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Bringing greenhouse gas removal down to earth: Stakeholder supply chain appraisals reveal complex challenges

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A R T I C L E I N F O

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A B S T R A C T

Greenhouse gas removal (GGR) approaches are considered essential in several projections to meet the climate mitigation ambition of the Paris Agreement. Biomass Energy with Carbon Capture and Storage (BECCS) and afforestation are included extensively in mitigation scenarios but there are concerns about the feasibility of these approaches. This was explored with stakeholders from industry, non-governmental organisations (NGOs) and policy who were involved in interviews and a one-day participatory workshop. Multicriteria mapping (MCM) methodology was used to appraise the 'real-world' feasibility of four specific greenhouse gas removal supply chains at a granular level in the UK context. The MCM analysis shows that afforestation performs better in comparison to three BECCS supply chains, on criteria such as business model, social acceptability, and environmental sustainability. This innovative application of the MCM methodology enables the abstract representations of GGR in integrated assessment models to be explored at a more granular level through a supply chain analysis and thus gain a deeper understanding of the issues facing these approaches. The data gathered allows a wide range of technical, environmental, social and political criteria to be systematically applied in appraising the practical performance of different future implementation options for afforestation and BECCS. If these GGR supply chains are to become a reality on the scale required for 1.5 °C global warming, factors such as global cooperation, land availability, and the longevity of policies and incentives were found to be major challenges.

1. Introduction

The Paris Agreement set the ambitious goal of limiting global temperature rise to well below 2 °C of pre-industrial levels and pursuing efforts to limit this even further to 1.5 °C. Most emissions scenarios that adopt the limit of 2 °C consider technologies to remove CO_2 and other greenhouse gases from the atmosphere will be available, acceptable, and affordable in the coming decades (Fuss et al., 2014; IPCC, 2018; Rogelj et al., 2018). Biomass Energy with Carbon Capture and Storage (BECCS) is one of the most salient technologies for greenhouse gas removal due to its large projected potential, with an anticipated global removal of up to 10 $GtCO_2$ yr^{-1} from the atmosphere by 2050 (Smith et al., 2016; van Vuuren et al., 2013). Here we use the term 'greenhouse gas removal' to mean removing carbon dioxide from the atmosphere, also known by terms such as carbon dioxide removal (CDR) and negative emission technologies (NET). The BECCS process involves the sequestration of CO_2 by plants, which are then used as bioenergy, followed by the capture of the CO_2 emissions and their permanent storage (CCS) (Kemper, 2015). However, BECCS does not yet exist at a commercial scale. Although there is a large and growing industry for bioenergy and available technologies for CCS, they have not been combined and demonstrated at scale. These and other aspects need to be examined in regard to the role of BECCS in future GGR. Afforestation is another of the main GGR approaches considered by Integrated Assessment Models (IAMs), also with significant potential for global carbon removal, with estimates up to 4 $GtCO_2$ yr^{-1} from the atmosphere by 2050 (van Vuuren et al., 2013). Here we use the term 'afforestation' to mean afforestation and reforestation together, in line with other GGR research (Minx et al.,

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2018; Waller et al., 2020). It involves planting trees to create forests that will sequester CO_2 as they grow. Afforestation however requires large amounts of land in order to achieve large quantities of carbon removal, which can put it into competition with other land uses, such as food, and requires careful land management practices (IPCC, 2019).

In recent years, considerable mitigation commitments have affected interest in GGR, including the international Carbon Neutrality Coalition in 2017 and the adoption of net zero targets in many countries and regions, for example in the UK (BEIS, 2019), the EU (European Commission, 2019) and China, amongst others. Businesses have also made recent commitments to move to net zero practices before 2050 (Evans, 2019; TPI, 2020), thus accelerating the demand for GGR in order to offset emissions that are difficult to mitigate. However, the implementation of GGR requires consideration of many elements. The most frequently referred to are typically technological and economic, however social and political dimensions are increasingly recognised in terms of their relevance (Cox et al., 2018; Forster et al., 2020; Waller et al., 2020), for instance enabling procedural justice and social legitimacy – also referred to as the 'social licence to operate' (O'Beirne et al., 2020; Thompson and Boutilier, 2011). Recent work with respondents at UN climate conferences found that the most important deployment constraints for BECCS were socio-political, with the major ones being a lack of political prioritisation, policy incentives, social acceptability and technical readiness (Fridahl and Lehtveer, 2018).

Whilst much research already exists on the technical aspects of CCS, bioenergy and GGR implementation (Bui et al., 2018; Kemper, 2015; Quader and Ahmed, 2017; Röder et al., 2019), literature on the stakeholder assessments within these areas remains much less common (Bellamy and Healey, 2018; Vaughan and Gough, 2016). It has been argued that a lack of consideration for the complexities regarding these approaches could hinder the implementation of the negative emission technologies (Markusson et al., 2020). These include creating a false sense of optimism around the ability to meet Paris Agreement temperature goals by relying on unrealistically large amounts of greenhouse gas removal in the coming decades (Anderson and Peters, 2016; Butnar et al., 2019; Geden et al., 2018). This indicates that a responsible innovation framing is also needed to attend to the social and justice dimensions of these technologies within a wider range of mitigation options and climate futures (Markusson et al., 2020; Waller et al., 2020).

Literature on expert assessments from the Earth System Model (ESM) and Integrated Assessment Model (IAMs) communities have identified that important constraints on BECCS are absent from modelling (Gambhir et al., 2019; Haikola et al., 2018; Low and Schäfer, 2020; Rickels et al., 2019). The recognition of a need to include other perspectives in integrated assessments for climate change via participatory methods is not new (Gough et al., 1998; Risbey et al., 1996; Rotmans and van Asselt, 2001; Salter et al., 2010). Some progress has been made at incorporating deliberative policy pathways in order to achieve more policy relevant assessments (Dooley et al., 2018; Edenhofer and Kowarsch, 2015; Kowarsch et al., 2016). Qualitative participatory processes are increasingly being recommended for combination with quantitative modelling to elicit and incorporate the multiple values and perspectives of stakeholders within policy design (Workman et al., 2020; Sharmina et al., 2019; Moallemi & Malekpour, 2018). However, such work has mostly comprised of surveys and interviews with stakeholders, but has not to date involved stakeholders in more granular evaluations of GGR supply chains.

Other disciplines have used GGR supply chains for assessments e.g. life-cycle analysis (Röder et al., 2019) and whole systems approaches (Fajardy and Mac Dowell, 2017). Vaughan et al. (2018) identified some of the differences in the detail of a generalised BECCS system used for an IAMs and a life cycle analysis (LCA). Expert elicitation research to date has used fairly generalised and/or simplified descriptions of GGR approaches such as BECCS (Bellamy et al., 2013; Forster et al., 2020; Vaughan and Gough, 2016). However, these descriptions do not convey the multiple stages, interrelations or possible variations involved in an approach, e.g. for BECCS different feedstocks (crops, forestry residues) or different energy conversion processes and uses (power, heat, hydrogen). This lack of specificity and granularity can result in misunderstandings by participants and abstract and generalised findings which can limit the insights of expert elicitation and their relevance for more detailed considerations of GGR.

