modelling assumptions and processes would be an interesting and useful addition to the analysis of the workshop data. Crucially for this

**Table 2.**

The 12 main issue themes and 61 sub-themes. Numbers denote the number of codes within each theme. Across all themes, the overall number of coded responses is  $n = 242$ .

Main theme	Sub-theme	Total
Technical	Forestry (8)	39
	Carbon capture storage (5)	
	System uncertainty (5)	
	Bioenergy (4)	
	Efficiency of supply chain (4)	
	Availability of feedstock (3)	
	Species composition (2)	
	Supply chains (2)	
	Forestry carbon (2)	
	Disconnect between supply chain components (2)	
	Data issues (1)	
	Technical (1)	
	Governance	
Leadership & political will (6)		
Decision making & political uncertainty (4)		
Governance (3)		
Risk & previous failed attempts (3)		
Short termism (2)		
Environmental	Lack of capacity & joined-up thinking (2)	30
	Biodiversity & ecosystem services (9)	
	Environmental (6)	
	Co-benefits (5)	
	Agriculture & food production (4)	
Land use	Responsibility & safe guards (4)	24
	Water use (2)	
	Availability & competition (10)	
	Energy v food crop (5)	
	Legislation & ownership (4)	
Economics & incentives	Land use (3)	20
	Affecting GHGs (1)	
	Long term planning (1)	
	Incentives & government support (8)	
Justice & ethics	Carbon markets & pricing (7)	17
	Comparing alternative GGR options & value for money (3)	
	Economics & incentives (2)	
Spatial scale	Justice & ethics (7)	17
	Distributional justice (6)	
	Moral hazard & mitigation deterrence (3)	
Temporal scale	Procedural justice (1)	16
	Spatial scale (8)	
	Infrastructure & input (7)	
GHG accounting	Envisioning & diversity at large scales (2)	14
	Development & infrastructure (7)	
	Temporal scale (4)	
Societal implications	Social & political (3)	12
	Permanence (2)	
	GHG accounting (7)	
Competing human needs	Carbon debt, overshoot & offsetting (3)	11
	Methodologies (2)	
	Impact on albedo effect (1)	
Real world complexity & diversity	Other GHGs (not CO <sub>2</sub> ) need accounting (1)	11
	Population & development (6)	
	Societal implications (4)	
Real world complexity & diversity	Public acceptance (2)	11
	Communities & livelihoods (4)	
	Food security (4)	
Real world complexity & diversity	Competing human needs (2)	11
	Water (1)	
	Real world complexity & diversity (8)	
Real world complexity & diversity	Modelling & systematising complexity (2)	11
	Innovations (1)	

analysis, we are considering IAMs that include modelling of land use (e.g., IMAGE (Stehfest et al., 2014), MESSAGE-GLOBIOM (Krey et al. (2016), REMIND-MAGPIE (Leimbach et al., 2010; Lotze Campen et al., 2008)) since these processes are most relevant to the assessment of BECCS and afforestation.

### 3. Results

#### 3.1. Issue mapping themes

In total, 12 main themes emerged from the issue mapping analysis with 61 sub-themes providing finer level detail, and 242 coded responses across all themes (Table 2). The main themes included three that mapped closely onto the classic ‘pillars of sustainability’ (environmental, economics & incentives, and social implications); and three that typically are discussed in the scientific literature around land use change (technical, governance and land use). Another group of themes related more specifically to general concerns around greenhouse gas removal, and bioenergy (spatial scale, temporal scale and GHG accounting). Lastly, three main themes emerged around issues of justice & ethics, competing human needs, and real-world complexity & diversity. These three collectively add greater depth to the societal issues contained within the other categories.

Between 3 and 12 sub-themes emerged within the main themes, detailed in full in Table 2. The number of sub-themes associated with each main theme potentially provides an indication of dimensionality, but also possibly a level of awareness by the participants. For example, many of the themes with a greater number of comments also tended to have more sub-themes, i.e., those relating to technical issues, governance, environmental issues and land use.

##### 3.1.1. Patterns in perceptions of issue mapping themes

Overall, participants’ perceptions highlight a shared and broad appreciation of the issues associated with large-scale afforestation and BECCS, with all of the themes mentioned by over 25%, and 10 of the 12 themes mentioned by more than 47% of participants (Table 3).

However, when the results were analysed by expertise and sector (Table 3), some differences between groups emerge. Looking first at expertise, the climate change group showed the greatest consistency in perceptions across all themes. In this group, 100% of participants mentioned issues related to the environmental and land use themes, and 80% of the group mentioned issues related to the technical, governance, justice and ethics, societal implications, and real world complexity and diversity themes. None of the themes were mentioned fewer than 40% of this group. Comparatively, the other two groups focused their responses on issues that related more closely to their expertise. For example, the CCS group had the highest percentage of participants mentioning technical issues (100%), GHG accounting, and spatial scale issues (both 67% of participants). Similarly, the bioenergy and forestry group appeared to have a stronger focus on issues that relate to their expertise, in particular the environment theme (100%). However, this group also had relatively high values for temporal scale (75%) and governance (80%).

