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Expert projections on the development and application of bioenergy with carbon capture and storage technologies

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Abstract

Bioenergy with carbon capture and storage (BECCS) is a crucial element in most modelling studies on emission pathways of the Intergovernmental Panel on Climate Change to limit global warming. BECCS can substitute fossil fuels in energy production and reduce CO_2 emissions, while using biomass for energy production can have feedback effects on land use, agricultural and forest products markets, as well as biodiversity and water resources. To assess the former pros and cons of BECCS deployment, interdisciplinary model approaches require detailed estimates of technological information related to BECCS production technologies. Current estimates of the cost structure and capture potential of BECCS vary widely due to the absence of large-scale production. To obtain more precise estimates, a global online expert survey ($N = 32$) was conducted including questions on the regional development potential and biomass use of BECCS, as well as the future operating costs, capture potential, and scalability in different application sectors. In general, the experts consider the implementation of BECCS in Europe and North America to be very promising and regard BECCS application in the liquid biofuel industry and thermal power generation as very likely. The results show significant differences depending on whether the experts work in the Global North or the Global South. Thus, the findings underline the importance of including experts from the Global South in discussions on carbon dioxide removal methods. Regarding technical estimates, the operating costs of BECCS in thermal power generation were estimated in the range of 100–200 USD/tCO_2, while the CO_2 capture potential was estimated to be 50–200 MtCO_2yr^{-1} by 2030, with cost-efficiency gains of 20% by 2050 due to technological progress. Whereas the individuals' experts provided more precise estimates, the overall distribution of estimates reflected the wide range of estimates found in the literature. For the cost shares within BECCS, it was difficult to obtain consistent estimates. However, due to very few current alternative estimates, the results are an important step for modelling the production sector of BECCS in interdisciplinary models that analyse cross-dimensional trade-offs and long-term sustainability.

1. Introduction

Global greenhouse gas (GHG) emissions are continuing to increase, further exacerbating global warming (IPCC 2023). The goals of the Paris Agreement aim to limit global warming to well below 2 °C above pre-industrial levels and ideally to 1.5 °C. To achieve this, net-zero, and for some countries even net-negative, emissions targets for CO_2 need to be realized, and other GHG emissions, e.g. methane, significantly reduced by the end of the century (Rogelj *et al* 2018a, IPCC 2023). In addition to reducing emissions, carbon dioxide removal (CDR) methods are vital for removing existing CO_2 emissions from the atmosphere and counterbalancing residual emissions in the medium term (Minx *et al* 2018, Rogelj *et al* 2018b, 2018a, IPCC 2023). If removal exceeds emissions, CDR methods could achieve net-negative emissions in the long term (IPCC 2023). The focus is primarily on the use of bioenergy with carbon capture and storage (BECCS), since BECCS is a crucial element in integrated assessment models (IAMs) that model emission pathways to limit global warming to 1.5 °C or well below 2 °C, which are a basis for the reports of the Intergovernmental Panel on Climate Change (IPCC) (Rogelj *et al* 2018a, Riahi *et al* 2022, Zhao *et al* 2024). In scenarios with average global temperature increases below or equal to 1.5 °C, BECCS deployment is estimated to achieve reductions of 3.4–6.8 $GtCO_2yr^{-1}$ by 2050. By 2100, this could increase to 5.7–14.9 $GtCO_2yr^{-1}$, depending on the scenario and the possibility of temporarily exceeding temperature targets (Rogelj *et al* 2018a). When accounting for sustainability criteria, emission reductions through BECCS deployment could be limited to 0.5–5 $GtCO_2yr^{-1}$ by 2050 according to Fuss *et al* (2018).

Until now, both research and industry have mainly focused on applying BECCS in industries that use biomass for producing electricity and heat, pulp and paper, or in energy conversion plants that produce liquid biofuel or biogas (Fajardy *et al* 2019, Rosa *et al* 2021). There has also recently been increasing research on the technical and economic feasibility of using BECCS in carbon-intensive industries producing cement and steel (Tanzer *et al* 2020, Cavalett *et al* 2021, Lopez *et al* 2022, Agora Industry and Wuppertal Institute 2023). CO_2 released by converting biomass to bioenergy is captured using carbon capture technology, compressed, transported, and stored in geological formations, preventing it from being released into the atmosphere (Bui *et al* 2018, Claire *et al* 2018, Fajardy *et al* 2019).

By substituting fossil fuels in energy production, BECCS reduces CO_2 emissions and simultaneously offsets residual emissions from hard-to-abate sectors by generating negative emissions (Rogelj *et al* 2015, Bui *et al* 2018, Claire *et al* 2018). However, the use of biomass for energy production can have feedback effects on land use, the agricultural and forest products markets, as well as biodiversity (Fajardy *et al* 2018, Hof *et al* 2018, Smith *et al* 2020, Babin *et al* 2021, Hanssen *et al* 2021). Furthermore, BECCS might put pressure on water resources since CCS technology is water-intensive and the irrigation of energy crops leads to additional water use (Byers *et al* 2015, Rosa *et al* 2020, Stenzel *et al* 2021, Zhipin *et al* 2021). On the other hand, studies have concluded that under specific conditions (e.g. type of feedstock, length of rotation, landscape), land use change to biomass production might lead to positive effects on ecosystem services and benefit biodiversity (Holland *et al* 2015, Donnison *et al* 2020, 2021, Englund *et al* 2020, Hanssen *et al* 2021, Hirata *et al* 2024). These trade-offs and co-benefits along with other aspects of uncertainty, e.g. costs and public acceptance of BECCS, fuel discussions among researchers, policymakers, and the public on the appropriateness of BECCS as a climate change mitigation measure (Fajardy *et al* 2018, Creutzig *et al* 2019, Haikola *et al* 2021, Donnison *et al* 2023).

