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Original research article

Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers

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ABSTRACT

Keeping global warming well below 2 °C entails radically transforming global energy production and use. However, one important mitigation option, the use of bioenergy with carbon capture and storage (BECCS), has so far received only limited attention as regards the sociopolitical preconditions for its deployment. Using questionnaire data from UN climate change conferences, this paper explores the influence of expertise, actor type, and origin on respondents' a) preferences for investing in BECCS, b) views of the role of BECCS as a mitigation technology, globally and domestically, and c) assessment of possible domestic barriers to BECCS deployment. Non-parametric statistical analysis reveals the low priority assigned to investments in BECCS, the anticipated high political and social constraints on deployment, and a gap between its low perceived domestic potential to contribute to mitigation and a slightly higher perceived global potential. The most important foreseen deployment constraints are sociopolitical, which in turn influence the economic feasibility of BECCS. However, these constraints (e.g. lack of policy incentives and social acceptance) are poorly captured in climate scenarios, a mismatch indicating a need for both complemented model scenarios and further research into sociopolitical preconditions for BECCS.

1. Introduction

To keep global warming well below 2 °C, current greenhouse gas (GHG) emissions must be halved by mid century and must then continue to decline [1]. This will require rapid changes in energy systems and land use practices. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) contains about 300 scenarios considered to have a good chance of meeting the 2 °C goal. However, most AR5 scenarios are around ten years old. Recently, a new scenario framework has been developed that combines different so-called shared socioeconomic pathways (SSPs), describing global development trajectories, with representative concentration pathways (RCPs) for different climate outcomes [2]. The SSP database assembles global energy system scenarios that account for recent technological developments, such as solar and wind power, and that have integrated land use models with improved representation of biomass availability [3].

In both the AR5 and SSP scenarios, bioenergy with carbon capture and storage (BECCS) is a key technology for meeting the 2 °C goal (see Fig. 1). It has the potential to achieve negative GHG emissions and can therefore, if implemented on a large scale, compensate for a mid-century temperature overshoot by more aggressive total emission reductions or even negative emissions in the second half of the century.

However, BECCS is currently only in the development phase. Much uncertainty surrounds estimates of storage capacity, biomass availability, conflicts with biodiversity and food security goals, costs and financing opportunities, and competition for land, fertilizers, and water [4,5]. There have been efforts to capture many of these aspects in the Integrated Assessment Models (IAMs). However, sociopolitical preconditions such as political support and public opinion have so far received little attention, despite their importance for transition management [6,7]. Building on questionnaire data from three UN Framework Convention on Climate Change (UNFCCC) conferences, this paper helps fill this research gap by exploring how expertise, actor type, and origin influence respondents'

a) preferences for investing in BECCS,
b) views of the role of BECCS as a mitigation technology, globally and domestically, and
c) assessment of possible domestic barriers to BECCS deployment.

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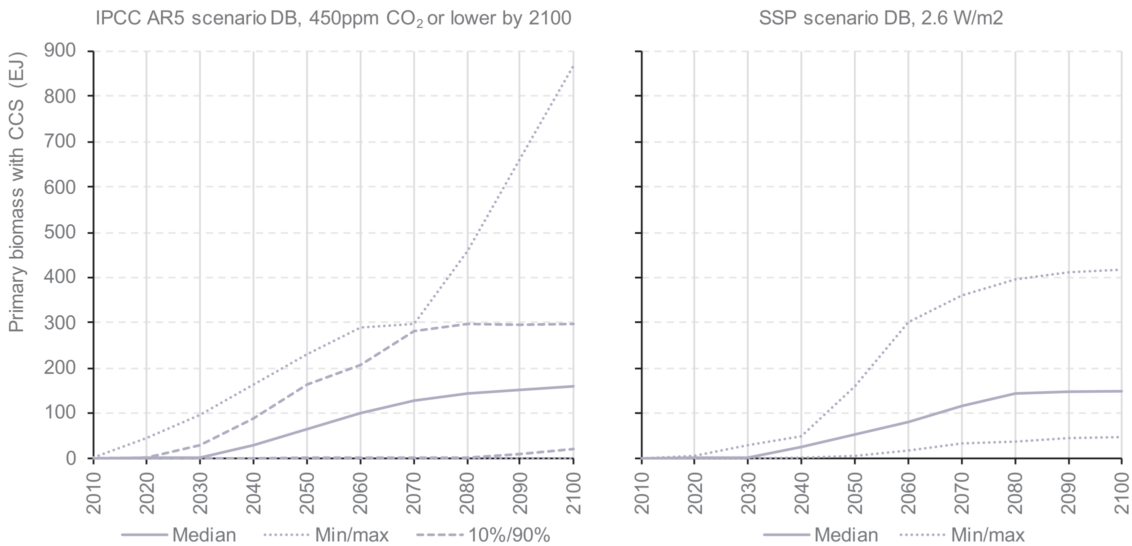

Fig. 1. Bioenergy use with CCS in primary energy supply in AR5 scenarios (left, https://tntcat.iiasa.ac.at/AR5DB) and in SSP scenarios (right, https://tntcat.iiasa.ac.at/SspDb). The figures can be compared with the total primary energy consumption in the EU (EU28) in 2014, which amounted to 68 EJ.

The results are related to scenario outcomes of current models in a forward-looking discussion of whether and how the models could be improved to produce more robust climate scenarios. The article extends a previous study by Fridahl [8] both in terms of number of responses and through introducing new survey items. Compared with the previous study, we have over twice the data on preferences for investing in BECCS, and the delegates' views of new issues are now gauged relative to global and domestic potential as well as possible deployment barriers. An expert sample has also been selected, enabling the exploration of differences between the broader sample and delegates with high knowledge of BECCS.

Section two summarizes the literature on the role of BECCS in climate scenarios, attitudes toward it, and drivers of and barriers to its deployment. Section three describes the questionnaire design, the data collection method, and the statistical analysis. Section four presents the results, which are then discussed in section five in light of the most recent scientific literature on social views of and political preferences for BECCS. Section six concludes that respondents put a low priority on investing in BECCS and that they anticipate constraints on its deployment in both the political and social domains. The results also point to a disparity between respondents' view that BECCS has little potential to contribute domestically and their slightly more positive view of its global potential. These results speak to the need for further research into the sociopolitical preconditions for BECCS deployment and for complemented model scenarios.

2. Background

Although it is a largely unproven technology, BECCS features strongly in long-term climate scenarios. When producing these scenarios, most models assume the carbon-neutral production of biomass. This assumption allows the generation of large-scale negative GHG emissions from BECCS, that is, the removal of CO_2 from the atmosphere into geological formations. Future negative emissions can potentially compensate for emissions in areas that will be difficult to mitigate completely, such as agriculture [9].

As shown in Fig. 1, BECCS is deployed in all of the new SSP scenarios compatible with an increase in radiative forcing of 2.6 W/m^2 by 2100 (i.e. likely to reach the 2 °C goal). Its deployment rapidly increases in all five model regions starting from mid century. While there have been only small changes in the AR5 and SSP median scenarios, the ranges of BECCS use have narrowed significantly in the latter, at least partially attributable to fewer scenarios.