The study presented in this paper applies a novel approach to elicit views about BECCS and afforestation supply chains at a granular level and from multiple perspectives. It uses Multi Criteria Mapping (MCM), an interactive multicriteria options appraisal method (Stirling and Mayer, 2001), to explore a range of perspectives on GGR supply chains among stakeholders working within organisations relevant to BECCS, forestry and climate change. In contrast to closed techno-economic assessments, MCM seeks to deliberately 'open up' the framings, inputs and outputs of appraisal processes that assess contending sociotechnical futures and options for addressing problems like climate change (Bellamy et al., 2016; Stirling, 2008). MCM has previously been employed to appraise geoengineering and hydrogen futures (Bellamy et al., 2013; McDowall and Eames, 2007). In this study, the MCM method was used to engage diverse stakeholders in: (i) exploring issues associated with BECCS and afforestation in the form of supply chains; (ii) developing criteria deemed important to assess the feasibility of GGR; and (iii) appraising the performance of different GGR supply chain options against these criteria. This process offers a deeper understanding of stakeholder opinions, building on previous work (Forster et al., 2020) on feasibility issues, uncertainties and complexities associated with the possible large-scale implementation of BECCS and afforestation.

2. Method

2.1. The Multi criteria mapping process and participants

The multi-criteria mapping (MCM) method (Stirling and Mayer, 2001) used in this study incorporated a two-step process of engagement with stakeholders (see Fig. 1): (1) individual MCM interviews where stakeholders discussed options, defined criteria, assigned appraisal

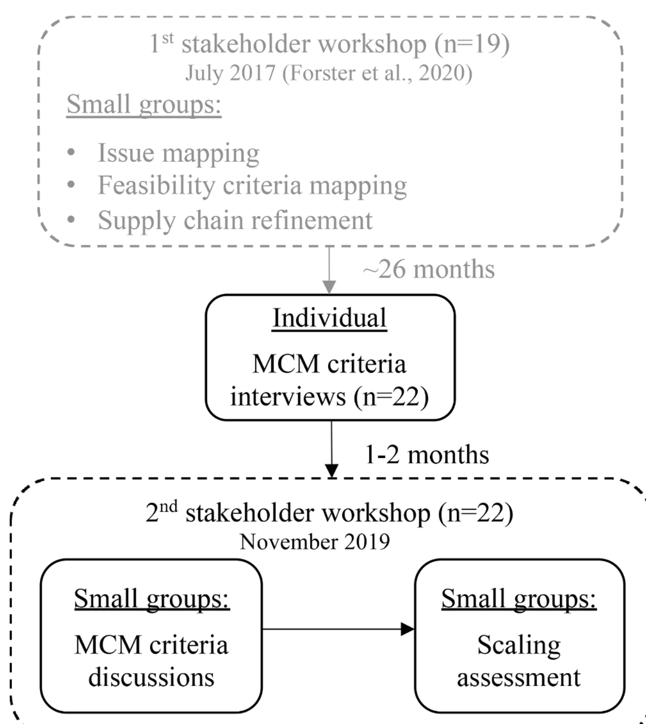

Fig. 1. Overview of the study engagement process (including previous workshop).

scores and weighted their criteria; and (2) small group discussions of the MCM interview results and methodology, as well as feasibility of scaling up BECCS and afforestation, at a subsequent workshop. In total, 26 stakeholders and experts participated in this study. Initial attempts were made to recruit the original 19 stakeholders from a previous project workshop (see Forster et al., 2020) in order to maintain longitudinal consistency across studies (See Table 1). Overall, 22 stakeholders were interviewed prior to the workshop (see Section 2.4) at their place of work, 18 of whom then participated in the workshop activities and discussion. All stakeholders self-stated their sector from three choices (business & industry, policy or NGO) and expertise, and were allocated to one of four 'dominant expertise' groups (carbon capture and storage (CCS), GGR, bioenergy or climate change) (Table 1).

The interviews and workshop context was set within the aspirations of the Paris Agreement to limit temperature rise to well below 2 °C and pursuing efforts to keep it below 1.5 °C. The overarching question provided to stakeholders was: "To what extent are large-scale GGR approaches (specifically BECCS and afforestation) feasible for addressing climate change in the UK context?". It was explained that the aim of the interviews was to engage with stakeholders from business, industry, government and civil society to assess the feasibility of possible supply chains for BECCS and afforestation in the future. The preamble to the interview mentioned that most future emissions scenarios consider that technology for CO_2 removal from the atmosphere, including BECCS and afforestation, will be available, acceptable, and affordable in the coming decades (see supplementary information with interview documentation).

2.2. The supply chains

Four supply chains were initially co-produced and subsequently revised by the project team based on existing literature and project research (version 1 – see supplementary information): these were presented at the first stakeholder workshop in July 2017 (see Forster et al., 2020) for comment and further revised by the project team in response to the workshop feedback (version 2 – see supplementary information). The development of these supply chains drew from interactive discussions and reflections between stakeholders and researchers (Beck, 2019) generating new more meaningful formats of the supply chains.

The final set of supply chains (version 2) were used in this study as a tool to support and facilitate discussions of BECCS and afforestation in the MCM interviews (see Table 2), by offering specific examples of these diverse technologies (Fajardy and Mac Dowell, 2017) and heterogenous practices i.e. afforestation (Doelman et al., 2020) (see supplementary information).

The supply chains are intended to capture the variety of potential options for BECCS in the UK, allowing the relative performance and challenges to be compared. Distinctive characteristics in the supply chains (version 2) used in the interviews were:

• Forestry residues: these are a potentially abundant global resource and are currently used to generate electricity in the UK.

• Combined Heat and Power (CHP): considered to be an important application at medium scale, small scale units were exluded due to the relative costs and CCS energy penalty making them unviable.

• Miscanthus: selected in preference to willow on the basis of: costs, farming know-how, culture and land use (miscanthus is perceived as an energy crop, whereas willow is considered in the UK more akin to forestry), suitability to UK growing conditions and opportunities for scale up.

• Municipal Solid Waste (MSW): although proposed as an alternative feedstock during the first workshop, the project team considered it to be too variable, dependent on location, season, time, and, ultimately, inconsistent with a long-term goal of zero waste.

• Afforestation: the supply chain (Table 2) was developed directly from one proposed during the first workshop.

2.3. The interviews

As part of the first step of the interview process, the four supply chains (Table 2) were used as core options for this appraisal (see supplementary information for interview documentation). While the study was not restricted to the four supply chain options (Table 2), no stakeholders opted to create further options. Interviews typically lasted 1–3 h during which stakeholders selected their own set of criteria, scored the options and weighted their criteria. Stakeholders were provided with a criteria list from the first stakeholder workshop (Forster et al., 2020) prior to the interview as an optional aid for the creation of criteria if desired by the stakeholder (see supplementary information).