The first operating BECCS plants are located in North America and Northern Europe. Information on the specific application concepts for these advanced projects is available (Global CCS Institute 2024). One example of a project in an advanced planning stage in the Global South, is the Brazilian biorefinery plant operated by Fueling Sustainability in Lucas do Rio Verde (PR Newswire 2024). Future model assessments support the establishment of large numbers of BECCS production sites in, e.g. sub-Saharan Africa, as this region possesses vast areas that could provide biomass energy and storage capacities (see e.g. Ricci and Selosse 2013, Hanssen *et al* 2020a). Given the broad range of possibilities and uncertainties, it is challenging to assess exactly how BECCS might develop over the next decades. It is yet unclear in which countries and areas of application BECCS will be implemented, and sustainability of BECCS might vary by country and sector. It is thus important to obtain additional information to, e.g. differentiate more strongly between the use of different biomass types when modelling BECCS technologies, to be able to capture region-specific effects on biomass demand and production more accurately.

Taking the aforementioned into account, interdisciplinary numeric modelling approaches can serve as tools to effectively assess potential trade-offs arising from the large-scale implementation of BECCS. Using economic models, it is possible to analyse future market developments and policy impacts which are difficult to grasp in their complexity (Schier *et al* 2022). However, these models require tangible information on the sectoral representation of BECCS and related production factors, e.g. biomass feedstock used, carbon capture potential, operating costs, and scalability as input to carry out cross-regional and cross-sectoral trade-off analysis, There are important differences in the estimates of technical aspects of BECCS across the published literature (Daioglou *et al* 2020), mainly because BECCS sites are currently pre-commercial and only a few pilot projects exist, mainly in North America and Northern Europe (Rosa *et al* 2021, Global CCS Institute 2022). Morris *et al* (2019) published production costs in the USA for BECCS in power generation fueled by non-specified biomass. These estimates are used by Fajardy *et al* (2021), for instance, to model the role of BECCS in achieving different global warming scenarios in the Economic Projection and Policy Model framework of the Massachusetts Institute of Technology. Furthermore, the Lawrence Livermore National Laboratory provides projections for BECCS deployment and production costs in California (Baker *et al* 2020) and the USA (Pett-Ridge *et al* 2023). Abegg *et al* (2024) conducted expert interviews with scholars on the costs and scalability of BECCS in which the experts assumed higher costs and lower scalability than the International Energy Agency forecasts (IEA 2021) but without differentiating in feedstock, BECCS technology or region.

In addition, literature reviews in several recent papers present cost estimates and capture potential of BECCS (Fuss *et al* 2018, Rueda *et al* 2021, Freer *et al* 2022, Abegg *et al* 2024). Due to uncertainties in operational factors, the future mitigation potential of BECCS is also increasingly questioned (Grubler *et al* 2018, Riahi *et al* 2021). Fuss *et al* (2018) find large variations in estimates due to uncertainties relating to assumed biomass feedstock and BECCS technology. Finally, Creutzig *et al* (2019) and Zhao *et al* (2024) both argue that BECCS net CO_2 removal efficiency depends mainly on the life-cycle emissions of the respective feedstock and the efficiency of BECCS plants.

An option for deriving information on future BECCS implementation refers to the projections made in climate change mitigation modelling, which rely mostly on IAMs (Calvin *et al* 2021). IAMs contribute to the assessment of climate policies and enhance the understanding of the importance of cost-effectiveness information for new technologies, amongst other things (Weyant 2017). However, uncertainties and diverging assumptions across modelling studies give rise to differences in estimates of BECCS potential (Calvin *et al* 2021). Daioglou *et al* (2020) provide a concise overview of the deployment of bioenergy technologies in IAMs and discuss the techno-economic assumptions. In particular, the increase in capital costs in bioenergy systems caused by implementing CCS technologies vary across IAMs, ranging from 2%–242%, and 10%–315% for electricity and liquid biofuels respectively (Daioglou *et al* 2020). Based on sensitivity analyses, Muratori *et al* (2020) found that uncertainties in technical assumptions in particular affect the timing and rate of deployment of BECCS. IAMs supply projections of biomass feedstock result from an interplay of biomass production characteristics and bioenergy demand, which themselves are influenced by numerous model characteristics (Rose *et al* 2022). In addition, IAMs may differ considerably regarding energy crop yields (Rose *et al* 2022, Whitaker *et al* 2018, Slade *et al* 2014), which could be exacerbated by uncertainties regarding the impact of climate change (Smith *et al* 2019). Land-use competition also affects the costs and supply of biomass feedstock (Smith *et al* 2016, Kalt *et al* 2020), alongside significantly varying factors (see Rose *et al* 2022 for an overview), leading to divergent BECCS projections.

Retrospective reviews of technological forecasts show that many of these tend to be imprecise and overconfident (Savage *et al* 2021). Experts can be subject to biases that may affect the selection of parameters and values used in forward-looking modelling exercises (Bonaccorsi *et al* 2020). Thus, the widely divergent and imprecise information in the literature regarding estimates on biomass use, scalability, and operating costs of BECCS is an obstacle to the sound integration of this technology in numerical simulation models (Daioglou *et al* 2020). This study aims to determine which parameter values from the current literature can be reasonably used for model-based assessments and which parameters require further research. To address this, we conducted an online survey with international industry, research, and policy experts active in the field of BECCS. The objective of the survey was to gain more precise estimates on the technical aspects of different BECCS technologies, focusing on future operating costs, capture potential, scalability, and biomass use. This survey provides an expert assessment of the current literature, including estimates and projections that have recently been published, to deliver justifiable parameters to be used in economic modelling. Moreover, we asked for expert opinions on the future technological development of BECCS to narrow down the wide range of estimates found in the literature, thus obtaining more consistent results to be able to refine economic modelling and trade-off analyses. While most IAMs present BECCS model results for 2050 onwards, we also requested estimates for 2030 and 2040, and for potential learning rates to allow for dynamic modelling when conducting trade-off analyses using computable general equilibrium or partial equilibrium models. Finally, we highlight areas in which experts' opinions are still incongruent, call for additional research, and identify the parameters that should be subject to rigorous sensitivity analyses when included in economic models.