The SSP framework considers five possible socioeconomic world developments. The sharpest increase in BECCS deployment occurs in a world characterized by delayed mitigation efforts (the so-called SSP5, see [2]). This is compatible with the literature, which asserts that delays in mitigation efforts increase the need for and importance of large-scale BECCS use late in the 21st century to compensate for the earlier temperature overshoot [4,9]. However, BECCS is deployed at significant levels in all SSPs. In fact, in the median scenario, BECCS is deployed for about 20% of the total primary energy supply in 2100. This speaks to the importance of understanding the drivers of and barriers to BECCS deployment to enable assessment of the feasibility of these scenarios.

2.1. Drivers of and barriers to BECCS deployment

Besides assuming sustainable biomass production, the scenarios informing climate policy-making also make assumptions about policy, including the assumption of a near-term globally uniform carbon price and robust international coordination. As noted by Peters [10], there "is an urgent need for scenarios based on more realistic policy assumptions" (p. 648). The literature has identified several potential drivers of and barriers to BECCS deployment that are omitted or only crudely captured in scenarios. These include the regional availability of biomass and storage capacity [9,11], political prioritization and design of policy incentives such as carbon taxes, subsidies, and price guarantees [12,11], social acceptance [13,14], and technological readiness [15].

The literature on how politicians and various non-state actors understand BECCS is very limited [16,14]. Almost all the scientific literature on negative-GHG-emission technologies comes from the natural, agricultural, or engineering sciences [7]. Analogous studies of fossil CCS report low levels of public acceptance, and demonstrate that market failure and a lack of financial incentives also act as barriers to deployment [17,18].

Dütschke et al. [13] and Fridahl [8] have, however, also demonstrated that acceptance of and preferences for BECCS differ from those for fossil CCS. The few studies focusing specifically on how BECCS is perceived conclude that both actor type and regional origin matter. For example, environmental NGOs are reportedly much more skeptical of BECCS than are governmental actors. Preferences relating to investing in BECCS also differ between world regions, with more positive views in regions with higher technical potential in terms of biomass availability and storage capacity [8]. It has also been found that public resistance to fossil CCS is stronger than to BECCS [13]. Vaughan and Gough [15], reporting on results from an expert elicitation process, concluded that

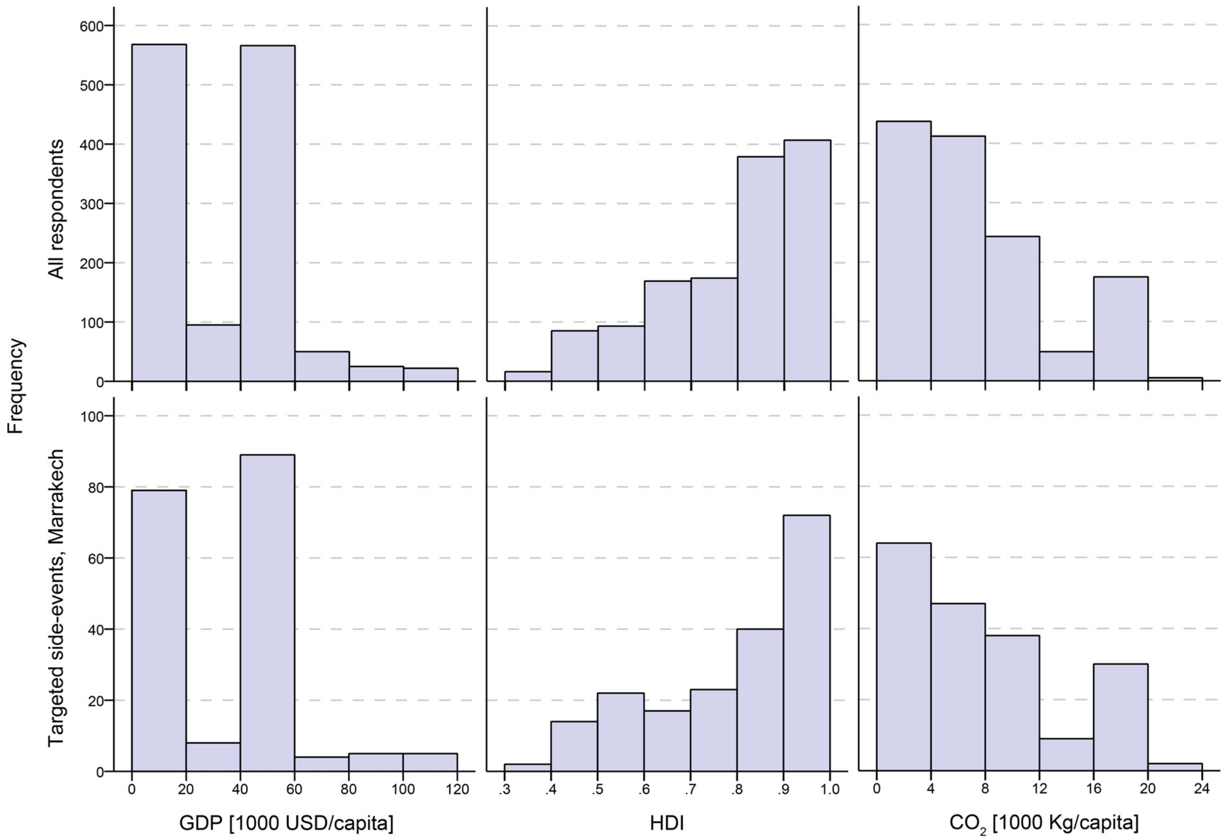

Fig. 2. Characterization of the sample: number of respondents by level of gross domestic product (GDP) per capita, human development index (HDI), and carbon dioxide emissions (CO_2) per capita in their country of residence. The pattern for the specific sample of targeted side events in Marrakech roughly mirrors the pattern for all respondents. Data on GDP/capita, HDI, and CO_2/capita were gathered from the World Bank Indicators for 2014 and connected to respondents' country of residence. Top: $n = 1329$ (274 out of 1603 respondents did not indicate their country of residence); bottom: $n = 190$ (44 out of 234 respondents did not indicate their country of residence).

the largest potential deployment barriers are in the social and political dimensions. These dimensions are also reportedly less researched than the technical dimension (assessed by the experts as a largely insignificant barrier) and storage capacity (assessed as a less significant barrier).

This article builds on these studies to explore both whether preferences for BECCS are influenced by the level of knowledge of BECCS and the extent to which experts' views of potential barriers to deployment are mirrored by state and non-state actors from different world regions.

Peters [10] also demonstrated the importance of understanding the priority assigned to BECCS in the context of a range of alternative technologies. This article therefore contextualizes preferences by probing respondents' views of the need to prioritize investments in BECCS vis-à-vis alternative low-carbon technologies.