At the sector level, differences between groups were also identified (Table 3). The business and industry group had the highest perceptions relating to governance (100%) and unsurprisingly, economics and incentives (78%). At the other end of the scale, this group had by far the lowest response rates for issues relating to human impacts (societal implications, 22%; and competing human needs, 0%). By comparison, both the NGO and policy groups had greater consistency in perceptions across all 12 themes. For the NGO group, with the exception of the GHG accounting theme (20%), all responses were greater than 40%, implying a holistic awareness of the issues surrounding this topic. The policy group also had >40% response rate for all themes, and comparatively high levels of perceptions for the GHG accounting theme (100%).

##### 3.1.2. Issue mapping sub-themes by expertise groups

Across the three expertise groups while the number of sub-themes mentioned did not differ by a particularly large margin, with 44, 39 and 34 sub-themes for the climate change, bioenergy and forestry, and CCS groups, respectively; there were notable differences in the individual

**Table 3.**

The 12 issue themes and the percentage of respondents from each expertise and sector category that mentioned each theme and the overall mean times mentioned for all respondents. The list of themes is ordered by the overall percentage scores mentioned by the respondents. The number of respondents in each expertise category is: Bioenergy & Forestry (8), CCS (6) and Climate Change (5); and in the sector category is: Business & Industry (9), Policy (5), NGO (5). Colour scale: red-orange-yellow-light green-green denotes high to low response values in 20% quintiles.

Theme	Overall %	% mentioning each theme per dominant expertise			% mentioning each theme per sector		
		Bioenergy & Forestry	CCS	Climate Change	Business & Industry	NGO	Policy
Environmental	89	100	67	100	78	100	100
Technical	79	63	100	80	78	80	80
Governance	74	88	50	80	100	60	40
Land use	68	63	50	100	67	60	80
Economics & incentives	63	63	67	60	78	40	60
Temporal scale	58	75	50	40	44	80	60
GHG accounting	47	38	67	40	33	20	100
Justice & ethics	47	38	33	80	33	80	40
Societal implications	47	50	17	80	22	60	80
Spatial scale	47	38	67	40	56	40	40
Competing human needs	37	25	33	60	0	80	60
Real world complexity & diversity	37	25	17	80	33	40	40

sub-themes mentioned. Table 4 highlights these key differences illustrated by participants' quotes, and further unpacks the detail underlying the patterns in group preferences. For example, starting with the technical theme, the CCS group in particular are comparatively more focused on the finer details associated with the supply chains. When unpacking the governance theme, while there were broad perceptions of a range of the key sub-themes (i.e., policy and regulation, leadership and political will) across the three participant groups, the sub-theme concerned with risk was not mentioned by the CCS group (but was by the other two groups). The environmental theme also presented key differences around the discussion of co-benefits (not mentioned by the climate change group), while the CCS group did not mention any sub-themes around biodiversity, ecosystem services or agricultural production affecting food security (although this may have been framed differently by these participants under the land use theme). Both the climate change and the bioenergy and forestry groups offered up many issues relating to availability and competition, legislation and ownership under the land use theme (compared to the CCS group).

Moving on to the theme of justice and ethics, the climate change group tends to be more aware of the complexities encompassed within this theme (such as issues of distributional and procedural justice, as well as moral hazards). Questions of scale—particularly around growing forests (the time it takes and the spatial scale required) were more often mentioned by the bioenergy and forestry group, while the CCS group provided the most comments around issues of infrastructure and input (physical disconnect between biomass sources and CCS storage sites as one example). While the broader theme of GHG accounting was touched on by all three participant groups to some degree, the CCS group provided the greatest number of detailed comments specifically relating to the process of GHG accounting.

Coming to the three main themes that relate to complex social and human needs, concerns from the climate change group include many of the sub-themes within these categories as they discuss overarching issues relating to food security, communities and livelihoods, as well as real world constraints and complexities. The bioenergy and forestry group also considered food security, and community issues. Notably, the CCS group did not mention issues relating to food security or

communities and livelihoods, and relatively few mentions of issues encompassing 'real world complexity'.

### 3.2. Feasibility criteria themes

In total, 11 main themes and 33 sub-themes (ranging from 2 to 6 sub-themes within each main theme, and a total of 109 coded responses in all) emerged from the feasibility criteria analysis (Table 5). These results, arose from the second activity of the workshop (a shorter session directed in plenary) and therefore elicited fewer participant comments and themes overall (approximately half the number of sub-themes (developed from less than half the number of coded responses) mentioned feasibility criteria, compared to the issues mapping analysis; see Tables 2 and 5 for comparison). Many of the themes echoed the concerns raised during the issues mapping analysis, including those relating to land use change and availability, technical infrastructural factors, environmental sustainability, governance and social acceptability. However it should be noted that the aim of this activity was to explore and unpack how participants may judge whether or not these greenhouse gas reduction technologies are *feasible* approaches (rather than the issues these approaches present) – and so while many of the themes may be similar, they are responses to two quite different questions. Nevertheless, several of the themes emerging from this analysis provided greater detail and depth to those picked up during the issues mapping. For example, feasibility criteria relating to biomass (production capacity, sustainability and supply) were more prominent here, as is the uncertainty around developing a fit-for-purpose carbon market. Finally, while the issue of co-benefits was mentioned previously, here it appeared to be unpacked in greater detail.