Table 1
The 26 stakeholders and their involvement in each stage of the study.

ID	Sector	Dominant self-stated expertise	Attended 1st workshop	Replaced colleague	Interviewed	Attended 2nd workshop
102	Business & Industry	CCS	✓	n/a	✓	✓
103	Policy	Bioenergy & Forestry	✓	n/a	✓	✓
105	Business & Industry	CCS	✓	n/a	✓	✓
107	Policy	Bioenergy & Forestry	✓	n/a	✓	
108	NGO	CCS	✓	n/a	✓	✓
110	NGO	Climate change	✓	n/a	✓	✓
113	Business & Industry	CCS	✓	n/a	✓	✓
115	NGO	Climate change	✓	n/a	✓	
116	Business & Industry	Climate change	✓	n/a	✓	✓
206	Business & Industry	Bioenergy & Forestry		✓	✓	✓
211	NGO	Climate change		✓	✓	✓
215	NGO	Climate change		✓		✓
217	Policy	Climate change		✓		✓
218	Business & Industry	Bioenergy & Forestry		✓		✓
320	NGO	Bioenergy & Forestry			✓	✓
321	Policy	CCS			✓	✓
322	Business & Industry	Bioenergy & Forestry			✓	✓
323	Policy	Bioenergy & Forestry			✓	✓
324	Business & Industry	CCS			✓	✓
325	Business & Industry	Bioenergy & Forestry			✓	✓
326	Policy	Climate change			✓	✓
327	Business & Industry	Climate change			✓	✓
328	Business & Industry	Bioenergy & Forestry			✓	✓
329	NGO	Bioenergy & Forestry			✓	
330	Policy	Bioenergy & Forestry			✓	
331	Business & Industry	Climate change				✓

Table 2
Overview of the four GGR supply chains (three BECCS and one afforestation) assessed by the stakeholders in the MCM interviews. The colour code shown for each supply chain is provided as cross reference for other visuals in this paper.

	BECCS				
Stage:	Power with residues	CHP with miscanthus	Hydrogen with SRC	Stage:	Afforestation
Biomass production:	From managed forest in North America	Miscanthus grown in UK	Short rotation coppice (SRC) grown in UK	Initial land use:	Low-quality agricultural land, e.g. sheep pasture
Biomass harvest:	Forestry residues from thinning	Perennial crop harvested annually	Coppiced every 2–5 years	Land conversion:	Preparation for planting
Biomass processing:	Pelletising	Baling	Chipping	Nursery development:	Growth of saplings
Biomass transport:	Ship, road & rail	Road	Road	Planting:	Mix of conifers, and broadleaved
Energy conversion:	Electricity generation of 4GWe	Combined heat and power (CHP) of $100MW_{el}$	Gasified in a 500 MW unit to produce Hydrogen	Maintenance & products:	Selective logs for timber. Residues for local heat market
Carbon Capture and Storage:	Post-combustion capture with storage in North Sea	Post-combustion capture with storage in North Sea	Pre-combustion capture with storage in North Sea		
Colour code:					

The MCM interviews followed existing guidance for this methodology (Coburn and Stirling, 2019) comprising of four steps which each interviewee undertook: (1) defining a set of criteria against which the supply chains options are assessed; (2) scoring the relative performance of each supply chain option, both pessimistically and optimistically on an arbitrary scale of 0 to 100, against the selected criteria; (3) assigning weights to each criterion, on an arbitrary scale of 0 to 50, based on their relative importance. These weights are then used to produce a 'ranking chart' (the sum of the weighted scores) and (4) the 'ranking chart' is reviewed with the interviewed stakeholder to confirm agreement with their opinion.

2.4. The workshop

A one-day workshop took place in November 2019 enabling 22 stakeholder participants to take part in discussion and activities surrounding the content of the MCM interviews and the global relevance of GGR. Following a brief introduction to the research project, the context and participants, the overall results of the scores from the interviews were presented to the stakeholders for reflection. The stakeholders were then divided into four breakout groups, each comprising of 5–6 stakeholders from a mix of sectors and expertise, and each with a facilitator and note-taker. Stakeholders completed two breakout sessions in these groups, each of which lasted 1 h 15 min.

For the first group breakout session, each stakeholder was provided a printed results pack containing their MCM results and the aggregated results. The workshop stakeholders that had not been interviewed prior to the workshop (n = 3) were provided with a results pack containing the results of their colleague as an aid for the discussion. The first breakout consisted of discussions among the stakeholders, supported by facilitators, on: (1) initial reflections on the overall MCM interview results; (2) reflections on the similarities and differences between MCM interview appraisals by the stakeholders within the groups; and (3) reflections on the appraisal process. Notetakers captured the main points of the discussions with attribution where possible, including a comparison of each stakeholder's criteria and scores to others' and to the overall group.

The second breakout session aimed to examine the feasibility issues that would be associated with a scale-up to the UK and global scale of the four selected supply chains in Table 2. Firstly, the four individual supply chains were provided on A1 posters in each of the breakout rooms. Stakeholders were asked to consider pinch points along individual supply chains (i.e. the scale used in the interviews, provided in the supplementary information). Next, the stakeholders were asked to consider the scale up from the supply chain scale to the scale of GGR expected to be required in the UK by 2050 - defined as 50–80 $MtCO_2$ and 20–30 $MtCO_2$ removed per year for BECCS and afforestation respectively, based on Committee on Climate Change's 'Net zero: The UK's contribution to stopping global warming' (2019) report. Finally, the stakeholders were asked to scale up the assessment from the scale required in the UK to the global scale - defined as 10 $GtCO_2$ and 1 $GtCO_2$ removed per year for BECCS and afforestation respectively. The stakeholders were provided with matching coloured post-it notes and sticky dots, to indicate where they identified potential risks in the supply chains. Each note included the stakeholder's initials, enabling comments to be grouped for analysis and conversations were captured by notetakers.

2.5. Data analysis

The Multicriteria Mapping online application (www.multicriteriamapping.com) was used to collect the data from the MCM interviews for analysis. This platform was used to analyse averaged scores for the overall group and specified groups such as sector and dominant expertise.

Data collected during the interviews and workshop were coded and analysed using NVivo 11 (Q.S.R. NVivo 2017). Criteria themes and subthemes were identified by the authors through an iterative coding process, however these groupings do not convey the full complexities of the issues encompassed within each theme. The lead-author of this paper led the initial coding process, which was followed-up with iterative cross-checks by the five other co-authors to ensure coding was accurate and unbiased. A NVivo coding matrix query was used to extract the number of stakeholders that mentioned each theme across the three sectors (business & industry, NGO, and policy) and the three dominant expertise (bioenergy & forestry, CCS, and climate change) categories (following the method outlined in Forster et al., 2020). Inductive reasoning was applied in further coding of the interviews and workshop discussions. However, it is important to note that stakeholders were provided with the criteria list developed in the first workshop (see Forster et al., 2020) as a reference material for the interview and workshop presented here.