2.1.1. Location of BECCS: role in the global response versus domestic deployment

The debate in the wake of the Paris Agreement has also addressed the inconsistency between the global temperature goal and states' contributions to achieving this goal. Several assessments conclude that the states' contributions under-contribute relative to cost-optimized pathways to meet the global goal [19–21]. Given that many models assume carbon-neutral biomass production and strong policy, there is an urgent need to mobilize state and non-state mitigation actions to meet the goal [10]. For example, globally uniform carbon prices in the near term are politically infeasible. This makes the exploration of different actors' views of the global versus domestic potential of BECCS pertinent. This article therefore also explores views of the role of BECCS in contributing to the 2 °C goal globally and to what extent BECCS has the potential to contribute to mitigation domestically.

3. Method

3.1. Questionnaire design and data collection

The data were obtained through questionnaires distributed at the UNFCCC's 42nd Subsidiary Bodies meeting in Bonn (June 2015), the 21st Conference of the Parties (COP21) in Paris (December 2015), and COP22 in Marrakech (November 2016). All survey items were part of the International Negotiations Survey (see e.g. [22]).

On the one hand, UNFCCC delegates are likely quite well informed about mitigation technologies and climate scenarios. The rationale for sampling this population is that many UNFCCC delegates are involved in designing, implementing, monitoring, and scrutinizing domestic climate policy and action. The UNFCCC conferences gather a broad range of actors involved in climate policy and mitigation – from policymakers to implementers and researchers to lobbyists – making these forums particularly valuable for gathering informed views of the potential for low-carbon development from around the world. This could be compared with, for example, sampling an IPCC conference gathering mostly academic experts and specialized civil servants. IPCC delegates are even more likely to be well informed of BECCS, but the more specialized population also lacks many types of actors that are important for transition management. On the other hand, other populations (e.g. industry actors and investors) might have a stronger direct influence on the trajectory of BECCS development. In the future, it would be advisable to compare UNFCCC delegates' views of BECCS with those of a sample of, for example, actors directly involved in the bioeconomy, the power and petroleum industry, and sustainable investment. This article, however, starts from the low priority assigned to BECCS by UNFCCC delegates as identified by Fridahl [8], who noted a need both to validate previous results through extending the sample and to seek explanations for why preferences are low, for example, by exploring views of likely domestic drivers of and barriers to deployment.

To locate respondents highly acquainted with BECCS, the questionnaires were distributed in person at selected side events at the conference venues in Marrakech. Events focusing on various aspects of scenario building, geoengineering, CCS, and transition pathways were targeted. In addition to questions about investment preferences, these respondents ($n = 289$) were also asked about drivers of and barriers to BECCS deployment, allowing us to explore whether the level of knowledge of BECCS influences attitudes. Additional data on investment preferences were also obtained in a larger sample through questionnaires distributed to delegates attending all other parts of the Marrakech conference ($n = 603$). Combined with responses from Paris ($n = 577$) and Bonn ($n = 134$), this approach gives a total of 1603 respondents (see Fig. 2).

Most countries of the world fall between 0.6 and 0.9 on the human development index (HDI), have a gross domestic product (GDP) of up to USD 20,000 per capita, and CO_2 emissions of up to 4000 kg per capita. In the population sampled, a relatively high number of respondents resided in countries above the world average in HDI, GDP, or CO_2 emissions. This reflects the fact that high-income countries can afford to send more delegates to these conferences than can low-income countries. This fact should be borne in mind when interpreting these results.

The questionnaire was designed using Likert-style response option items, which measure attitudes toward options related to a stem statement, providing respondents with a bipolar weighting [23,24]. The respondents were asked to agree or disagree with statements concerning their knowledge of BECCS, investments in energy transitions, and deployment barriers. For statements about alternative technologies for energy transitions, the questionnaire focused on a key sector for BECCS: electricity production. This was done to limit the scope to a manageable number of alternative items. The remaining questions concerned deploying BECCS in multiple sectors.

Each statement was followed by individual Likert items to be prioritized relative to one another on a response scale ranging from one (“disagree strongly”) to seven (“agree strongly”). The article follows the convention in the survey-design literature of treating the middle option, “neither agree nor disagree,” as reflecting indifference or ambiguity rather than as indicating “don’t know” [25].

It should be noted that the so-called acquiescence bias, that is, the tendency of respondents to agree rather than disagree with a Likert statement, likely generated a slightly more positive response pattern than if the attitudes had been measured using other methods [26]. Although this has an important effect when measuring absolute preferences, it is less significant when comparing relative preferences, as is done here. (See the online Supplementary material for the BECCS-related questionnaire items as well as additional information on the sample properties.)

3.2. Method of analysis

The responses ($n = 1603$) were divided according to the respondents’ primary role at the UNFCCC, the responsibility of their country of residence to act, and their level of knowledge of BECCS. These categories were based on previous literature highlighting the different roles and views of governmental and nongovernmental actors, actors from different world regions, and actors with different types and levels of expertise.

In terms of their primary role, the respondents can be divided into *governmental actors* representing local and national governments and *nongovernmental actors*, such as actors from environmental, research, workers’, women’s, and business NGOs. This division results in 631 governmental and 972 nongovernmental respondents.

The UNFCCC’s division of countries into Annex 1 countries (i.e. developed countries with high responsibility to act) and non-Annex 1 countries (i.e. developing countries with low responsibility to act) is used as a proxy for responsibility to act. The data are accordingly divided into groups of respondents residing in countries with high (Annex 1) and low (non-Annex 1) responsibility to act. The division results in 548 respondents from countries with low responsibility and 760 from countries with high responsibility to act. In addition, HDI is used as a proxy for capacity to act. All tests based on groups with high or low responsibility to act were also run using the 2016 UN Development Programme’s cutoff points for countries with high versus low HDI (i.e. low HDI $< 0.700 \leq$ high HDI). Dividing respondents into Annex 1 and non-Annex 1 groups or low- and high-HDI groups produces the same statistically significant differences between groups, but at slightly different probability levels. The similarities can be explained by the fact that many countries with high HDI are also listed in Annex 1 and many with low HDI are non-Annex 1 countries. As such, we also use responsibility to act as a proxy for capacity to act.

The level of knowledge among the respondents attending specific side events at COP22 (see Section 3.1) was measured using a self-assessment on a scale ranging from low (1) to high (7). Due to the positive bias in Likert response options, the cutoff point for low knowledge was set at 5 (i.e. low knowledge $< 5 \leq$ high knowledge). This division results in 129 respondents with high and 105 with low knowledge of BECCS.

The dataset is non-normally distributed and ordinal, and thus requires nonparametric statistical analysis. Several nonparametric tests are adequate when comparing differences between two groups. One of the most powerful is the Mann-Whitney U test [27], which was used to confirm statistically significant differences among the groups of respondents described above. The test assumes that the groups’ responses have similar distributions, which is the case for all the data used here. When differences are confirmed, an effect size is calculated to estimate the influence of belonging to a specific group. Appropriate nonparametric effect sizes calculated by Fritz et al. [28] were used here. The effect size is reported as r and is often considered small if in the 0.10–0.30 range, medium if 0.30–0.50, and large if greater than 0.50 [29]. However, effect size estimates are highly context dependent. What is considered small in one context may be large in another, and a small effect size does not mean that a difference is necessarily insignificant in applied terms. The results reported here can, by the standard measures described above, be considered small (i.e. between 0.10 and 0.30). A small effect size can also be expressed as a percentage of nonoverlap in responses, for example, 15–38%, or as the probability that a randomly sampled member of one group is more likely to score higher than a randomly sampled member of the other group, that is, a probability of 56–66% [28].