#### 3.2.1. Patterns in perceptions of feasibility themes

Similar to the issues mapping analysis, participants' highlight many common perceptions relating to feasibility criteria, with all of the themes mentioned by at least 28% of participants (Table 6), however due to the lower response rates overall, there is greater variance in perceptions at the group level. Furthermore, while many of the group level perceptions about feasibility criteria map quite closely to the

**Table 4.**  
Selected quotes highlighting key differences in issues perceived by expertise groups.

Main theme	Key differences		Selected quotes
	Expertise	Sub-theme	
Technical	CCS	Disconnect between supply chain components	<i>Economic disconnect and locational disconnect between biomass sources and CCS storage sites</i>
		Efficiency of supply chain	<i>Carbon debt and mobility of several supply chains to 'pay back' within a few decades/avoid overshoot</i>
Governance	B & F	Availability of feedstock	<i>Availability of large scale supply of sustainable biomass for BECCS</i>
		Forestry carbon	<i>Land availability and ability to plant: forestry economies, regulated landscapes... Afforestation positive even without BECCS</i>
Environmental	CC	Risk & previous failed attempts	<i>Failure to learn from or take action to rectify the human consequences... little hope that BECCS can be better...</i>
		Risk & previous failed attempts	<i>Public sector must be willing to take considerable risks and as a consequence accept that some projects will fail</i>
Land use	B & F	Co-benefits	<i>Impacts of wider sustainability, goals of afforestation and energy crop including co-benefits</i>
		Responsibility & safe guards	<i>What potential is there for delivery of multiple co-benefits?</i>
Justice & ethics	CC	Availability & competition	<i>Co-benefits such as improved soil fertility</i>
		Legislation & ownership	<i>Ensuring that social safeguards are properly implemented and upheld</i>
Spatial scale	B & F	Distributional ethics	<i>Preconceptions that suitable land is 'empty' or 'unused' or 'degraded' when usually it is none of these things to people and nature</i>
		Infrastructure & input	<i>How does BECCs integrate with rural development?</i>
Temporal scale	B & F	Moral hazard	<i>Impact on communities already using land (e.g., indigenous/marginalised) and land rights</i>
		Procedural justice	<i>Preconceptions that suitable land is 'empty'... implementation [impacts] people on land and ecosystems</i>
GHG accounting	CCS	Distributional ethics	<i>Avoiding re-bound effect/moral hazard</i>
		Infrastructure & input	<i>Governance and decision-making in the process: who gets to decide and why?</i>
Societal implications	B & F	Spatial scale	<i>Land availability... land ownership, social resistance, payments – who pays?</i>
		Development & infrastructure	<i>Economic and locational disconnect between biomass sources and CCS storage sites (different scales...)</i>
Complex human needs	CC	Public acceptance	<i>Availability of large scale supply of sustainable biomass for BECCS</i>
		Food security	<i>Appropriate scale to avoid any negative impacts at forest level</i>
Real world complexity & diversity	B & F	Communities & livelihoods	<i>Scalability of biomass development in UK. How fast can we put biomass energy crop in UK land?</i>
		Food security AND Communities & livelihoods	<i>Timescale to implement both in establishing forest and building projects</i>
Real world complexity & diversity	CC	Modelling & systematising complexity	<i>Valuable forests take a long time to grow</i>
		Real world complexity	<i>Lack of adequate GHG accounting schemes</i>

patterns seen in the issues mapping, this is not always the case. For example, looking first at expertise, the bioenergy and forestry group had the lowest average (34%) but most uniform response rate (all < 50%) across all themes compared to the other two expertise groups. However, this group did not mention the governance theme at all (a pattern echoed with the other groups where certain feasibility themes are not mentioned once at the group level (Table 6)). With respect to the bioenergy and forestry group, we have interpreted this as a combination of the lower response rates overall for this session (on average only mentioning four feasibility themes, compared to an average of seven and six for the CCS and climate change groups, respectively), coupled with governance having some of the lower response rates for the session discussing feasibility criteria (Table 5).

In comparison, the CCS group followed a similar pattern to their earlier responses around issues, with high feasibility criteria frequency rates associated with infrastructure and technical factors (67%), carbon budgets and mitigation (50%), and carbon markets (83%). They also had by far the lowest response rates (no mentions) regarding social acceptability and justice criteria, compared to the other two groups.

Interestingly, the climate change group produced the same percentage response rate across the technical, governance and social themes (all 75%), implying the same holistic focus to identifying feasibility criteria, as they did with the issue mapping themes. Yet, they had the lowest rates of response compared with the other groups, for the carbon budgets and mitigation (25%) and carbon market themes, with no mentions at all.