3. Results

3.1. Feasibility criteria from the individual MCM interviews

The 22 stakeholders that were individually interviewed generated a total of 253 criteria, which were coded by the authors into themes and sub-themes (Fig. 2). Some themes are general (e.g. social, politics & governance, financial and environmental impacts), whilst others are specific to BECCS and afforestation (e.g. land & biomass, infrastructure, co-benefits and carbon removal). The greatest number of criteria were those grouped under land & biomass (n = 70), echoing previous expert elicitation findings (Vaughan and Gough, 2016) and more general

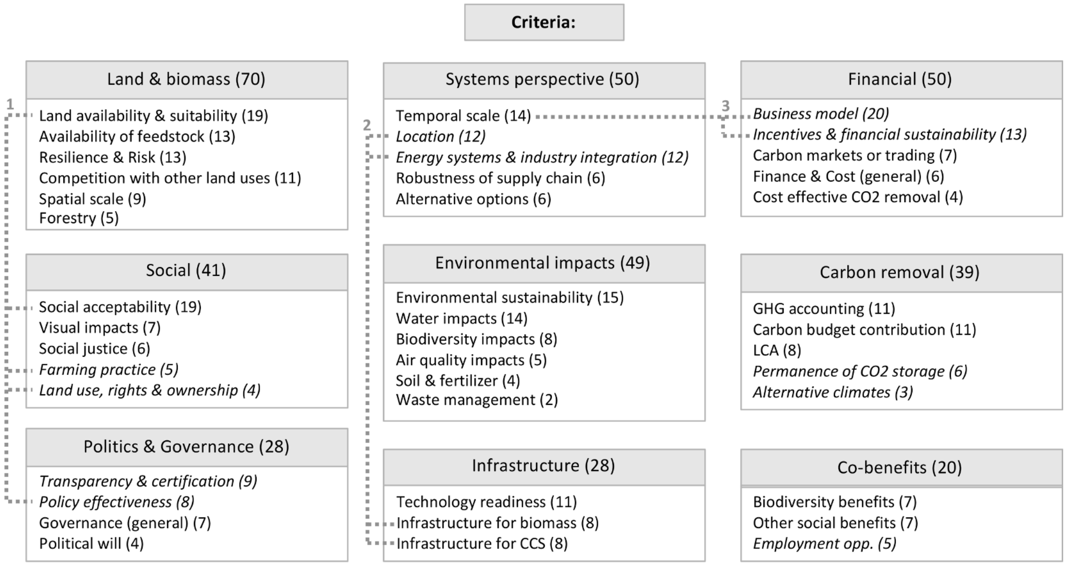

Fig. 2. Criteria from individual multicriteria mapping (MCM) interviews. Criteria themes (grey) and sub-themes (in boxes within themes). Numbers represent the quantity of criteria coded under each theme, with a total number of criteria generated of n = 253. In italics are sub-themes absent from the previous study (Forster et al., 2020). Dotted lines (numbered 1, 2, & 3) show links where three or more criteria were coded under more than one sub-theme.

concerns (Smith et al., 2016). A novel theme was also identified, systems perspective, indicating a whole systems approach to the feasibility of GGR, involving consideration of interconnected factors and synergies.

There are strong links (defined as three or more co-coded criteria illustrated with dotted lines in Fig. 2) between certain sub-themes where criteria comments were coded under more than one sub-theme. Links were observed between land availability & suitability, social acceptability, policy effectiveness, farming practice and land use, rights and ownership (*dotted line 1*). This highlights the relationship between social acceptance and effective policies and their land use implications which, despite a strong UK focus, also included reference to tropical and trade contexts. Connections were also evident among criteria on location, infrastructure for biomass, infrastructure for CCS and energy systems and industry integration (*dotted line 2*) showing the importance of location in connecting the stages of the supply chains. In their comments on the criteria, the interviewees connected the temporal scale to business model, incentives and financial sustainability (*dotted line 3*) due to the identified importance of long-term financial support along the length of the supply chain. These links provide important nuanced insights into the themes identified.

The analysis identified 11 novel sub-themes, not previously reported in existing published work eliciting feasibility criteria for afforestation and BECCS (Table 3 & Fig. 2, highlighted in italics). These new themes include 'business model', 'incentives & financial sustainability' and 'policy effectiveness' which may reflect the significant UK policy changes in the 28-month period since the previous stakeholder engagement, such as the adoption of a net zero target for the UK (BEIS, 2019). Others such as 'land use, rights & ownership' and 'farming practice' with strong links to 'land availability & suitability' may align to recent policy discussions about UK land use post-Brexit (e.g. Agricultural Bill) and UK and global land use change to address climate change (CCC, 2018; IPCC, 2019). The framing in the MCM interviews to specific supply chains with more detail and granularity (see supplementary information) than previous studies may have reflected in more detailed exploration of feasibility criteria by stakeholders, resulting in the new themes of 'location', 'energy systems & industry integration', 'permanence of CO_2 storage' and 'alternative climates' (Table 3).

The overall results from the MCM interviews (Fig. 3) show how well each supply chain satisfies self-defined criteria presented for the group as a whole, where a higher score indicates better performance. At this most aggregated level, afforestation performs better at its upper and

Table 3
Novel themes and illustrative selected quotes. Numbers in square brackets denote stakeholder ID described in Table 1.

Novel themes	Selected quotes
Location	'Co-locating potential - considering location needs for feedstock, heat networks, CO_2 storage, etc.' [325]
Energy systems & industry integration	'Ability to load follow on power grid, especially with CO_2 storage lags, heat demand profile.' [102]
Permanence of CO_2 storage	'Permanence, in context of changing climate and CCS storage' [329]
Alternative climates	'Resilience to alternative climates and land use changes.' [321]
Business model	'Is it money making? investable?' [321] 'Investment capital expenditure. Are you going to be able to raise sufficient finance?' [102]
Incentives & financial sustainability	'Support regimes – incentives, how will it be funded?' [105]
Farming practice	'Farming culture suitability. Willingness of farmers to embrace a new land use.' [328]
Land use, rights & ownership	'Social sustainability – land rights, modern slavery, etc.' [325]
Policy effectiveness	'UK government policy in aiding supply chain performance' [107]
Employment opportunities	'Jobs in the supply chain, continued employment to ensure just transition' [328]
Transparency & certification	'Transparency of CO_2 market.' [116]

lower range than all three BECCS supply chains on criteria defined by interviewees. Interviewees expressed these contrasts in a variety of ways. Some of the stakeholders suggested that the planting and harvesting of biomass for BECCS could risk the loss of irreplaceable habitats provided by old growth biomass, whereas afforestation may provide benefits for biodiversity and climate. One policy stakeholder suggested that the contribution of a supply chain towards achieving national carbon budgets may be one of the most important considerations for governments. Whilst other stakeholders raised concerns over the ability of a supply chain to encourage the mitigation of fossil fuels rather than simply offsetting them, likely due to apprehensions from UK plans to switch the aviation industry to biofuels, or similar.