Spearman’s rho was applied to analyze correlations. It is a nonparametric method to assess the strength of relationships between two variables [30]. The result ± 1 denotes perfect correlations while 0 denotes no correlation. A relationship between 0.5 and 0.9 (or -0.9 and -0.5) is usually considered strong, 0.3 and 0.5 (or -0.5 and -0.3) moderate, and -0.3 and 0.3 weak.

4. Results

4.1. Investment preferences

In general, the respondents disagree with the statement that the electricity production system of their country of residence is low carbon and agree that investments in technology are required for the system to become low carbon in the long term (i.e. between 2040 and 2060). When prioritizing such investments, respondents generally assign BECCS a lower priority than renewables and a higher priority than fossil

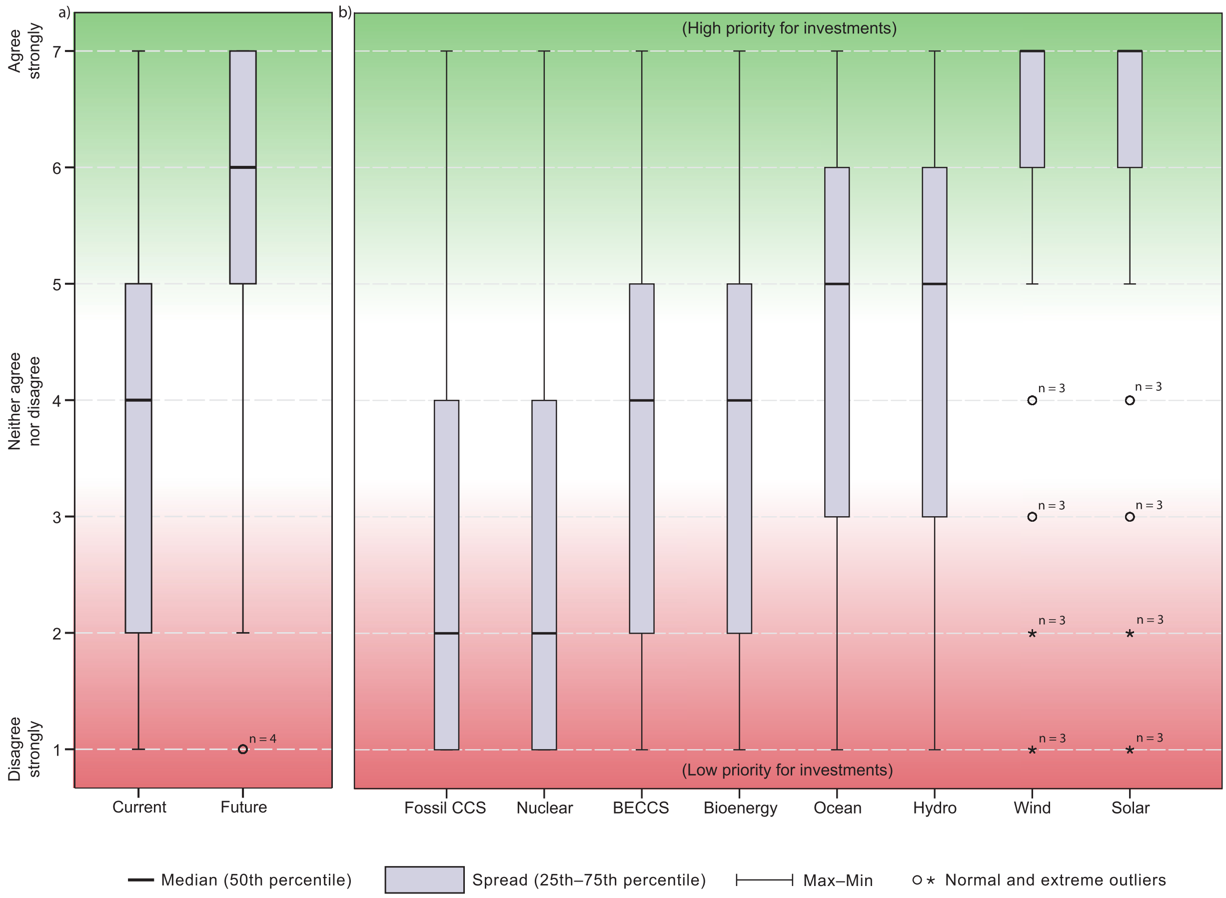

Fig. 3. Global (all respondents) agreement (7) or disagreement (1) with questions regarding a) the extent to which current electricity production system in the respondent's country of residence is low carbon and the need for investment if future electricity production is to be low carbon, and b) investment preferences for transformation of the electricity production system toward a low-carbon configuration. Mild outliers are denoted by circles and extreme outliers by asterisks; *n* refers to the number of outliers.

CCS and nuclear energy (see Fig. 3).

There is no statistically significant correlation between the respondents' view that investments are required to achieve low-carbon electricity production in the future and the priority they assign to BECCS for such investments. There is a positive correlation between the view that current electricity production system is low carbon and prioritizing investments in BECCS, but the correlation is weak (Spearman's rho = 0.151, $p = .000$). Furthermore, a Mann-Whitney U test provides no evidence that the respondents' level of knowledge of BECCS influences their views of current and future electricity production systems. However, the same test indicates that respondents from NGOs consider current electricity production more carbon intensive ($n = 389$) than do governmental actors ($n = 293$, $p = .000$, and $r = 0.10$). Respondents who reside in countries with high responsibility and capacity to act ($n = 318$) are more likely to agree that current electricity production in their country of residence is carbon intensive than are respondents residing in countries with low capacity to act ($n = 244$, $p = .020$, and $r = 0.20$).

There is no evidence that respondents who know more about BECCS are either more positive or more negative toward prioritizing investment in the technology than are respondents who know less about BECCS. This is evident from a Mann-Whitney U test that shows no evidence that the level of knowledge of BECCS influences investment preferences. On the other hand, whether a respondent represents a governmental organization or an NGO does influence their investment preferences. The preference for investing in BECCS among governmental actors ($n = 451$) significantly exceeds that of nongovernmental actors ($n = 725$, $p = .000$, and $r = 0.17$). There is also a statistically significant difference between respondents who reside in countries with high ($n = 609$) versus low ($n = 415$, $p = .000$) capacity to act. However, the influence of the country of residence is very small ($r = 0.08$). The fact that respondents from countries with low capacity to act are more positive toward BECCS mirrors the general response pattern regarding low-carbon electricity generation technologies. Respondents residing in countries with low capacity to act are more in favor of investments in all technologies except nuclear power (about which they are as negative as are respondents residing in countries with high capacity to act) and wind and ocean power (about which they are slightly less positive, though still positive overall).