At the sector level, there were some differences between groups, but most echoed the patterns shown in the earlier analysis and none were significantly notable (Table 6). For example, the NGO and policy groups take a holistic view of the feasibility criteria, much like they did when asked about issues relating to afforestation and BECCS. The business and industry group also shared a relatively holistic vision of the feasibility criteria, though had slightly higher responses regarding the cost effectiveness, competition and finance (63%), and carbon markets (63%) themes, and relatively low response rates for sustainability (13%) compared to the other two groups (40% for NGO, and 80% for policy).

**Table 5.** The 11 main feasibility themes and 33 sub-themes. Numbers denote the number of codes within each theme. Across all themes, the overall number of coded responses is  $n = 109$ .

Main theme	Sub-theme	Total
Infrastructure & technical	Infrastructure & technical (5)	17
	Spatial scale (5)	
	Temporal scale (4)	
	Innovation (3)	
Biomass (production capacity, sustainability & supply)	Biomass (production capacity, sustainability & supply) (5)	13
	Spatial scale (5)	
	Temporal scale (2)	
	Efficiency of feedstock (1)	
Sustainability (environmental)	Diverse environmental objectives (4)	13
	Biodiversity issues (2)	
	Energy vs food security (2)	
	Priorities & trade-offs (2)	
	Water (2)	
Carbon markets	Sustainability (environmental) (1)	11
	Metrics (5)	
	Carbon markets (3)	
Co-benefits & multiple objectives	Operational issues (3)	10
	Co-benefits & multiple objectives (5)	
	Afforestation & BECCS (3)	
Cost effectiveness, competition & finance	Positive social outcomes (2)	10
	Cost effectiveness, competition & finance (7)	
Carbon budgets & mitigation	Investment (3)	8
	Carbon budgets & mitigation (5)	
Land	Accounting (3)	8
	Land (4)	
Governance	Availability (4)	7
	Governance (5)	
Social acceptability & justice	Institutional frameworks (1)	7
	Political will (1)	
	Social acceptability & justice (6)	
Risk & robustness (of supply chain)	Empowerment (1)	5
	Risk & robustness (of supply chain) (3)	
	Feedstock supply security (2)	

### 3.3. Representation of issues in integrated assessment models

#### 3.3.1. Secondary analysis

Taking the results of the analysis described in Section 2.1, the 61 issue sub-themes (from Table 2) were re-grouped according to how they are represented within IAMs (Table 7), reducing the number of sub-themes to 33. For example, the theme ‘competing human needs’ appears in the table twice, separating three sub-themes (food security, water, competing human needs) from ‘community and livelihoods’ within this theme. The issues in the former group are represented within IAMs to different extents (as indicated in Table 7), whilst the latter is not at all. The 33 sub-themes are thus rated from limited or no representation (red), to moderate (orange), to extensive (green) to describe the extent to which the issues are represented within a typical IAM - based on model description literature, researcher experience [NV & CG] with IAMs and detailed discussion between researchers. This analysis was also cross-checked with an independent senior colleague from the IAM community. We further unpack these scores in the final columns of Table 7 to describe five categories of challenges to accurately modelling these real world processes (Table 8).

#### 3.3.2. Findings

IAMs aim to cover relatively long-time frames (up to 2100), different global regions and all economic sectors. Given the associated uncertainties and the need for transparency, many of the factors that determine future emissions are therefore simplified in IAMs. The credibility of the option of large-scale afforestation and BECCS (and consequently avoided deforestation and energy system decarbonisation) as represented in the models, depends on how well the idealised modelled world reflects real-world constraints, and hence the identification of key elements that may limit or enable certain technologies and practices. These limitations are recognised by the IAM community (Clarke et al., 2014). More broadly, here we seek to explain why IAM results should not be interpreted as an indication of feasible levels of greenhouse gas reduction, but rather to contextualise levels of greenhouse gas reduction that might be associated with specific emission pathways and carbon budgets. Thus, our analysis aims to support a better understanding of the expectations of IAM results with regard to judgements of feasibility, highlighting specific areas that should be informed by different types of analysis.

**Table 6.**

The 11 feasibility themes and the percentage of respondents from each expertise and sector category that mentioned each theme and the overall mean times mentioned for all respondents. The list of themes is ordered by the overall percentage scores mentioned by the respondents. The number of respondents in each expertise category is: Bioenergy & Forestry (8), CCS (6) and Climate Change (4); and in the sector category is: Business & Industry (8), Policy (5), NGO (5). Colour scale: red-orange-yellow-light green-green denotes high to low response values in 20% quintiles.