Aggregated MCM scores were also generated for the most frequently mentioned sub-themes (see supplementary information) to provide an understanding of how the supply chains performed on these sub-themes

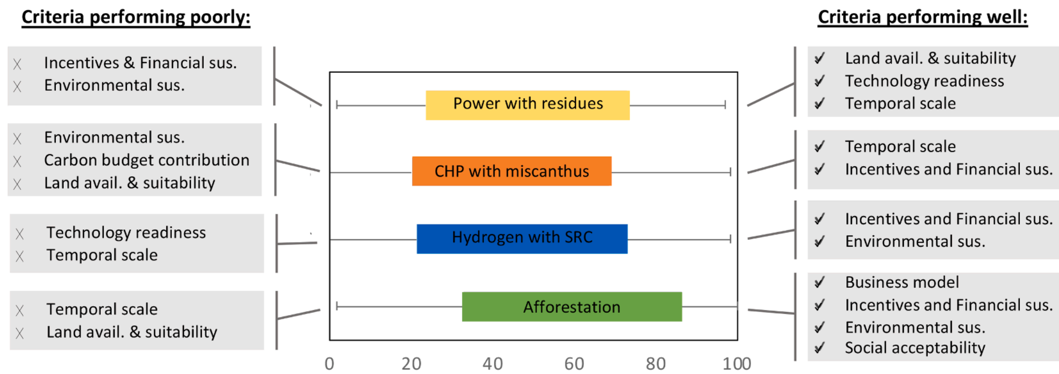

Fig. 3. Overall stakeholder (n = 22) interview scores for the four GGR supply chains (centre, in colour) annotated with sub-themes (in grey boxes) that they scored well on (right annotations) or poorly on (left annotations). Note: The chart displays an arbitrary scale from 0 to 100 expressing the aggregated weighted scores of all participants for each supply chain; higher scores indicate higher performance at meeting the criteria. The left end of the bar indicates the mean average of all pessimistic scores, and the right end of the bar indicates the mean average of all optimistic scores, while the T-bars indicate the lowest and highest scores given to each supply chain by any stakeholder.

(used for the annotations in Fig. 3). For example, afforestation performs well on criteria related to the 'Business model', 'Incentives & financial sustainability', 'Environmental sustainability' and 'Social acceptability'. However, afforestation does not perform as well on criteria such as 'Land availability & suitability', 'Temporal scale' and 'Carbon budget contribution', due to the large amounts of land required for afforestation and the time taken for forests to grow. Comparisons between the three BECCS supply chains reveals high scores for the 'power with residues' supply chain for criteria such as 'Land availability & suitability', 'Technology readiness' and 'Temporal scale'. However, the 'hydrogen with SRC' supply chain scores better on criteria such as 'Incentives and financial sustainability' and 'Environmental sustainability', thus illustrating its potential as a future GGR supply chain but lacking near-term deployment potential as the hydrogen economy is at an earlier stage of development compared to the present-day use of power with residues in the UK (i.e. Drax power plant in Yorkshire).

These results are broken down by stakeholder sector (Business & Industry, Policy and NGO) in Fig. 4. This shows a large difference in opinion on the 'power with residues' supply chain between the business & industry and NGO sectors. The NGO sector interviewees overall gave lower scores for 'power with residues' supply chain compared to the other CCS supply chains, showing some caution towards the environmental sustainability of biomass residues. It is possible that stakeholders' views may have been affected by their familiarity with the 'power with residues' supply chain due to its technology readiness level and carbon removal potential (Bui et al., 2018; The Royal Society, 2018). The NGO sector rated the 'hydrogen with SRC' supply chain highest of the CCS supply chains, explained during the interviews in relation to higher biodiversity benefits and lower chemical use. On the other hand, stakeholders from the policy sector did not score the 'afforestation' supply chain higher than the CCS related supply chains, mostly due to low scores for availability of feedstock along with land availability and suitability.

Fig. 5 shows the breakdown of the results of the MCM interview scores by dominant expertise: Bioenergy & Forestry, CCS and Climate change. Considering this breakdown in relation to that by sector (Fig. 4), some similarities can be seen between the NGO sector and the interviewees with expertise in climate change: both groups assign the highest scores to 'afforestation', followed by the 'hydrogen with SRC' supply chain as the highest scoring CCS related option. This is likely due to the similarity in group composition, with half of the group with dominant expertise in climate change being composed of NGO stakeholders. There are similar opinions from business & industry and policy stakeholders with similar backgrounds of the topic. Overall the bioenergy and forestry group scored afforestation highly but not as highly as the other groups; 'power with residues' was favoured over the other CCS related options. Stakeholders with expertise in CCS interestingly scored the 'afforestation' supply chain highest and the CCS related options rather similarly, perhaps suggesting these as equally leading technologies for the implementation of CCS at the time of this study.

The large ranges in the scores in Figs. 3, 4 and 5 partly result from the aggregation of stakeholder scores and also reflect the uncertainties in stakeholder views on the futures associated with the technologies in the supply chains, with differing effects on many criteria such as environmental sustainability, social acceptance, policy and governance. The large score ranges across the interviewee group convey the lack of certainty surrounding the realistic implementation of BECCS and afforestation to meet the amounts of carbon removal suggested by IAMs

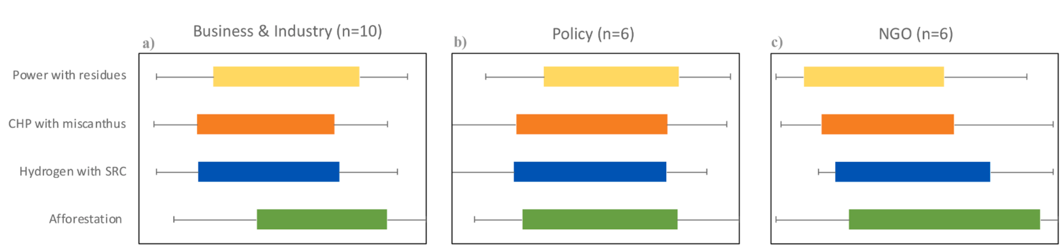

Fig. 4. Sector breakdown of the stakeholder scoring for the four GGR supply chains: a) Business & Industry (n = 10, with expertise breakdown of: 4 Bioenergy & Forestry, 4 CCS and 2 Climate change) b) Policy (n = 6, with expertise breakdown of: 4 Bioenergy & Forestry, 1 CCS and 1 Climate change) and c) NGO (n = 6, with expertise breakdown of: 2 Bioenergy & Forestry, 1 CCS and 3 Climate change). The charts display an arbitrary scale from 0 to 100 expressing the scores assessed for each supply chain; the higher values indicate higher performance. The left end of the bar indicates the mean average of all pessimistic scores in that sector, and the right end of the bar indicates the mean average of all optimistic scores in that sector, while the T-bars indicate the lowest and highest scores given to each supply chain by any stakeholder in that sector.