4.2. The domestic–global dimension and views of likely deployment barriers

The respondents generally disagree with the statement that BECCS will contribute substantially to mitigation in their country of residence. Their view of BECCS's global potential to contribute to achieving the goal of global warming well below 2 °C is slightly more positive. However, they still generally neither agree nor disagree that BECCS will contribute substantially to meeting the goal of global warming well below 2 °C.

A Mann-Whitney U test provides no evidence that responsibility or capacity to act influences respondents' views of the potential of BECCS to contribute to meeting the 2 °C goal nor its potential to contribute to mitigation in the respondent's country of residence. Whether respondents have high or low knowledge of BECCS, on the other hand, significantly influences their view of the global potential of BECCS. Respondents with high knowledge of BECCS ($n = 100$) are significantly

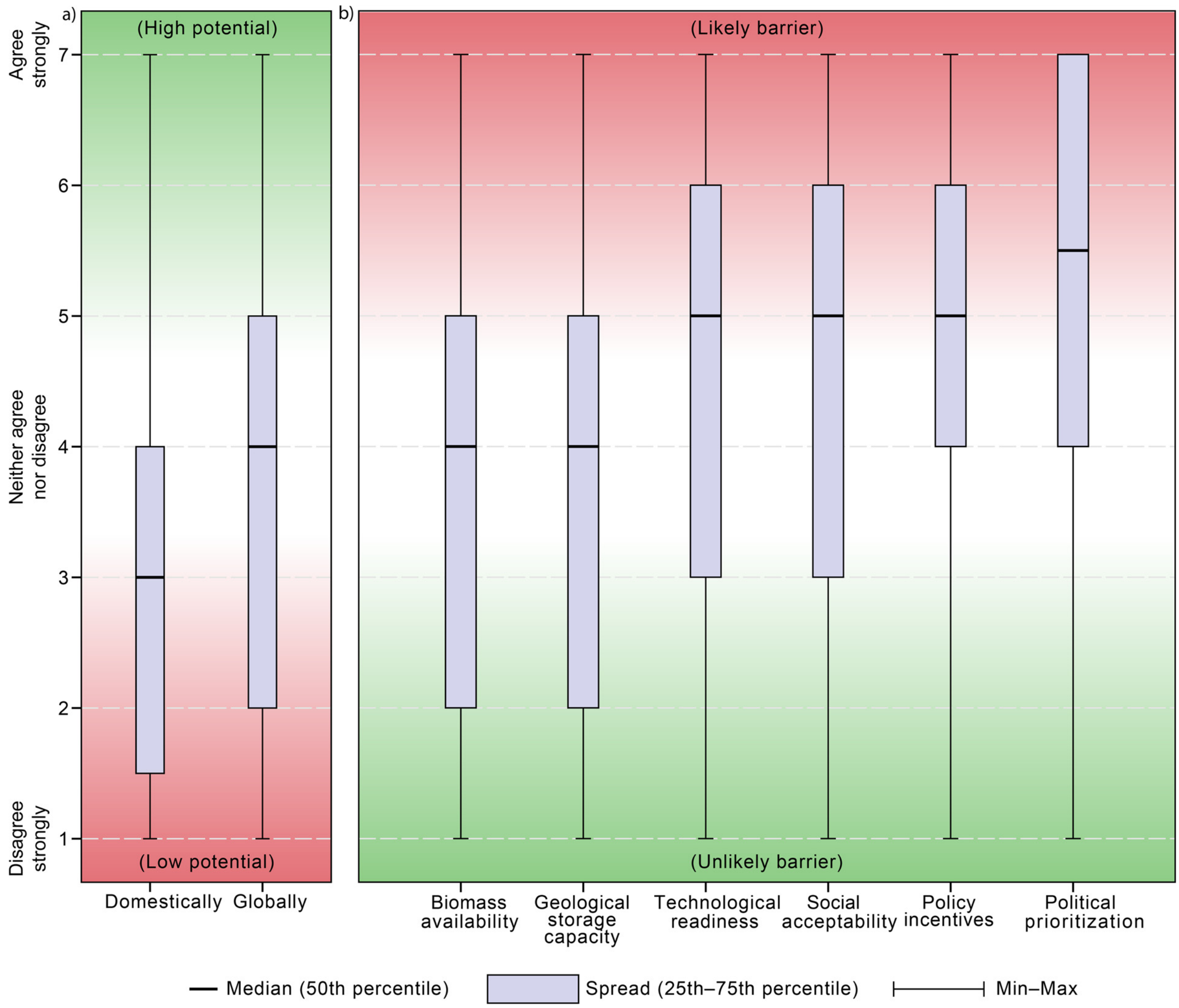

Fig. 4. Global (all respondents) agreement (7) or disagreement (1) that: a) BECCS is likely to contribute substantially to mitigation in the respondent's country of residence and that, globally, it will contribute substantially to achieving the goal of global warming well below 2 °C, and b) the lack of preconditions for BECCS is likely to limit deployment in the respondent's country of residence.

more positive about its global potential than are respondents with low knowledge (n = 100, p = .036, r = 0.15). High knowledge does not significantly influence views of BECCS's domestic potential (p = .564). As with investment preferences, the same test indicates that non-governmental actors (n = 150) are more skeptical about both global and domestic potential than are governmental actors (n = 58, p = .001, and r = 0.23 for global potential, and p = .009 and r = 0.18 for domestic contribution to mitigation).

The respondents anticipate that a lack of political prioritization and policy incentives are likely barriers to BECCS deployment, whereas a lack of biomass and geological storage capacity are less likely barriers (Fig. 4). There is a strong positive correlation between respondents' view of the potential of BECCS to contribute to mitigation in their country of residence and their willingness to prioritize investments in BECCS (Spearman's rho = 0.633, p = .000). This relationship is slightly weaker – although still strong – for respondents' view of the global potential of BECCS and their willingness to prioritize investments in BECCS in their country of residence (Spearman's rho = 0.592, p = .000).

A Mann-Whitney U test provides no evidence that actor type influences views of potential constraints on BECCS deployment in the respondent's country of residence. Whether respondents have high or low knowledge of BECCS, on the other hand, significantly influences their view of potential constraints on BECCS deployment. Respondents with higher knowledge of BECCS are more inclined to view lack of policy incentives (n = 91) and lack of social acceptance (n = 89) as potential barriers to deployment than are respondents with less knowledge of BECCS (n = 86, p = .008, and r = 0.20 for policy incentives, and n = 87, p = .001, and r = 0.26 for social acceptance).

Furthermore, whether respondents are from countries with high or low responsibility and capacity to act has a significant effect on what they foresee as likely barriers to deployment in their country of residence. Respondents residing in countries with low capacity to act are more inclined to anticipate a lack of technological readiness (n = 63) and less inclined to anticipate a lack of social acceptance (n = 59) as potential barriers to deployment than are respondents residing in countries with high capacity to act (n = 89, p = .001, and r = 0.26 for technological readiness, and n = 92, p = .043, and r = 0.16 for social acceptance).