Theme	Overall %	% mentioning each theme per dominant expertise			% mentioning each theme per sector		
		Bioenergy & Forestry	CCS	Climate Change	Business & Industry	NGO	Policy
Co-benefits & multiple objectives	50	50	67	25	63	20	60
Infrastructure & technical	50	25	67	75	38	60	60
Biomass	44	50	33	50	50	60	20
Cost effectiveness, competition & finance	44	50	50	25	63	20	40
Land	44	50	50	25	50	20	60
Carbon budgets & mitigation	39	37.5	50	25	38	40	40
Carbon markets	39	25	83	0	63	20	20
Sustainability (environmental)	39	37.5	33	50	13	40	80
Governance	33	0	50	75	25	40	40
Risk & robustness (supply chain)	28	25	33	25	38	20	20
Social acceptability & justice	28	25	0	75	13	60	20

**Table 7.**

Extent of representation of the issue themes in a typical Integrated Assessment Model that includes land use. Sub-themes and groups of similar sub-themes are rated qualitatively from limited (red), to moderate (orange), to extensive (green) to describe the extent to which these issues are typically represented in IAMs, which include land use. The following five columns unpack the ratings to identify how this representation differs to the real world with respect to the five categories described in Table 8; (i) debate over numbers, assumptions, (ii) process or element missing, (iii) policy implementation, (iv) complexity and diversity or (v) this does not exist yet. Where issues are not widely represented in the models (rated limited (red)) we did not unpack the rating further. Numbers after each sub-theme denote the number of codes.

Theme	Sub-theme or group of similar sub-themes	Extent of representation	Numbers, assumptions	Process or element missing	Policy implementation	Complexity & diversity	This doesn't exist at scale yet
Economics & incentives	Carbon markets & pricing (7)						✓
Technical	Carbon capture storage (5)						✓
GHG accounting	GHG accounting (7), Methodologies (2), Other GHGs (not CO2) need accounting (1)				✓		
GHG accounting	Offsetting, carbon debt & overshoot (3)				✓	✓	
Land use	Availability & competition (10), Energy v food crop (5), Long term planning (1)		✓		✓		
Economics & incentives	Incentives & government support (8), Economics & incentives (2)			✓		✓	
Spatial scale	Spatial scale (8), Infrastructure & input (7)		✓			✓	
Temporal scale	Development & infrastructure (7)		✓			✓	
Societal implications	Population & development (6)			✓			
Technical	Bioenergy (4), Forestry (8), Forestry carbon (2), Availability of feedstock (3), Species composition (2)		✓			✓	
Economics & incentives	Comparing alternative GGR options & value for money (3)		✓				
Technical	Efficiency of supply chain (4), Supply chains (2), Disconnect between supply chain components (2), Data issues (1)		✓	✓		✓	
Environmental	Biodiversity & ecosystem services (9), Agriculture & food production (4), Water use (2)		✓	✓			
Temporal scale	Temporal scale (4)						✓
Real world complexity & diversity	Modelling & systematising complexity (2)					✓	
Governance	Policy & regulatory implications (11), Governance (3)				✓		
Environmental	Environmental (6)					✓	
Land use	Land use (3), Affecting GHGs (1)		✓	✓			
Spatial scale	Envisioning & diversity at large scales (2)					✓	
Competing human needs	Food security (4), Water (1), Competing human needs (2)		✓	✓			
Environmental	Co-benefits (5)						
Environmental	Responsibility & safe guards (4)						
Societal implications	Societal implications (4), Public acceptance (2)						
Technical	System uncertainty (5), Technical (1)						
Real world complexity & diversity	Real world complexity & diversity (8), Innovations (1)						
Governance	Leadership & political will (6), Decision making & political uncertainty (4)						
Land use	Legislation & ownership (4)						
Justice & ethics	Justice & ethics (7), Distributional justice (6), Procedural justice (1)						
Competing human needs	Communities & livelihoods (4)						
Governance	Risk & previous failed attempts (3), Short termism (2), Lack of capacity & joined-up thinking (2)						
Justice & ethics	Moral hazard & mitigation deterrence (3)						
Temporal scale	Social & political (3), Permanence (2)						
GHG accounting	Impact on albedo effect (1)						

**Table 8.**

How representations in typical IAMs differ to the real world: five categories.

Category	Description
Numbers, assumptions	There is either a lack of data or a wide range of estimates in the literature reflecting an active discussion in the wider scientific community about the data or assumptions made within the model. For example, current and future land use availability estimates vary greatly
Process or element missing	A process or element of a process may be missing from the model that would be needed for the issue to be fully represented. For example, the different types of incentives and government support necessary for BECCS to be deployed at a national level.
Policy implementation	The difference between an idealised and uniformly implemented policy in the model versus the real world rule breaking or weak enforcement and the heterogeneous national contexts. For example, in the model it is possible to protect land for food production, in the real world there will be cases of rule breaking and weak environmental governance.
Complexity and diversity	The difference between the complexity and diversity found in the real world compared to the idealised presentation in the model. For example, the breadth of biomass and forestry feedstocks, energy conversion processes and storage options, and socio-political contexts.
This does not exist at scale yet	Practices, policies or technologies that don't exist at scale yet. For example, CCS does not exist at large scale yet (only 18 projects > 0.5 Mt CO <sub>2</sub> yr <sup>-1</sup> globally) nor do many carbon markets and pricing mechanisms.



Three distinct groups of issues emerge from this analysis (Table 7) based on similar ratings for the extent to which they are represented in IAMs. Each group contains a roughly equal number of issues, the only outlier is the impact on albedo, an element previously identified as absent from models (Vaughan and Gough, 2016; Vaughan et al., 2018), but which we assessed to be possible to include in future model developments.