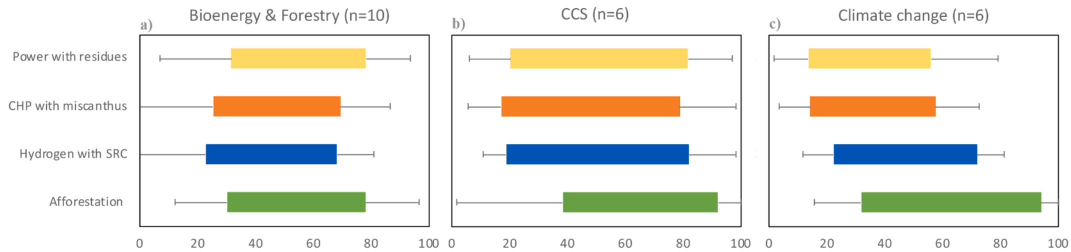

Fig. 5. Dominant expertise breakdown of the stakeholder scoring for the four GGR supply chains: a) Bioenergy & Forestry (n = 10, with sector breakdown of: 4 Business & Industry, 4 Policy and 2 NGO) b) CCS (n = 6, with expertise breakdown of: 4 Business & Industry, 1 Policy and 1 NGO) and c) Climate change (n = 6, with expertise breakdown of: 2 Business & Industry, 1 Policy and 3 NGO). Note: The chart displays an arbitrary scale from 0 to 100 expressing the scores assessed for each supply chain, higher values indicate higher performance. The left end of the bar indicates the mean average of all pessimistic scores in that expertise, and the right end of the bar indicates the mean average of all optimistic scores in that expertise, while the T-bars indicate the lowest and highest scores given to each supply chain by any stakeholder in that expertise.

models. It can be seen from individual MCM scores (provided in the supplementary information) that some stakeholders rated afforestation much higher than the other options (e.g. 102, 322 & 329), whereas others rated afforestation lower (e.g. 107, 206, 328).

Fig. 6 unpacks further the performance of the supply chains by the percentage of participants whose criteria were grouped under the nine themes, shown first by sector (Fig. 6a) then by dominant expertise (Fig. 6b). Overall each theme was mentioned by at least 45% of all stakeholders, with the 'carbon removal' and 'land & biomass' themes being mentioned by 95% of stakeholders overall (see supplementary information). 'Social', 'financial' and 'environmental impacts' themes were mentioned by over two-thirds of participants across sector and expertise. Interestingly, 'co-benefits' is the least mentioned theme, especially by the 'CCS', 'Business & industry' and 'NGO' stakeholders. Only one third of stakeholders with a self-stated expertise in 'climate change' mentioned 'infrastructure' and 'systems perspective' as scoring criteria. This suggests that although this group is familiar with the factors affecting and affected by the implementation of large-scale GGR, they may be less aware of the technical details surrounding the infrastructure and synergies of such implementation.

From a sector perspective, the policy group appear to consider a wider range of criteria in their scoring of the supply chains, with over half of the group having mentioned all themes which emerged from the feasibility criteria (in Fig. 2). The business & industry stakeholders also typically mentioned most themes although 'Co-benefits' was only mentioned by a small proportion of the group. The NGO group also made few mentions of the 'Co-benefits' and 'Infrastructure' themes. It is possible that this reflects groups mentioning more frequently the criteria that align closely with their experience and expertise. However, the low percentage mention (33%) of 'Co-benefits' by the NGO group is surprising.

3.2. Feasibility criteria from the breakout group discussions at the workshop

The aims of the breakout groups were to discuss the overall and individual results of the MCM interviews in order to explore and identify any consensus/differences in opinion around the results. Two key points that arose in these sessions had not been mentioned in the interviews. Firstly, the future of hydrogen and its use in a domesticated gas grid, rather than for power, which is dependent on a suitable gas network being in place. Secondly, group discussions naturally shifted to global supply chains, geo-politics and the change in political appetite for action on climate change in recent years.

The environmental sustainability of biomass was also debated at length during the workshop, with conflicting views. One business & industry stakeholder suggested that the 'power with residues' supply chain is a "disaster" from a carbon accounting perspective as it "relies on regrowth time" [327]. This was defended by another business & industry stakeholder saying "It's just journalists making noise, not scientists" and "residues get piled up and burned by forest managers if they aren't used productively" [328].

Feedback was also obtained on how stakeholders had used the scoring ranges within the MCM interviews and views on the MCM method used in this study. Some stakeholders expressed difficulty in scoring the full supply chains without a preference for one element of the supply chain – "taking hydrogen for example, if I think the technology will work then I would give it a high score" [105]. Overall, the workshop feedback on the results of the MCM interviews suggested the stakeholders found the results surprisingly optimistic for the feasibility of BECCS. Although the range of scores is large, the results seem to indicate some optimism for BECCS if done sustainably. Some specific feedback on supply chains was also obtained. Some of the breakout groups

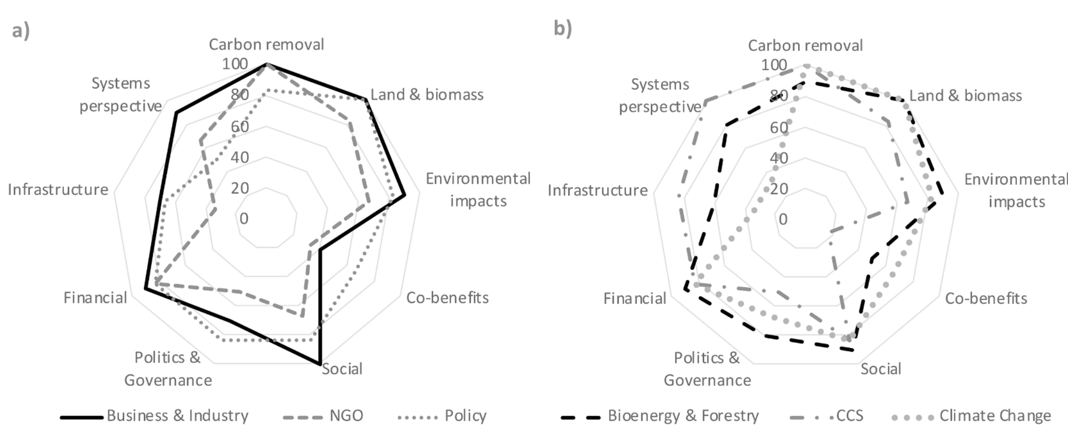

Fig. 6. Percentage of stakeholders mentioning each theme from a) each sector and b) each dominate expertise. Number of stakeholders in each category is: Business & Industry (10), NGO (6), Policy (6), Bioenergy & Forestry (10), CCS (6) and Climate Change (6).

mentioned that the 'CHP with miscanthus' supply chain would need a demand for the heat generated, which could be its downfall if the heat is not required. Whereas the 'hydrogen with SRC' supply chain was suggested to be more efficient if the hydrogen generated was injected directly into the UK gas network.