2. Method

For this survey we invited experts with technical expertise from the value chains of CCS, BECCS, or bioenergy production. To find suitable experts, we screened scientific papers, searched for contacts at universities, scientific institutes, and consultancies, and approached companies conducting or planning BECCS field trials. The survey was conducted anonymously, and the initial invitation and two reminders were sent by email to 145 international experts in December 2021 with a response rate of 16% ($N = 25$). Further information on survey design

Table 1. Overview of survey questions and answer options.

Questions	Answer options
Potential of BECCS	
- How would you estimate the potential for market development of BECCS for regions in Europe, Asia, Australia and Oceania, America, Middle East and Africa until 2040?	Rating scale: very high potential, high potential, low potential, very low potential, no potential
- Rank the following location factors according to their importance for deploying BECCS: closeness to biomass feedstock, closeness to key market for produced products, closeness to CO_2 storage site, usage of existing energy production infrastructure.	Ranking: 1 = very important to 4 = least important
Suitable biomass sources for BECCS	
- Please rank the following energy crops according to their importance as biomass sources for BECCS: roundwood, wood residues, wood pellets, short-rotation coppice, grasses, sugar crops, oil crops.	Ranking: 1 = very important to 7 = least important
- How likely is it that the production of the following biomass types (vegetable oils/lignocellulose/grains/ sugarcane) for the biofuel industry will be coupled with CCS by 2030?	Rating scale: very likely, rather likely, rather unlikely, very unlikely
- Please rank the following areas of application (liquid biofuel industry/thermal power generation/pulp and paper industry) according to their suitability for using short rotation coppice.	Ranking: 1 = very suitable to 3 = least suitable
Cost estimations of BECCS	
- Please indicate your estimate for the total costs of CCS applied in the liquid biofuel industry, biomass-fueled thermal power generation and pulp and paper industry.	Estimates in USD/tCO_2
- What cost efficiency gains due to technological progress do you expect for CCS in the liquid biofuel industry, biomass-fueled thermal power generation and pulp and paper industry compared to your estimated current costs until 2030/2040/2050?	Estimates for each industry and each year in %
- What are the total cost shares of CCS for the liquid biofuel industry, biomass-fueled thermal power generation and pulp and paper industry?	Estimates for capital, labor, energy requirements, external services and maintenance. Shares must total 100%.
Application of CCS and capture potential	
- How likely is it that CCS will be applied in the liquid biofuel industry, biomass-fueled thermal power generation and pulp and paper industry?	Rating scale: very likely, rather likely, rather unlikely, very unlikely
- Which share of the total carbon content of biomass used for the liquid biofuel industry (corn ethanol, lignocellulosic ethanol, biodiesel), biomass-fueled thermal power generation and pulp and paper industry can be captured by CCS?	Estimates in %
- Please indicate your estimate for the global CCS potential of the liquid biofuel industry, biomass-fueled thermal power generation and pulp and paper industry by 2030/2040/2050.	Estimates in MtCO_2

can be found in the supplementary material (S1). Despite looking for experts on the global level, countries of the Global South were underrepresented in our expert pool. Sovacool (2023) has already highlighted how the discourse on carbon removal potential has been limited mainly to the Global North without adequately representing countries of the Global South. After noticing the bias in our first survey, we conducted an additional survey round inviting further experts only from countries of the Global South. The survey was sent to 37 additional experts in October 2023, of which seven experts responded (for a total of $N = 32$ and a response rate of 18% for both surveys). In the additional survey, we specifically aimed to include experts from China, given the number of recent relevant publications by Chinese scholars (e.g. Huang *et al* 2020, Xing *et al* 2021, Weng *et al* 2021). More than half of the emails were not transmitted and the remaining invitees did not reply. Thus, regrettably, we were unable to include expertise from China.

Table 1 provides an overview of the survey questions presented to the experts. Most answer options entailed either rating scales (e.g. 'very suitable' to 'very unsuitable'), in order to assess the attitudes and opinions of the experts, or ranking options ('1 = very important' to '7 = least important'), to classify preferences (Moors *et al* 2016, Del Grande and Kaczorowski 2023). For the questions on technical estimates, the experts could choose from several possible answers of

Table 2. Number of respondents by disciplinary background and region.

	Humanities and business administration	Environmental science	Chemical engineering	Other engineering	Other natural sciences	N[a]
North America	3	1	2	1	1	5
Europe	4	2	2	4	2	11
Rest of the World	2	2	1	1	7	9
Not stated	3	3	3	3	4	7
Total	12	8	8	9	14	32

[a] Multiple answers on disciplinary background were possible, so that the sum of columns is not equal to N. North American nations represented in this survey are Canada and the USA; Europe includes the UK, Norway, Sweden, the Netherlands, and Germany; the Rest of the World includes India, Saudi Arabia, and Brazil, which are further defined as countries in the Global South, and South Korea. 'Humanities and business administration' includes economics, business administration, political sciences and psychology; 'Chemical engineering' and 'Environmental science' include only chemical engineering and environmental science, respectively; 'Other engineering' includes mechanical engineering, material science, energy engineering, techno-economic system dynamics, and environmental engineering; 'Other natural sciences' includes natural science, agriculture science, and geography.

estimates from the literature. More detailed information on each question and its answer option is provided in the supplementary material (S1).