The first group of issues ( $n = 11$ ) were those which we considered to be well represented within IAMs; they include a number of technical aspects, economics and incentives, GHG accounting, land use and population and development (Table 7). Assumptions on 'driving forces' such as population growth, income development, and the efficiency and structure of the energy demand determine the size and nature of the energy system in the models. Obviously, how these driving forces develop over time is not certain and in Table 8 we present five categories to describe different challenges to accurately modelling these real world processes. For example, while carbon capture and storage technologies exist, they have not been deployed at scale yet, with only 18 storage sites ( $> 0.5 \text{ MtCO}_2/\text{yr}$ ) in operation globally, many of these located in North America in Enhanced Oil Recovery applications (Global CCS Institute, 2019). The large-scale use of CCS in modelled outputs is therefore based on assumptions that this experience can be scaled up.

The economic incentives and government support issue, is approximated within IAMs by coherent and consistent rules at a macro scale. In practise, however, there is significant heterogeneity at regional, national and sub-national levels reflecting a complexity and diversity that cannot be fully captured with models. The same holds for greenhouse gas accounting issues, while this can easily be operationalised in IAMs, realising the policy implementation to ensure accurate greenhouse gas accounting is likely to be beset by many challenges, as seen with REDD+ (Tulyasuwan et al., 2012; Hargita et al., 2016). Under the societal implications theme, we consider that processes or elements are missing in relation to population and development - in particular, social and cultural drivers that evolve over time and may result from social and technical innovations over the course of the 21st century. When comparing alternative GGR options and value for money, the IAM representations are hampered by the limited data on the costs of alternatives (i.e., numbers and assumptions), such as direct air capture and enhanced weathering, leading to often only a limited representation of these novel approaches (Rogelj et al., 2018).

The second group of issues ( $n = 9$ ) includes a more diverse set of themes and sub-themes, which IAMs represent, but less extensively than the first group. Four of the issues in this group present concerns relating to both numbers and assumptions and process or element missing. For example, agriculture and food production, water use, land use and competing human needs such as food security are represented to differing extents within the models, either directly or indirectly. Although these IAMs use state of the art tools to represent these factors, based on empirical trends, given the necessary simplification of the model assumptions, the breadth of data and the interconnected nature of areas covered by these sub-themes, they are rated as being moderately represented. Limitations in how the issue of policy and regulation implications is represented in the models are principally due to the gulf between the idealised modelled policy implementation and the multiple levels and governance mechanisms, and the associated interconnected implications, required to deliver these approaches at a global scale. Four issues are associated with particular complexity and diversity challenges, ranging from the breadth and complexity of the supply chains that could deliver BECCS to environmental and social issues raised by the large-scale application of afforestation and BECCS globally. Issues raised by participants under the temporal scale theme included questions about the timescale in which modelled quantities of  $\text{CO}_2$  removed could be achieved and the time-dependency of  $\text{CO}_2$  sequestration, particularly in relation to implementing the Paris Agreement; primarily arising from the fact that BECCS and large-scale afforestation do not exist at scale yet.

The final group ( $n = 12$ ) of issues raised by our experts (Table 7) are not typically represented in IAMs - issues such as justice and ethics, public acceptance, innovation, leadership and political will, and, legislation and ownership of land. Quantitative models (certainly, those focusing on economics, energy system and greenhouse gas accounting) are not well designed to capture the nuances of social and cultural drivers of change. However, whilst the IAMs play an extremely valuable role, by highlighting the issues raised by stakeholders which are not represented in the models (and therefore the emission pathways), we argue that they should not be used in isolation to interrogate the feasibility of particular technologies or practices.

#### 4. Discussion

This study offers unique insights to advance understanding of issues and feasibility criteria associated with biomass energy with carbon capture and storage (BECCS) and large-scale afforestation for greenhouse gas reduction (GGR). Eliciting expert perceptions from a variety of stakeholders from business and industry, non-governmental organisations and policy makers, demonstrated a broad and diverse range of issues associated with these GGR technologies and practices, which collectively expand the current knowledge base on this nascent area of development. Specifically, our findings show the importance of societal and governance aspects of feasibility, in particular issues around justice and ethics, competing human needs, and 'real world' complexity and diversity. These issues are not only under-represented within current academic literature (Minx et al., 2017), as we have shown, they are also excluded from typical integrated assessment models that have become a central tool in the global assessment of climate change and which hold a strong influence on climate policy and societal responses to the threat of dangerous climate change.