3.3. Scaling exercise at the workshop

In the scaling exercise, most of the comments referred to two main pinch points about: (1) land availability and (2) the availability of CCS infrastructure (see Fig. 7). Further interesting points were raised around the resilience of supply chains to future changes in climate and increasing global population, which would have a greater impact on the climate. It was noted that the implementation of CCS is dependent upon an increased demand for energy emitting greenhouse gas emissions; however future power generation may be provided through other renewable energy sources e.g. Wind/PV, thus negating the need for biomass energy. A skilled workforce was identified as a potential pinch point for large-scale forestry and BECCS supply chains: if forestry stocks are to be increased at a national or global scale, this will need to be provided by an increase in skilled foresters.

At the UK scale, it was identified that there may be conflicting willingness from landowners and tenants to grow the biomass required by the supply chains (Table 4). There was also concern over the UK's tree seed collection and tree nursery capacity, which may lead to the importation of biomass crops to be grown. Consistent potential 'pinch points' identified across the breakout groups of this scaling exercise included: land use management and regulation, carbon accounting, carbon markets, incentives, public acceptance and cross-border risks.

It was also identified during the scaling exercise that the GGR supply chains are likely to compete with other forms of negative emission technologies such as direct air capture and storage (DACS) which have been less commonly used by integrated assessment models (Butnar et al., 2019). One participant stated that "Competition of infrastructure with DACS will be a critical pinch point in my opinion" [217]. Although BECCS may bring benefits of generating power alongside providing greenhouse gas removal, some stakeholders suggested that a future energy system with more wind and solar may lead to less need for carbon removal technologies that generate power.

The global scale-up discussions were again mainly dominated by concerns over land availability and infrastructure for CCS; also 'Global cooperation' was frequently mentioned, reflecting the greater international focus of these supply chains. Some stakeholders mentioned that the UK is well placed for biomass power generation and CO_2 storage potential. However, they also pointed out that the availability for planting in the UK will rely on tree seed collection and UK nursery capacity.

The conversation around global use of land raised questions over governance, such as the longevity of policies and incentives put in place to change land use to over to forests, combined with risks posed by fires and pests that may decrease carbon stocks. The stakeholders suggested there would also be albedo effects from higher global coverage of forest. Financial models for funding carbon removal may be feasible for businesses that are looking to neutralise their emissions; however cross-border carbon accounting would require careful regulation. There were some concerns over the timescale for the scale up of technologies required to meet the necessary amount of carbon removal and competition with direct air capture and storage (DACS) infrastructure. It was suggested that location for carbon storage is key for supply chains and that biomass for export will need to be grown near to the coast for ease of transport. However, the length and complexity of the international supply chains was raised as a risk with the potential for countries to change plans and impact supply chains. It was suggested that risk sharing along the supply chain was needed i.e. from biomass providers, energy producers and carbon storage providers.

Table 4
Pinch points and relevant selected quotes identified when considering scaling up BECCS and afforestation at a UK scale and a global scale. (Note: Numbers denote stakeholder ID – see Table 1).

Pinch points	Selected quotes
UK Scale	
Willingness of landowners to convert land	'Willingness of farmers to take the risk that conversion plant gets built/keep operating, and so plant crops ahead of time.' [102] 'Farmers/Landowners reluctant to commit their land long-term.' [326]
Tree seed/nursery capacity	'Tree seed collection is too restrictive.' [320] 'Nursery supplies or new crops/varieties take years to develop and ramp-up supplies for planting.' [102]
Policy & incentives required	'Availability of suitable incentive regime.' [105] 'Absolute policy commitment for biomass, afforestation & CCS.' [206]
Global Scale	
Global cooperation on carbon removal strategy	'Political concerns – if there is a trade war, countries mostly relying on other countries' production might be negatively impacted.' [331] Geopolitical scenarios & implications – effect on conventional supply e.g. Russia & Indonesian gas. [323]
Regulation	'Risk of exporting environmental problems. Will land use practise abroad be well managed? There is no existing agricultural industry which is sustainable globally. E.g. palm oil remains badly managed after decades of pressure.' [215] 'Carbon accounting/carbon leakage/transboundary regulations.' [113]
Resilience to future climates	'Availability of land/biomass under climate change.' [113] 'Population.' [321]

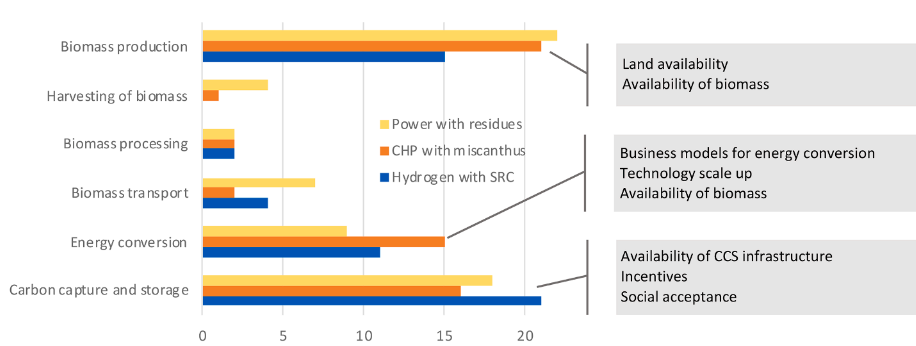

Fig. 7. Number of comments from the scaling exercise, identifying potential problems (referred to as 'pinch points' during the workshop) along the three BECCS supply chains. Number of comments plotted against stage in the supply chain for the three BECCS supply chains. Annotations (on the right) are the most common issues identified for the three most commented stages (biomass production, energy conversion and CCS).

4. Discussion

This study used Multicriteria mapping (MCM) methodology in a novel way to assess the 'real-world' feasibility of four specific greenhouse gas removal supply chains, at a granular level. Stakeholder insights were elicited from a diverse group of business and industry, non-governmental organisations and policy participants. The results provide detailed insights into the criteria that stakeholders deem to be important considerations for the feasibility of large-scale (UK level) implementation of BECCS and afforestation for GGR, providing a deeper understanding of the issues facing these approaches.

Of the most frequently mentioned criteria, availability and suitability of land, reflect in part existing studies which identified competition for land for BECCS and afforestation as an important factor affecting the feasibility of GGR approaches (Dooley and Kartha, 2018; Rickels et al., 2019). Three new key criteria emerged from this work which were not evident in research during the first phase of this project (Forster et al., 2020): 'business model', 'energy systems and industry integration' and 'farming practice'. These relate to business opportunities for GGR approaches and how these may be funded, and have been identified as salient in a recent review of the literature (Waller et al., 2020). Integration of different formulations of BECCS within the existing and emerging UK energy and industry decarbonisation landscape was identified as a challenge with a lot of trade-offs (Bui et al., 2021; García-Freites, et al., 2021). Throughout the process, participation of the farming community was identified as a key challenge and considerable concerns were expressed over who owns the land intended for use by these supply chains, and how likely are they going to move away from current land uses, even with better profit margins. In the UK, of particular relevance are the development of the Environmental Land Management schemes (ELMs) and Bioenergy strategy, affected by existing UK legislation e.g. The Planning Act, 2008; Compulsory Purchase Act, 1965 and Acquisition of Land Act, 1981 (O'Beirne et al., 2020). Farming community participation was identified as a potential problem both within the UK and globally, with some participants suggesting that a form of risk sharing for actors along the supply chains might be the best way of overcoming this. However this is likely to become a significant challenge at a global scale, with scale previously being identified as an important factor affecting decision-making for GGR (Cox et al., 2018). Biomass species will likely require purchasing from overseas, subjecting the UK to a need for 'global cooperation', market conditions and regulation standards, crucial for the delivery of global CO_2 removal (Fajardy and Mac Dowell, 2020).