Table 2 lists the geographical location of primary employment and the disciplinary background of the respondents. Further information on the experts, i.e. their expertise and working experience, are presented in the supplementary material (S1).

3. Results

3.1. Expectations regarding the implementation of BECCS

As shown in figure 1, respondents consider the highest development potential for implementing BECCS by 2040 in the USA, Canada, and the European Union (EU), followed by the United Kingdom (UK), Brazil, and China. At least 40% of the respondents rate the potential for each of the regions as high or very high. Whereas the EU, UK, USA and Canada have the lowest variation in the assessment and the lowest share of respondents answering 'do not know,' the opposite is true for China. Here, the variance in responses and the share of respondents choosing the 'do not know' option is among the highest of all regions, thus demonstrating a high degree of uncertainty. For all regions besides the European countries, Brazil, the USA, and Canada, more than 40% of the respondents are uncertain regarding development potential. Development potential relates only to the establishment of a BECCS production site because biomass may be sourced from other regions, and carbon can be transported to other regions. However, transport costs for biomass and carbon may affect the assessment of the regional development potential for establishing BECCS production sites.

Related to this, figure 2 presents the relevance of distance to biomass production and carbon storage for the location of a BECCS production site, and shows that there is no consensus on which location factor plays the most important role for BECCS sites. A paired t-test confirms that there are no significant preferences between 'Usage of existing energy production facilities' over 'Closeness to CO_2 storage sites' and 'Closeness to biomass feedstock.' However, whereas the importance of 'Usage of existing energy production facilities' and 'Closeness to biomass feedstock' have the highest ranking for 1 and 3 (not statistically differentiable), 'Closeness to CO_2 storage sites' has one median for 2. Differences between respondents from the Global North and Global South are observed in preferences for 'Closeness to CO_2 storage site' and 'Usage of existing energy production facilities.' In contrast to the experts from the Global North, those from countries in the Global South significantly ($p < 0.05$) rate 'Closeness to CO_2 storage site' as more relevant than 'Usage of existing energy production facilities.' All respondents agree that proximity to consumers of energy or fuels is significantly ($p < 0.01$) least relevant.

The importance of the respective cultivated feedstocks for BECCS by all respondents is presented in figure 3. A relatively wide range of sources could potentially supply biomass for BECCS. Three main categories can be distinguished worldwide: municipal and industrial wastes, agricultural, forest and wood residues (secondary biomass), and bioenergy crops (primary biomass) (Balaman 2019, Zhang *et al* 2020, Wu *et al* 2024). The list of feedstocks is oriented towards the products typically modelled in partial or general equilibrium models. Apart from wood residues, secondary biomass was not included in the survey due to uncertainties in sustainable availability, feedback links, and prices (Hanssen *et al* 2020b). Including these feedstocks would require additional clarification that exceeds the range of this study, because integrating secondary biomass use in economic models is a challenge on its own.

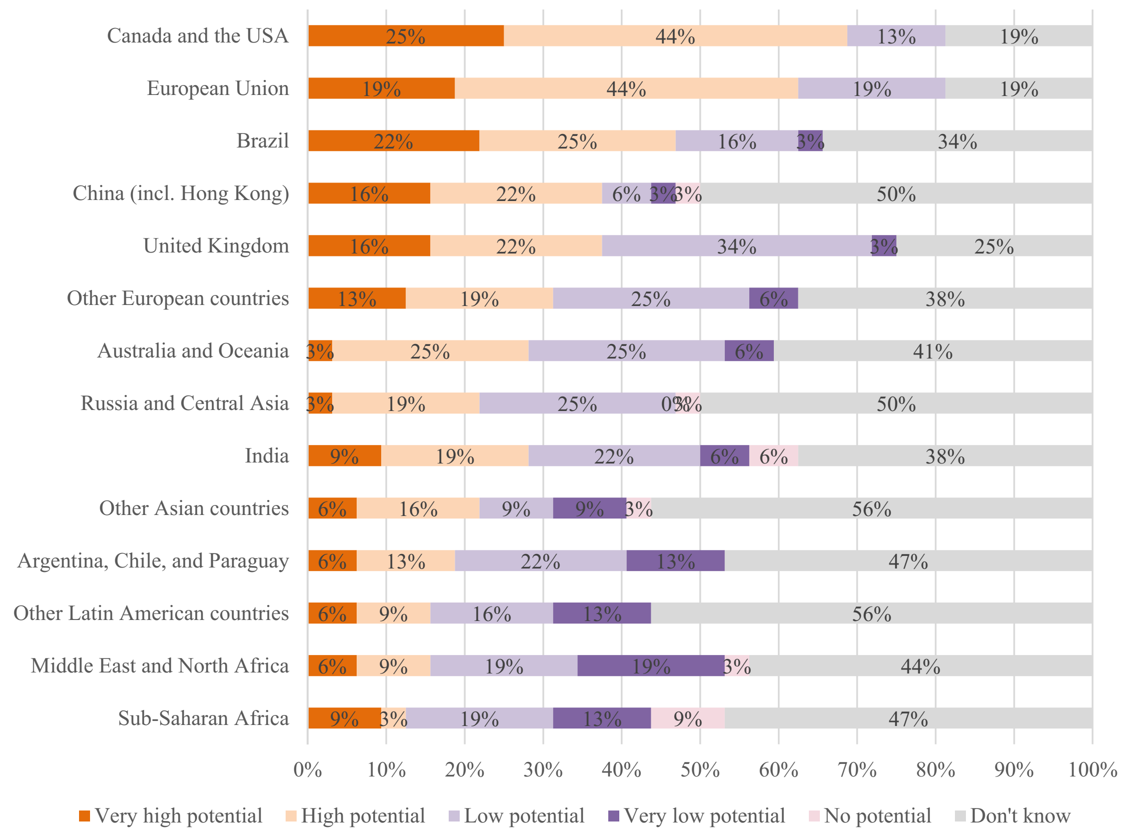

Figure 1. Region-specific potential for market development of BECCS by 2040 ($N = 32$). Note: regions are listed in descending order of mean potential (excl. 'do not know').