While acknowledging the specificities of the UK workshop setting drawn on in this paper, this study devised a novel expert elicitation approach, that complements parallel works (e.g., Low and Schäfer, 2020) to open up expert and stakeholder perspectives on the feasibility of BECCS and AR, to produce a more diverse map of issues and criteria that should be taken into consideration in the future development of GGR approaches. Given the biophysical and techno-economic emphasis of many existing assessments of GGR, it is not surprising that workshop participants placed greater emphasis on these dimensions, as reflected by the most frequently raised issues (technical, environmental, land use, economics and incentives, see Table 2) and criteria identified (infrastructure & technical, biomass, environmental sustainability, carbon markets, cost effectiveness, see Table 5). Despite such biases, a recent review of the international academic literature (Waller et al., 2020) has shown an increasing number of studies either emphasising or analysing the social and political dimensions of GGR approaches, including BECCS and AR. Key themes relating to social and political dimensions of GGR feasibility identified in this review include: societal engagement; governance, regulation and politics; innovation; complexity and uncertainty; and ethics, equity and justice (ibid). While the methodological approach we developed differs from previous works (for example, see Bellamy and Healey (2018) for future scenario workshops on GGR; and Rickels et al. (2019) and Low and Schäfer (2020) for survey and interview approaches to examine feasibility of NETs), there are some significant commonalities between themes in the social science and energy literature and those emerging from the expert and stakeholder views elicited in our study (see Tables 2 and 3), which included: governance, justice and ethics, societal implications, competing human needs, and 'real world' complexity and diversity. This indicates the wider applicability and relevance of the themes identified in our current study and further verifies the situated importance of socio-political themes emerging in the international literature.

These findings suggest that social, political and equity issues and criteria need to become more central to anticipatory assessments of GGR and climate futures more broadly. Yet, our analysis has shown that

these dimensions are routinely excluded from climate assessments and thus decision-making processes. The secondary analysis presented in Table 7 highlights the valuable role of IAMs. However, as models based on global economics, energy system and greenhouse gas accounting, they are not designed to, and indeed cannot, capture the nuances of social, political and cultural drivers of change. Our analysis indicates how real-world complexities and socio-political issues raised by workshop participants (e.g., justice and ethics, social implications, competing human needs, governance, leadership and political will) are not included and represented in the IAMs and the emissions pathways they generate. Therefore, we argue that, while IAMs are able to model and represent some of the options, issues and criteria that should be considered in pathways for achieving emissions reductions, given the complexities they do not render, some crucial dimensions are excluded or left out. Based on the evidence and analysis presented here, we suggest it is critically important that these exclusions are attended to either through altering the practices of IAMs and their communication or through complementing IAMs with other approaches (e.g., through the use of complementary ‘bridging’ approaches, see Geels et al., 2016). In doing this we aim to add support to the small but growing body of literature (Edenhofer and Kowarsch, 2015; Haikola et al., 2019; Rickels et al., 2019; Low and Schäfer, 2020) seeking to open up new agendas for research and practice which aim to better understand the limitations of the models in a constructive way and thus introduce new approaches which can enable the inclusion of ‘uncomfortable knowledge’ (Saltelli and Giampietro, 2017) in the wider assessment process.

Table 9 outlines a range of approaches which we suggest can help to open up models and assessments of GGR and climate futures or otherwise complement them by offering different ways of being responsible about and attending to social and political dimensions of climate assessments, innovations and governance processes. These categories of approaches loosely range from those more focused on models and assessment processes themselves (cf. Beck and Mahony 2018), through to those concerned with wider processes of climate innovation, democracy and governance which shape the emergence of GGR. In doing this we are not suggesting a particular order or firm categorisation of these approaches, which often blur and overlap in practice. We simply suggest this range of approaches needs to collectively become more apparent, whether practiced independently or in conjunction with IAMs in different combinations.

As Table 9 shows, one approach advocates critical reflection on model assumptions and exclusions, and explicitly expressing these alongside model outputs – if these qualitative dimensions are not included in the models via proxies - thus complementing model outputs with a recognition of the complexities of societal issues and governance dimensions (e.g., Edelenbosch et al., 2018). These would inform the communication of scientific modelling outputs, aid in contextualising them, and incorporate them into more inclusive conversations on possible and desirable futures. A further possibility is to openly question and scrutinise the framings and exclusions of IAMs with publics in participatory integrated assessment processes (e.g., Kasemir et al., 2000). A deeper ‘responsible assessment’ approach (Beck and Mahony, 2018) would advocate reflecting on the implications and effects that might result from the adoption, or otherwise, of decisions based on IAMs. This goes beyond communicating uncertainties and exclusions, to reflexively questioning the future socio-technical imaginaries (Jasanoff and Kim, 2013) implicit in model projections, the implications and effects of imagined social worlds, and how they might be configured and appraised otherwise.

Where the first three approaches in Table 9 expose the net-zero imaginations within IAMs as being too narrow, there is a role for appraisals that deliberately open up the framings, inputs, perspectives and outputs of assessments to consider more widely which collective futures societies want, which may be feasible, and why and how they can be achieved (e.g., Bellamy et al., 2016). Yet while inter- and trans-disciplinary arrangements are important, there remain instances where social science and humanities analyses of social and equity dimensions of climate futures are necessary in their own right (e.g., Gonzalez-Ricoy and Rey, 2019). Beyond this, instead of formal procedures, it might be that social and justice dimensions of GGR and climate change should be dealt with through ongoing democratic deliberation, mobilisation and debate at multiple scales (e.g., Chilvers and Pallett, 2018). Such approaches may enable attending to those components that IAMs represent poorly or almost not at all (those listed in red in Table 7). Ultimately, however, attending to the social and justice dimensions of GGR and climate futures needs to move beyond the domains of expert assessment and democratic debate and become a core consideration of distributed commitments, innovations and governance, through embedding processes of responsible innovation and governance at multiple scales (e.g., Stilgoe et al., 2013; Voß and Simmons, 2018). This can

**Table 9**  
Approaches to assist or complement IAMs in attending to social and justice dimensions of GGR and climate futures.