5. Discussion

5.1. Investment preferences

To contextualize the discussion, we start with the least surprising finding: that most respondents view the current electricity production systems in their countries of residence as high-carbon systems. This finding is in line with global GHG emissions data indicating that twothirds of global electricity is generated from fossil fuel [31]. However, countries with lower responsibility to act generally also have lower levels of absolute emissions. This helps explain why respondents from the lower-responsibility countries are more inclined to view their electricity production systems as low carbon than are respondents from countries with higher responsibility to act. Low absolute and per capita levels of emissions, however, can still mean that the carbon intensity of the electricity production is high. On the whole, respondents neither agree nor disagree that current electricity systems are sufficiently low carbon and strongly agree that investments are required to maintain or make future electricity generation low carbon.

The question about investment needs, although not resulting in any surprising findings, is still important; there is no doubt that the respondents are generally of the view that investments are needed to meet climate policy goals. The fact that the respondents put a relatively low priority on BECCS for these investments is at odds with the required large-scale and long-term investments in R&D needed to scale up CCS technologies [32–34].

SSP scenarios tend to feature both fossil CCS and BECCS. Although the combined amount of primary energy used for fossil CCS and BECCS by mid century is similar in most SSPs, the deployment pattern varies. In most scenarios, levels of fossil CCS are reduced in the second half of the century. Scenarios associated with a world characterized by low mitigation and adaptation challenges (SSP1) tend to have lower use of fossil CCS, while scenarios associated with high mitigation and low adaptation challenges (SSP5) have the highest use. This is explained by the high initial fossil fuel use in SSP5, which requires a rapid drop in GHG emissions after 2050 to be compatible with RCP 2.6 (i.e. $+2.6\ W/m^2$ in radiative forcing by 2100) and also allows the use of previous investments by adding CCS components to existing plants.

Although BECCS has its own specific technological problems compared with fossil CCS,[1] BECCS is likely to benefit from innovations in fossil CCS. However, it should be noted that various types of CCS systems are being developed in parallel, and that this is slowing the pace of innovation compared with a more concentrated development focus [32,35,34]. The low priority assigned to fossil CCS and BECCS, as reported here, constitutes a warning against producing SSP climate scenarios with strong policy assumptions. It would be advisable for politicians to focus R&D programs on BECCS, which is viewed relatively more positively than fossil CCS. However, given present policy structures, fossil CCS makes more economic sense for most regions if serious attempts to mitigate climate change are to be made.

The fact that actor type influences the respondents' views may be explained by their different roles in climate governance. Many environmental NGOs take on the role of scrutinizing governments and businesses and have been skeptical about plans to implement fossil CCS and expand biofuel production. They have voiced concerns that CO_2 storage may suffer both abrupt and long-term leakage and that CCS extends the fossil fuel era at the expense of decarbonization. The environmental NGOs' early cautious optimism about biofuels, arguably analogous to our current understanding of the social acceptance of BECCS [36], has shifted to criticism of land grabbing, extended neocolonial practices, negative effects on food security, poor working conditions, and production-driven deforestation that undermines climate benefits and exacerbates biodiversity losses.

Climate-oriented business NGOs also typically ask governments for ambitious long-term commitments to create stable investment environments for low-carbon technologies. At present, the global goal is not backed by strong domestic commitments, a situation that does not favor investments in BECCS. This may explain the low appetite of business NGOs to prioritize investments in BECCS. Governmental actors are understandably more positive, relatively speaking, toward directing investments into BECCS considering the weight given to BECCS in 2 °C-compatible climate scenarios and governments' responsibilities to implement international treaties such as the Paris Agreement. Still, their overall low prioritization of BECCS vis-à-vis alternative technologies also raises questions about the feasibility of the BECCS deployment rates in the climate scenarios. For example, is it likely that frameworks will be put in place that increase the carbon price to levels that make the IAMs favor BECCS deployment? Will policymakers strive to put a price on biogenic CO_2 rather than focusing only on fossil CO_2? Will governments and businesses be willing to invest in the necessary R&D before large-scale deployment is possible?

5.2. The domestic–global dimension

The Paris Agreement has been described as a great diplomatic success [37]. The goal of holding global warming well below 2 °C, not to mention the 1.5 °C aspirational goal, makes the Agreement more ambitious than most commentators would have thought possible [38]. This unexpectedly high level of ambition, however, has been plagued by the so-called "emissions gap" between scenarios for and actual nationally determined contributions to achieving the goal [21]. The discrepancy between the respondents' views of the global and domestic potentials of BECCS raises related concerns about the possibility of realizing the climate scenarios.

BECCS' deployment potential is often described as context dependent [14]. Even though, for example, technological readiness is seen as a likely constraint on BECCS deployment in countries with lower capacity to act, including most tropical countries in which climate models assume that most biomass for bioenergy will be produced [39], it may not limit their production of biomass for export to be used in BECCS operations elsewhere. It is also possible that deployment in countries with high potential could compensate for low deployment in other countries. However, respondents from countries with high potential for BECCS[2] are even more negative than others as regards both the global and domestic potentials of BECCS. This begs the question of where the global potential for BECCS is actually going to materialize.

In terms of actor type, the pattern mirrors that for investment preferences: nongovernmental actors are more skeptical toward global and domestic potentials than are governmental actors. Again, this mirrors the few previous findings regarding the public acceptance of BECCS, as discussed in Section 5.1. Although it is hard to speak of a not-in-my-backyard (NIMBY) effect when discussing the results along the domestic–global dimension, it is worth noting that such effects have been acknowledged for fossil CCS at the community scale. The NIMBY effect, however, is lower or even disappears for BECCS compared with fossil CCS [13,40]. Previous findings about the NIMBY effect as well as the results presented here regarding views of potential along the global–domestic dimension speak to the need for further research into public understandings of BECCS, to enhance the assessment of climate scenario feasibility.

One explanation as to why the global potential is generally viewed as higher than the domestic potential might be the lack of real deployment. Geden [41] has described BECCS as an artifact of global modeling that was introduced to get "around past 'make-or-break' points for the 2 °C target" (p. 28). While the technology features prominently in global climate scenarios, it remains to be demonstrated on a large scale. It is possible that while the respondents are aware of the modeled, theoretical potential, they still – as indicated by the survey results – foresee various domestic barriers to BECCS in their countries of residence. In the aggregate, this creates a conundrum in which most

[1] Especially in electricity generation, for example, there are challenges related to smaller maximum loads and feedstock pretreatment, which in turn lead to challenges in achieving positive economies of scale. Other technological challenges include higher levels of moisture and impurities in flue gases, which affect the separation and transportation of CO_2.

[2] For example, Sweden, Norway, the USA, the UK, and Brazil ($n = 41$), which have advanced bioeconomies and access to storage sites.

respondents are not explicitly refuting a possible global potential but few can explain where it will actually materialize.

The fact that respondents with high knowledge of BECCS are significantly more positive toward its global potential than are others, yet remain skeptical of its domestic potential, may also support this explanation. Experts on BECCS are probably even better acquainted with the global climate scenarios than are other delegates. Currently, the scenarios emphasize the global potential, though the literature also stresses that, at present, policy incentives are largely lacking. Social acceptance also seems to be low, even though previous literature indicates that it may be higher for BECCS than for fossil CCS (see Section 2.1). As demonstrated by Vaughan and Gough [15], experts tend to regard the technical potential as relatively high yet also that the realizable potential is substantially lower due to a lack of supportive policy and social acceptance.