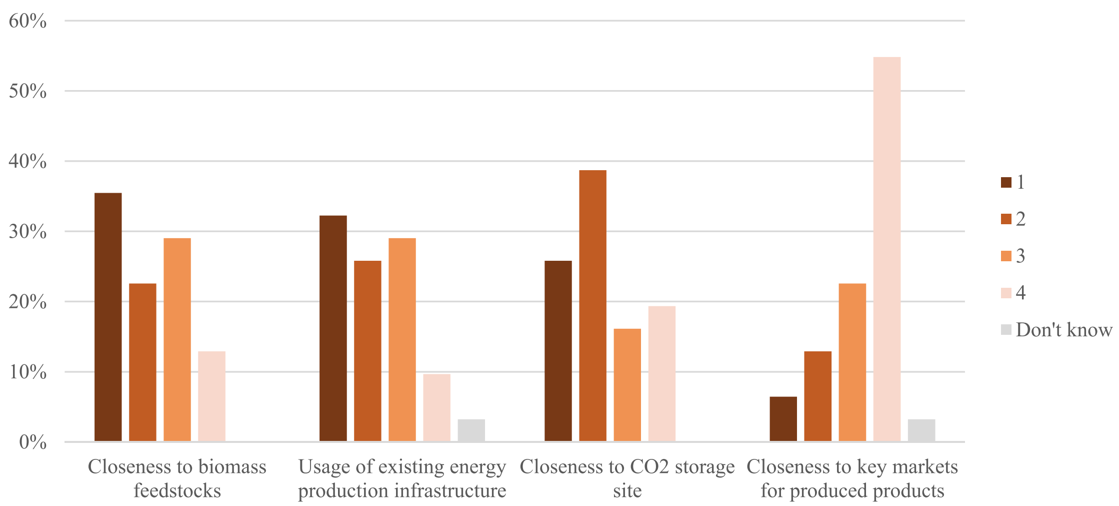

Figure 2. Importance of different location factors for BECCS deployment (1 = very important to 4 = least important) ($N = 31$, one expert did not answer the question).

The Kruskal–Wallis test (see Kruskal and Allen Wallis 1952) shows significant differences in the feedstock assessment between respondents from the Global North and Global South. In contrast to respondents from the Global South, experts from the Global North value wood residues and pellets as significantly more important than sugar crops and grains. However, the Wilcoxon signed-rank test (see Wilcoxon 1945) reveals that all respondents agree that grasses, roundwood, and oilseeds are significantly assumed to be least important.

Whereas for most feedstocks the area of application is obvious, there are some uncertainties considering short-rotation coppice (SRC), which is ranked in the group of important feedstocks. We therefore asked the experts which possible area of application for BECCS (thermal power generation, liquid biofuel, or pulp and paper industry; see Fuss *et al*

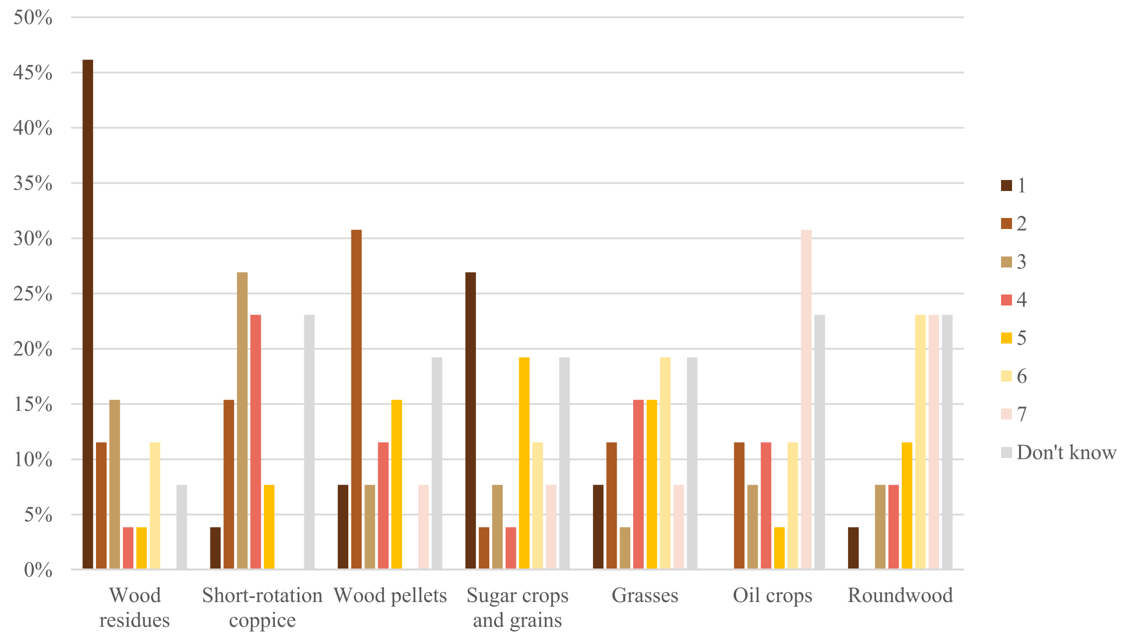

Figure 3. Importance of different energy crops as a biomass feedstock or product for BECCS (1 = very important to 7 = least important) ($N = 25$, seven experts did not answer the question). Note: feedstocks are ordered by mean of responses, starting with the lowest mean on the left (excl. 'do not know').