Category of approach	Characteristics	Examples and references
Expressing model assumptions and exclusions	Expressing social assumptions, exclusions and complexities in or alongside model representations	Edelenbosch et al. (2018)
Participatory integrated assessment	Extended peer review of IAM framings and outputs through public and stakeholder participation, aimed at improving their quality and social robustness.	Darier et al. (1999a) Kasemir et al. (2000) Darier et al. (1999b) Cohen et al. (2006) Cohen (2007) Scherhauer et al. (2018) Beck and Mahony (2018)
Responsible assessment	Caring for the future implications, politics, effects and social orders produced through assessments/models of GGR and climate change.	
Opening up social appraisals and assessments	Appraisal processes that seek to open up the framings, inputs, perspectives and outputs of GGR assessments, including alternative problem framings, criteria, metrics, and future choices and pathways of change.	Multi-criteria mapping (Stirling and Mayer, 2001) Deliberative mapping (Bellamy et al., 2016) Q Method (Cairns and Stirling, 2014) Scenario workshops (Pérez-Soba and Maas, 2015) Forecasting and backcasting (Robinson, 2003; Iden, 2017) Gonzalez-Ricoy and Rey (2019)
Climate justice	Develop analyses of social and justice dimensions of climate futures in their own right.	Hanusch (2017)
Participatory democracy and deliberation	Social, political and justice dimensions of GGR and climate change can be dealt with through ongoing democratic deliberation, mobilisation and debate at multiple scales.	Chilvers and Pallett (2018) Fiorino (2018)
Responsible innovation and governance	Anticipating and responding to implications, downsides and social futures in the process of innovating net-zero carbon technologies (like GGR) and climate governance instruments.	Stilgoe et al. (2013) Voß and Simmons (2018) Raman et al. (2015)

enable a more attentive and embedded consideration of equity and justice dimensions *in advance and in their own right*, rather than as additions or after-thoughts of international climate regimes.

We acknowledge that the wider adoption of these approaches will be challenging, not least because they question incumbent modes and paradigms of climate assessment, governing and decision-making. Yet, if social, political and justice dimensions of emerging responses to net-zero carbon futures (including GGR approaches) are to be taken seriously - as advocated by many experts and stakeholders in our expert workshop and increasingly by the international social science literature - then all approaches put forward in Table 9 will have to play a part. Indeed, it will be necessary for these approaches and the different communities associated with them to interact and complement each other, rather than working in competition. Many of these approaches already occur in isolation, so a key challenge will be to experiment, test and evaluate them together as part of a wider framework for attending to the social dimensions of GGR and climate futures. The expert workshop reported on in this paper can be seen as one small initial contribution to this wider programme. Ultimately, however, this will depend on properly funding, resourcing and building capacities in these approaches, which have their origins in the social sciences and humanities.

## 5. Conclusion

This study has shown that stakeholders view and evaluate large-scale afforestation and BECCS through a diverse range of different criteria. Analysis of the workshop contributions indicated that participants with broader climate change expertise referred to a wider range of themes, similarly the NGO and policy groups, whilst other participants referred to issues and criteria more closely associated with their specific areas of expertise. Importantly, our analysis has shown that many of the issues and criteria developed by participants are currently not included or represented in IAM processes and outputs, most notably those relating to social and political dimensions. IAMs thus partially frame decision making on future greenhouse gas emission options through excluding other possibilities and foreclosing discussions around potential alternative futures. In response to this we have identified a series of approaches which can assist or complement IAMs to ensure that the social and political dimensions of GGR and climate futures are given due consideration in climate assessments, innovations and decision processes. Our findings suggest that some communities will be more receptive to these approaches than others, given our workshop participants' attention to a range of feasibility themes. Thus, we call for more serious and long-term experimentation and engagement with and across the various proposed approaches to understand the feasibilities and complexity associated with large-scale afforestation and BECCs, supported by adequate and directed funding. As part of this we propose that engagement with modellers may serve to interactively consider those elements currently excluded or under-represented in IAMs, to foster discussions on the rationales and justifications for doing so and whether there may be other means through which some of these could be accounted for in IAM outputs. We also propose that a deeper understanding of which elements may enable or preclude in the delivery of large-scale afforestation and BECCS is required, to provide detail to inform discussions on greenhouse gas removal options in the wider context of real-world complexity. Finally, we acknowledge that future assessments and demonstrations of mitigation options should include wider transdisciplinary knowledge and interests, beyond the expert views expressed in our workshop, to more openly and deeply explore the real-world complexities and socio-political dimensions of GGR and alternative climate futures.

## CRedit authorship contribution statement

**Johanna Forster:** Conceptualization, Methodology, Formal

analysis, Writing - original draft, Writing - review & editing, Funding acquisition. **Naomi E. Vaughan:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Clair Gough:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Irene Lorenzoni:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Jason Chilvers:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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