Overall, stakeholders indicated the BECCS and afforestation supply chains examined in this study to be feasible to different extents, based on the criteria used for their assessment. However, the successful implementation of these supply chains is by no means guaranteed and depends on a number of factors. Interestingly, the 'afforestation' supply chain scored higher overall compared to the BECCS supply chains in stakeholder MCM appraisals (although it should be noted that there were significant overlaps in option performance between these supply chains). This is particularly interesting as many of the stakeholders who participated are aware of the extent that large-scale GGR approaches are needed to meet net zero targets, and are likely aware of the lower carbon removal potential of afforestation compared to BECCS. This preference for afforestation may reflect public considerations that technology based solutions would not address the root causes of climate change (Climate Assembly UK, 2020) hence would not provide a meaningful contribution to a sustainable world in the long-term (Cox et al., 2020).

Afforestation scored high on some criteria because it was considered to be low cost, environmentally sustainable and socially acceptable. Interestingly, a recent study of UK citizens found a similar preference for nature based solutions over technological solutions when asked which GGR methods should be part of how the UK gets to net zero (Climate Assembly UK, 2020). We note caution in these comparisons as there appears to be substantial heterogeneity amongst stakeholder (and public) meanings of afforestation, varying from publicly accessible deciduous woodlands to timber industry monoculture stands. However, the results presented here are based on discussions relating to a specific configuration of an afforestation supply chain and reflect the views of experts and practitioners, less likely to be influenced by a 'natural climate solution' framing. Nevertheless, different types of afforestation would likely lead to differences in MCM performance and may be perceived as 'nature based' to differing degrees. Some of the stakeholders mentioned the need for considering together the dual crisis of rapid climate change and unprecedented biodiversity loss reflecting similar calls in the framework for sustainable development (Raworth, 2012) and the Sustainable Development Goals, and more recently the increased collaboration between IPCC and IPBES. These findings underline both the value of using detailed supply chains and of assessing GGR approaches in terms wider than cost and carbon removal.

By assessing full-scale refined BECCS supply chains in a real-world context, this work differs notably from previous studies that have used generalised and abstract descriptions of BECCS and afforestation. The work builds on the first attempt to map perceptions around the feasibility of BECCS for GGR from a diverse range of stakeholders (Forster et al., 2020) by applying multicriteria mapping in a novel way, to open up the appraisal of four GGR supply chains. Although perhaps somewhat counter-intuitively, the more detailed supply chains used in our study generated themes consistent with previous technology appraisals (Bellamy et al., 2016) but also resulted in the more detailed consideration of complexities and uncertainties. A recurrent theme in the MCM analysis, as illustrated by large ranges and overlaps in option performance between supply chains, is the large uncertainties surrounding the futures of these approaches. This is perhaps not surprising given that at 'large scale' these are still very much imagined and emerging technologies: BECCS does not yet exist at large scale whereas afforestation is very heterogenous and not currently available at a large scale in the UK. Pilot-scale trials of these GGR technologies may assist in reducing some of the uncertainties observed in this study, by exploring options of how GGR supply chains could be enabled with specific incentives, regulations and policies (Lomax et al., 2015). By taking a more granular approach, this work has revealed some important details that may otherwise be overlooked or not considered if the foci of the study, such as BECCS and afforestation, are kept general and non-specific.

Importantly, this analysis shows that when GGR approaches like BECCS and afforestation are taken out of abstract representations in integrated assessment models and explored at a more granular level through a supply chain analysis, additional uncertainties, complexities and challenges to the realisation of carbon dioxide removal emerge. This suggests that future attempts to demonstrate and then scale up these approaches are not going to be as smooth as often assumed in modelling studies, and will thus open up possibilities for fuller consideration of multiple values and viewpoints that could strengthen the robustness of new policies on GGR (Forster et al., 2020). We recognise that this MCM study considered only three BECCS and one afforestation supply chain and that location specific details were absent from the analysis. However, place-based considerations, which are important for a realistic appraisal of these options (Devine-Wright, 2013), will only stand to further increase rather than decrease complexities, uncertainties and social contingencies as attempts to actually realise GGR gather pace.

Overall, then, the analysis presented in this paper has demonstrated the value of assessing detailed specific supply chains. If UK net zero policy targets are to be met by 2050 then GGR approaches (alongside emissions reductions options) need to be examined carefully in more situated ways, drawing on diverse perspectives and expertise in the context of varying societal demands and alternative climate futures. The iterative participatory approaches used in this study enable more effective decision-making that takes complexity into account (Forster et al., 2020; Hoolohan et al., 2019) and open up opportunities for multiple layers of influence. In addition to the research insights directly influencing the decision-making process (CCC, 2019; BEIS, 2019), participants from a variety of different sectors interact with and learn from each other during the engagement processes (interviews, workshops), enabling further influence as they share their experiences with colleagues in their respective institutions in subsequent conversations. Through the more detailed and nuanced assessments of real-world supply chains, our study contributes to discussions on responsible and careful consideration of such GGR approaches (Fuss et al., 2020), as more countries commit to net zero targets. This attention to context and use of detailed supply chains helps to illuminate key issues and opportunities; further research could explore the application of the methods in this study to other national contexts, with diverse publics (Cox et al., 2020; Waller et al., 2020) and in relation to governance and climate policy requirements.

5. Conclusions

This study's novel use of a multicriteria mapping methodology revealed that stakeholders considered more feasible an afforestation supply chain over three BECCS supply chains.

The methodology used more detailed descriptions of BECCS and afforestation than earlier work, which elicited new insights such as the importance of location, business model and land ownership: the location of GGR would be key for integrating into existing supply chains which could assist the business outlook. Although this could be impeded by the need to adapt farming practices to accommodate some of the supply chain requirements. We suggest that policy decisions made regarding the implementation of BECCS and afforestation supply chains consider the diverse range of criteria generated by this stakeholder group. We recommend that future assessments of such supply chains build on this robust set of evidence to consider the views of those beyond the stakeholders of this workshop and incorporate this work into wider discussions about mitigation options and climate futures.

6. Author statement

The authors certify that all authors have seen and approved the final version of the manuscript being submitted. They warrant that the article is the authors' original work, hasn't received prior publication and isn't under consideration for publication elsewhere.

Data sharing statement

Interviewees did not consent to their data being retained or shared due to the sensitive nature of the information. Anonymised data is provided in the results section of this paper.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2021.102369.

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