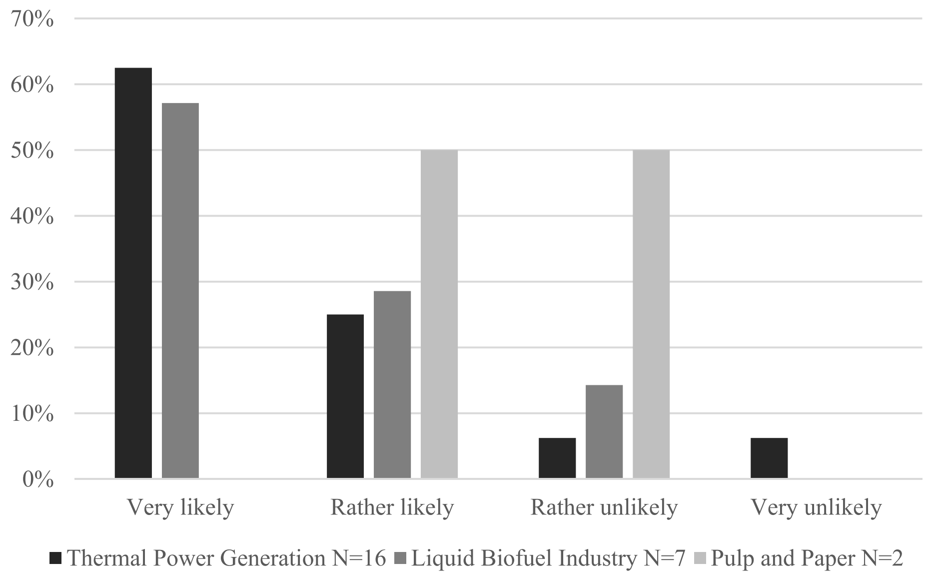

Figure 4. Likelihood of BECCS implementation by area of application.

2018, Rosa *et al* 2021) could be the most suitable for SRC. Considering all respondents, no significant ranking was observed; however, taking into account only respondents from the Global North shows that SRCs are preferably used in thermal power generation than in the pulp and paper industry.

3.2. Production technology and costs of BECCS

This section presents estimates for the production costs of BECCS. As mentioned above, based on Rosa *et al* (2021), we identified three areas of application for BECCS: thermal power generation, the liquid biofuel industry, and the pulp and paper industry. The experts were requested to self-identify their expertise and were only asked those questions relating to these self-identified areas of expertise. The questions on production technology and costs contained the same questions for each area of application.

We first asked respondents to assess the likelihood of BECCS being deployed in each application area (see figure 4). Around 60% of the respective experts estimate that BECCS is very likely to be implemented in thermal power generation and the liquid biofuel industry. The experts from the pulp and paper

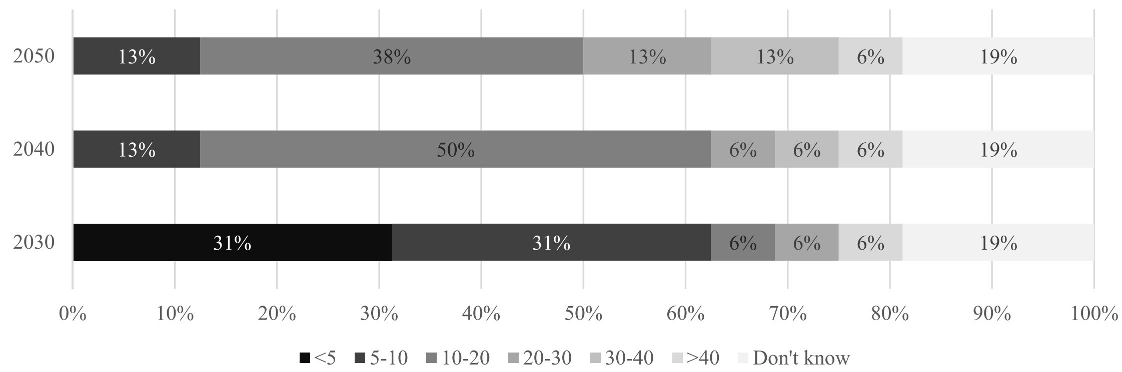

Figure 5. Cost efficiency gains due to technical progress for CCS in biomass-fuelled thermal power generation by 2030, 2040, and 2050 ($N = 16$).

industry viewed the implementation of BECCS in this sector as likely as not since they chose the two answer categories 'rather likely' and 'rather unlikely' with equal frequency. However, only a minority of respondents identified themselves as experts in the liquid biofuel ($N = 7$) and the pulp and paper ($N = 2$) industries. Only some of these experts ($N \leqslant 5$) were able to answer the questions on production costs and development potential, leading to a sample too small for statistical analyses. We therefore only present results for BECCS in thermal power generation here. The results for the liquid biofuel industry are given in the supplementary material (tables S1–S8).

All experts indicate that BECCS in thermal power generation will cost 100–200 USD/tCO_2, with two medians at 100–120 USD/tCO_2 and 181–200 USD/tCO_2. To obtain more precise estimates within the 100–200 USD/tCO_2, we offered answer intervals in 20 USD increments; however, the responses show an almost equal distribution across the intervals. According to two experts, uncertainties in the cost estimates provided might be related to the expected large spread in costs between individual projects and the feasibility of economies of scale given the chain of logistics. Besides opportunities for economies of scale, expected technical progress is also important when assessing future technologies. Figure 5 displays expected cost efficiency gains by 2030, 2040, and 2050, respectively. More than half the experts expect less than 10% cost efficiency gains by 2030, half the experts indicate an efficiency gain of 10%–20% by 2040, and around one-third assume more than 20% by 2050. These numbers do not differ between experts from the Global North and Global South.