It should also be noted, however, that while the global potential is viewed as higher than the domestic potential, in relative terms, and while most respondents do not refute the global potential, few respondents explicitly agree that BECCS will contribute substantially to achieving the goal of global warming well below 2 °C. That the respondents generally neither agree nor disagree that BECCS will contribute substantially to global mitigation also indicates that the future of BECCS is largely an unknown. The almost overwhelming uncertainties related to the long-term potential of BECCS helps explain why this is so. This potential is likely to remain unknown as long as the appetite to invest in R&D and demonstration projects is low. At present, few policy incentives are put in place to encourage such development. This underlines what is also often explicitly stated in the literature [9,41]: climate scenarios need to be interpreted cautiously.

5.3. Views of likely deployment barriers

5.3.1. Policy incentives and political prioritization

In the scientific literature, the lack of current BECCS deployment is attributed to the lack of strong policy incentives [5,42]. This is mirrored in the present data: the most likely constraints on BECCS deployment are, according to the respondents, the lack of sufficiently strong policy incentives and the lack of political prioritization.

The literature identifies low carbon prices as the primary barrier to deployment [32,12,18]. Carbon prices can be set by measures such as taxation, trading schemes, or offset markets. The SSP scenarios compatible with an increase in radiative forcing of 2.6 W/m^2 by 2100 have a median carbon price of EUR 44/tCO_2 by 2030 and EUR 206 by 2050, rising above EUR 1000 by the end of the century (at EUR 2005). To scale up BECCS in electricity production, the needed carbon price is estimated to be EUR 50–65/tCO_2, but varies substantially among types of operating entities [43,44,42]. However, at the end of January 2018 the carbon price in the EU Emission Trading System (EU ETS) was about EUR 9.0/tCO_2. A ton generated from the Kyoto Protocol's Clean Development Mechanism could be traded for EUR 0.2 [45]. Sweden is highlighted as a front-runner in carbon taxing, pricing carbon at about EUR 119/tCO_2. However, this tax covers only sectors outside the EU ETS and targets only fossil CO_2, which means that many installations with high potential, such as pulp and paper mills as well as combined electricity and heat production, are not incentivized to develop BECCS. The story is similar in other countries. For example, Finland's carbon price is EUR 59/tCO_2 for transport fuels and EUR 48/tCO_2 for heating fuels, Switzerland's is EUR 78/tCO_2 for thermal fuels, and Norway's is EUR 44/tCO_2 for natural gas [46]. Unless carbon markets and tax schemes are reformed, they likely will not suffice to drive BECCS R&D and deployment.

Accounting rules also require reform to enable credits and allowances for negative-GHG-emission technologies [47]. To incentivize BECCS, a tax should ideally not distinguish fossil from biogenic carbon. Also, since a carbon tax only incentivizes emission reductions down to zero, it has to be complemented by some way of incentivizing negative emissions [42,35]. However, the upstream emissions of bioenergy are uncertain and hard to accurately quantify, making robust accounting for the total supply chain of net-negative emissions a relatively complex endeavor [33].

A few studies have explored the possible economic consequences of large-scale BECCS deployment [48,12]. Muratori et al. [12], assuming idealized conditions such as a globally homogeneous price on carbon, found that "the presence or absence of BECCS from the portfolio of available technologies produces noticeable differences in net government tax revenue, patterns of energy trade, and food prices" (p. 8). They concluded that including BECCS in their model while reaching the 2 °C goal leads to decreased tax revenues due to a need to subsidize BECCS, prolonged fossil fuel use and trade, and decreased food prices due to less pressure on biomass resources. Developing policy to incentivize BECCS, even under such idealized assumptions, is likely to be a highly complex governance endeavor. Since examples of implementing the technology are virtually nonexistent and the potential technological challenges associated with deployment and diffusion are still unaddressed, the governance challenges require immediate political attention if BECCS is to be scaled up as suggested by the scenarios.

This leads to the second most likely constraint on BECCS deployment identified by the respondents: lack of political prioritization. Even if BECCS does not currently have a central position in long-term climate strategies' mitigation portfolios, it has at least been mentioned in recent years. The USA and the UK have among the most advanced programs to develop BECCS. The US Department of Energy, with contributions from industry partners, runs a pilot project in Decatur (Illinois) and the UK has a CCS commercialization program in place, focusing partly on BECCS. The USA is also emphasizing the role of BECCS in meeting its long-term goals and as a potential business opportunity, even though the current Trump administration has reduced the likelihood of exploiting this opportunity. Other countries, such as Canada, Sweden, and Norway, have opened the door to using BECCS in the long term, yet provide little support specifically for BECCS and only limited support for CCS.

Whereas the models often assume a currently unrealistically high and globally homogenous carbon price as well as full access to technology, lack of incentives was a major concern among all delegates. This concern was strongest among delegates with high knowledge of BECCS. Although the literature on expert views of likely barriers to BECCS is very sparse, Vaughan and Gough [15], in their analysis of expert assessments, warned that IAM scenarios make "unrealistic assumptions about the development of adequate societal support structures (e.g. cohesive policy frameworks and societal acceptance) needed to enable large-scale negative emissions" (p. 6). The respondents' understandings of the lack of political prioritization and policy incentives as likely constraints on BECCS deployment are therefore mirrored in the literature. Concerns about the lack of policy incentives are also often raised in the few government R&D programs supporting BECCS. Alongside developing policy incentives, government-led investments in R&D must increase to test and scale up BECCS.

5.3.2. Social acceptance

In 2009, the International Energy Agency (IEA) envisioned that about 100 full-scale commercial CCS projects would be needed by 2020 to achieve a cost-effective 50% reduction in the energy sector's GHG emissions by 2050 relative to 2005 levels [49]. The IEA acknowledged that increasing the number of projects from the existing four projects to 100 projects over a period of 11 years would be a tremendous challenge. Since then, several CCS projects have been put on hold or cancelled, and R&D expenditure has declined. The main reason for this has been public protests in Germany and elsewhere [13]. While low social acceptance is reported for all aspects of CCS and BECCS (i.e. separation, transportation, and storage), protests regarding storage have been the strongest [13,50,40]. This may also explain the reluctance of the German government to include BECCS in its long-term climate strategy while holding the door open for so-called carbon capture and utilization (CCU) that avoids storage.

It is hard to explain why social acceptance is regarded as a less likely barrier to deployment in countries with lower responsibility/capacity to act. Buck [36] argued that good analogous cases for understanding the technological trajectory of BECCS, such as biofuel production and carbon forest projects, display patterns of strong public resistance in developing countries too. However, even though social acceptance is understood as a less likely barrier in developing than developed countries, the fact remains that respondents from these countries still viewed it as a likely barrier.