Figure 6 shows the cost shares of CCS production technology in biomass-fueled thermal power plants. Whereas all experts indicate that the technology is capital-intensive, the estimates for capital share are most widely spread compared to the other costs. This includes outliers that have a comparably low capital intensity. According to one expert, operating costs depend on the set-up of the supply chain for BECCS, which is difficult to forecast. The median (mode) share of costs for CCS are 52.5% (60%) capital, 12.5% (15%) labour, 20% (20%) energy, and 10% (15% and 10%) external service and maintenance. The aggregated share of costs do not equal 100% due to the distribution in responses for each individual cost.

Finally, the experts were asked to (a) state the share of total carbon content of biomass used for thermal power generation that can be captured by CCS, and (b) estimate the global CCS potential of thermal power generation by 2030 and 2040 (see tables 3 and 4). Most experts expect carbon leakage in the CCS process to be less than 10%. Unfortunately, the distribution of replies does not lead to a more exact appraisement. For BECCS CO_2 capture potential, most respondents agree on 50–200 MtCO_2yr^{-1} until 2030, while the estimates diverge for 2040. Most experts assume a capture potential of 500–1000 MtCO_2yr^{-1} by 2050.

4. Discussion

The results of the survey provide information regarding experts' expectations of future BECCS deployment. The experts' assessments help contextualize the current literature on BECCS development and the respective BECCS potential for the various feedstocks, geographical location, and sectors of implementation, and therefore provide crucial information elaborating on BECCS sector development in economic models. Whereas several studies emphasize the sustainability of using grasses for bioenergy production (Morales *et al* 2015, Robertson *et al* 2017, Zhao *et al* 2022, Domingues *et al* 2022), the experts assume the importance of grass as a feedstock for BECCS as medium to low. They consider the use of woody biomass and sugar crops as more suitable. Moreover, for regions other than Europe, Northern America, Brazil, and China, regional potential for BECCS is assessed to

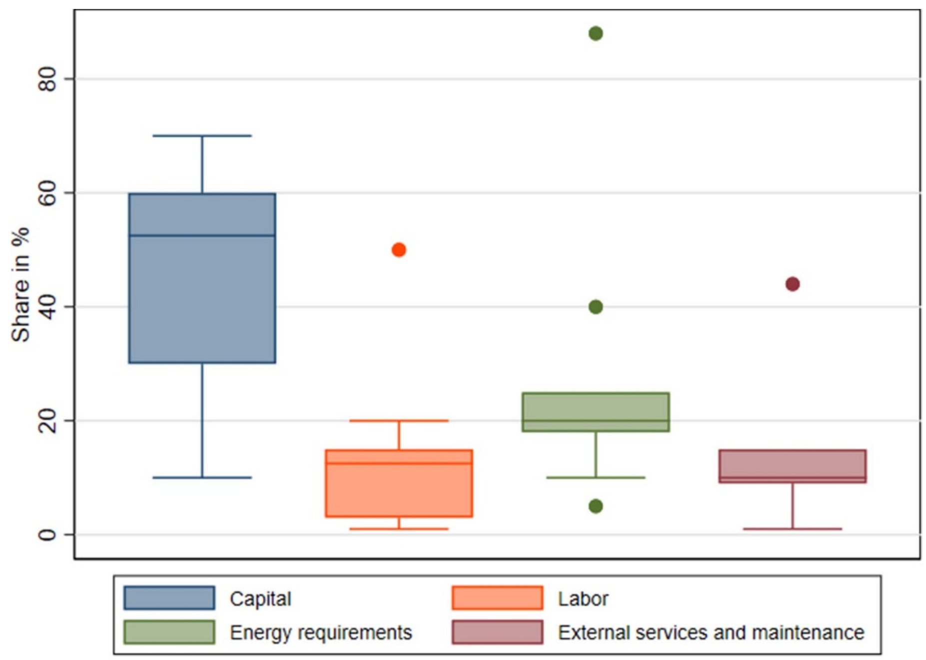

Figure 6. Boxplot of total share of costs for BECCS in thermal power generation ($N = 10$, six experts did not answer this question). Note: boxes are bounded by the upper and lower quartiles; the line inside the boxes indicates the median, whiskers denote the min. and max. within the 1.5 interquartile range, and dots represent outliers.

Table 3. Global CCS potential of thermal power generation by 2030, 2040, and 2050 in $MtCO_2yr^{-1}$ Note: N = 11, five experts answered 'do not know'; Mt = 10^6t.

Year\Mt CO_2	<50	50–200	200–350	350–500	500–1000	>1000
2030	2	***7***		1		1
2040	1	1		3	***4***	1
2050		2			***5***	3

Table 4. Share of total carbon content of biomass used in thermal power generation captured by CCS Note: N = 14, two experts answered 'do not know'.

Capture rate %	<85	85–89	90–94	95–99
Number of experts	1	5	4	4

be low or uncertain in practice, despite the biomass potential of these areas (Ricci and Selosse 2013).

Although experts from different backgrounds were invited to participate, most of the experts who responded to the survey have expertise in BECCS for thermal power generation. Considering the application sectors of BECCS, around two-thirds of the experts rate the application of BECCS in the liquid biofuel industry and thermal power generation as very likely. However, this assessment could have been influenced by the technical and geographical background of the respondents. Bonaccorsi *et al* (2020) discuss the relevance of expert biases in technological foresight surveys, suggesting the concurrent use of various methodologies. Bowling (2005) also argues that the mode of questionnaire distribution has a biasing effect on data quality. For this study we intended to employ the Delphi method, which is widely used for technology foresight studies and eliminates some bias (Bolger *et al* 2011, Ecken *et al* 2011, Bonaccorsi *et al* 2020, Belton *et al* 2022), but only a few experts participated in the second Delphi round, with no experts adjusting previous estimates. Experts' willingness to participate needs to be considered when developing more complex and time-consuming survey approaches.