Buck [36] also stressed that “governments worldwide will need to employ a stronger hand in many aspects of the process of scaling up NETs [i.e. negative-emission technologies]” (p. 164). This refers to the importance of making BECCS an early political priority for spurring large-scale mid-century deployment, by providing regulatory frameworks that establish guidelines for action and by producing strong policy incentives. Buck’s results, as well as previous research, emphasize that if governments start acting on BECCS, they should approach it as a complex technological system rather than as a simple artifact. This system may spur large-scale social change by, for example, transforming land use practices [36]. Such changes may raise protests, particularly in developing countries where concerns about increasing food prices and land grabbing have been pronounced due to the lack of regulatory frameworks [36,51]. The only known case of a planned BECCS operation in a developing country comes from Tanzania, where it led to protests related to the process of securing land for biomass production (rather than plans for sequestration, transportation, and storage). Experience with similar protests over fossil CCS in developed countries, and, for the most part, the lack of similar experience in developing countries may help explain differences in the views of the likelihood that social acceptance will become a barrier to BECCS deployment.

5.3.3. Technological readiness, biomass availability, and storage capacity

The IAMs take a narrow view of technological potential. They often assume that the only constraints are the availability of biomass, net conversion rates, and sometimes limited storage capacity [43]. From this perspective, technological readiness is seen as a relatively insignificant barrier. This attitude is mirrored by the respondents assigning relatively low importance to biomass availability and storage capacity as likely deployment barriers compared with other potential barriers.

Technological readiness can, however, be conceived of as a broader concept including not only technological maturity and load/storage constraints but also such things as the capacity to operate technologies (i.e. know-how) and systems to feed biomass operations with raw material. From this perspective, BECCS is a relatively complex technological system [36,15]. The respondents emphasize this as a potential barrier, particularly in countries with low responsibility/capacity to act. Such countries often lack regulatory frameworks to guide investments in these technologies and also have relatively lower levels of the required know-how. There is accordingly a need to move from narrow definitions focusing on the availability of biomass, conversion rates, and storage capacity to definitions factoring in other, softer aspects of technological readiness when modeling climate scenarios.

That biomass availability is regarded as relatively less important than other barriers does not mean that it is deemed insignificant. In other words, the respondents generally neither agree nor disagree that biomass availability is likely to constrain BECCS deployment in their country of residence. The relatively low importance assigned to biomass availability can partly be explained by the higher importance attributed to factors of greater significance earlier in a policy process: biomass availability – of great importance in the implementation phase – is less likely to constrain BECCS if there is lack of political willingness, social acceptance, or policy incentives that disfavor BECCS in the agenda-setting and policy-formulation phases. A weak negative correlation also exists between viewing biomass availability as a likely deployment barrier and viewing the domestic potential for BECCS as low. In other words, the more a respondent believes that the domestic potential is low, the more likely the respondent is also to view biomass availability as a likely deployment barrier.

5.4. Scope for scenario improvements

It is important to note that the use of BECCS in model scenarios does not necessarily indicate that climate goals cannot be reached without it. Most models rely on utility or cost optimization that favors the most effective technology. Therefore, a separate analysis that excludes BECCS as an option is needed to assess the feasibility of climate goals without BECCS. This has been conducted for models used in the AR5 scenarios but so far not in the SSPs. It is therefore unclear whether BECCS is necessary in scenarios reaching 2.6 W/m^2 by 2100, although excluding it will definitely increase the projected cost of reaching the goal [4].

Significant improvements have been made in recent years to better capture biomass availability and land use effects by integrating dedicated land use models [3]. Different pathways for population development and the resulting demand for food have also been explored [52]. Effort is also going into better representing the interlinkages between energy and water [53]. Geological storage potential is often represented at a global level, for example, by Lehtveer and Hedenus [54], but can be relatively easily regionalized. Technological readiness is sometimes represented in models by different regional costs of technology or by availability in different time periods. As can be seen, the focus is often on technical factors and potentials, while socioeconomic readiness factors, such as supply of engineers or institutional-level organization, are ignored.

Some efforts have been made to better represent social preferences in IAMs, notably in the transport sector (e.g. [55]); however, to our knowledge, there are no applications of social preferences related to BECCS. Policy incentives are often provided at a country level and are thus difficult to include in models with large regions, though some effects can potentially be captured in regionalized technology costs, availability, and allowed expansion rates.

Many of the technological changes represented in the models are also treated as globally homogenous. For example, as mentioned in Section 2, BECCS is generally assumed to be deployed in all regions and with rather similar deployment patterns. In reality, diffusion could well differ between regions due to varying socioeconomic, resource, and technical conditions. As discussed in Section 5.3, our results indicate significant differences in perceived barriers depending on whether the respondents reside in countries with high or low capacity to act. A first step here could be regional differentiation, taking into account factors such as current investment preferences, social acceptance, existing infrastructure, level of development, and economic capacity to invest in such large-scale projects. Since the costs of transport by sea are low, it is possible that some regions, especially ones with good wind and solar conditions, would be providers of biomass while others with more limited resources would rely on imported biomass to reduce their GHG emissions.

6. Conclusions

This paper explores how expertise, actor type, and country of origin influence UNFCCC delegates’ views of bioenergy with carbon capture and storage (BECCS). Investing in BECCS is considered a low priority by all actors, with nongovernmental actors being more negative than governmental actors. This reflects the environmental NGOs’ longstanding criticism of CCS for extending the fossil fuel era and their opposition to unsustainable biofuel production.

Previous literature has reported on the importance of lack of social acceptance of the cancellation of fossil CCS projects [13]. As shown here, all actors recognize social acceptance as a likely barrier to BECCS deployment as well. However, a lack of policy incentives and insufficient political prioritization are given even more weight. The importance of politics for BECCS R&D and commercialization has previously been stressed [33,34]. This article provides additional empirical evidence that BECCS is unlikely to scale up without being incentivized by political attention and supportive regulatory frameworks.

Without deployment, lack of social acceptance is less likely to play a decisive role. On the other hand, lack of social acceptance may reduce politicians' appetite to prioritize policy incentives for BECCS. This is likely to be particularly important in countries with higher social access to politics; respondents residing in such countries are more inclined to view social acceptance as a likely constraint on BECCS deployment than are other respondents. A lack of technological readiness has previously been reported as an unlikely constraint on deployment [43]. However, this paper finds that a lack of technological readiness is noted by actors residing in countries with relatively lower responsibility and capacity to act, reflecting their countries' lower levels of know-how and resources to support mitigation actions.

Finally, a new finding concerns the need for further exploration of the potential discrepancy between the global potential of BECCS and domestic willingness to engage in piloting frameworks and instruments to incentivize BECCS. There is a risk that while many governments and businesses may acknowledge the global theoretical potential of BECCS, in light of domestic deployment barriers, few will be willing to invest in its realization.

These results speak to the great need for further research into the sociopolitical preconditions for BECCS deployment as well as the scope for model scenario improvements. Social acceptance and political preferences are poorly captured in climate scenarios and are also at odds with the timescales needed for R&D. A lack of political priority, social acceptance, and strong policy incentives would result in an environment that was unconducive for the R&D required for BECCS. This calls into question the ability to deploy BECCS on the scale suggested by most climate scenarios from the past ten years. At this stage, it would be advisable to complement the survey reported here with, for example, interviews, to yield a richer understanding of the rationales underlying the respondents' answers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.erss.2018.03.019.

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