In accordance with the technological background, we mainly obtained costs and deployment estimates for BECCS in thermal power generation. The experts estimated the operating costs of BECCS in thermal power generation at 100–200 USD/tCO_2, which is confirmed by Fuss *et al* (2018) and is within the range of other studies (20–340 USD/tCO_2) (Abegg *et al* 2024). Whereas the individual experts provided more narrow estimates than those in the literature, the almost equal distribution of expert responses within this interval reflects the high degree of uncertainty regarding operating costs.

Since, to the best of our knowledge, estimates on the share of costs of BECCS used in thermal power generation are scarce, the estimates given by the experts provide an important input for BECCS economic models that require specific cost-share information on production factors and intermediate inputs. The mode share of cost for capital for CCS thermal power generation with biomass is 60%, which confirms the assumptions of Morris *et al* (2019). However, responses do not indicate a uniform pattern in the shares of the remaining costs. Once the already established pilot projects have matured and more experience has been accumulated, further research should be conducted to derive more precise estimates for operating costs and production cost shares.

In addition to the share of costs, the estimates obtained on technological progress deliver valuable information for enhancing the numerical modelling of future trade-offs, costs efficiency, and competitiveness of BECCS. Given the remaining uncertainties, additional sensitivity analyses when investigating trade-offs could increase the reliability of such assessments (Muratori *et al* 2020). Considering capture potential, several experts expect a CO_2 capture potential of 50–200 $MtCO_2yr^{-1}$ for BECCS until 2030 and assume that technological progress will increase the cost efficiency of carbon sequestration by 20% by 2050. This is an important assumption when modelling the costs of future BECCS production and competitiveness in CO_2 markets. The estimated capture potential for BECCS by 2030 meets projections of the IEA (IEA 2023b) of 60 $MtCO_2yr^{-1}$, but is below Consoli (2019) and Grant *et al* (2021) of up to 800 and 430 $MtCO_2yr^{-1,}$ respectively. Experts interviewed by Abegg *et al* (2024) estimate lower capture potential until 2030 with 0.1–35 $MtCO_2yr^{-1}$.

The sample sizes obtained for the liquid biofuel industry and the pulp and paper industry were too small for statistical analysis. The pulp and paper sector was particularly challenging for obtaining information. Although previous studies highlight the potential of BECCS in this sector in Europe, seemingly little is known about production costs, sequestration potential, and carbon capture efficiency (Rosa *et al* 2021). It is highly recommended, therefore, to obtain the opinion of practitioners and their assessment of the potential for BECCS, and a further expert study focusing on the pulp and paper industry is consequently needed.

In this study, we assessed the use of various biomass feedstocks for BECCS. Since the use of primary biomass (bioenergy crops) raises sustainability concerns (Vaughan *et al* 2018), it seems important to capture experts' expectations for their potential use. There is also the question of whether biomass feedstock for BECCS is locally sourced or imported. Favero and Masetti (2014) expect large incentives for the international trade in biomass, so that important biomass-producing countries (e.g. Latin and North America, Central Asia, China, and sub-Saharan Africa) are not necessarily the main consumer countries of BECCS feedstocks (e.g. OECD countries) (Ricci and Selosse 2013). Finally, secondary biomass (municipal and industrial wastes, as well as agricultural residues) have been discussed for use in bioenergy production (Kalt *et al* 2020, Hanssen *et al* 2020b) or BECCS (Wu *et al* 2023, 2024) but were not included in this survey. Because this is a highly relevant topic on its own, experts' opinions on the feasibility and sustainability of using organic waste, manure, and agricultural residues for BECCS should be addressed in a separate study.

Responses regarding suitable feedstocks and production factors for BECCS indicate that respondents from the Global North and Global South might focus on different sectors. Although the respondents were not asked to answer the questions with respect to the geographic area they worked in, it seems they intuitively did this. Whereas respondents from countries in the Global South value sugar crops and grains and the liquid biofuel industry as the most relevant feedstocks and industry sector for BECCS, respondents from the Global North prefer wood residues as feedstock, and thermal power generation as the most promising sector. There are also various assumptions on which biomass will be used in prospective BECCS projects in the Global South (Jaschke and Biermann 2022). Here, our study contributes to the research suggesting that established (primary) biomass feedstock such as sugar crops and grains are expected to be employed, rather than lignocellulosic feedstock. Further, the experts' statements show that the regional availability of biomass presumably plays a crucial role in the use of BECCS in a region, regardless of the existence of international trade.

Using existing energy-production infrastructure to minimize capital costs is less relevant for respondents from countries in the Global South, who value proximity to CO_2 storage as more important. This outcome could potentially differ if Chinese experts had contributed to the survey, since retrofitting coal power plants for BECCS is likely to be a key element in Chinese BECCS development (Xing *et al* 2021, Fan *et al* 2023, Sammarchi *et al* 2024). Experts from countries in the Global North also prefer to reduce costs by using existing energy production infrastructure and reducing the distance to biomass feedstocks (see figure 2). The range in the experts' ratings reflects this ongoing debate of centralized versus decentralized bioenergy production (Guest *et al* 2011, Mangoyana and Smith 2011, McGovern and Klenke 2018, Albanito *et al* 2019, Donnison *et al* 2020). For instance, Freer *et al* (2022) show that, for the UK, the non-optimal location of BECCS, e.g. by using pre-existing production sites, can adversely affect the emission balance through increased supply chain emissions from biomass and/or carbon transport.

Distance to markets for energy produced is the least important factor, likely due to already established transport modes for energy, e.g. via electricity grids.

Although the survey was distributed globally, most of the respondents were primarily employed in Europe. As discussed in Wähling *et al* (2023), including one or more globally networked partners in the distribution of a survey could achieve a higher global response rate. The survey results underline the statement by Sovacool (2023) that including scholars and experts from the Global South in scientific and technological debates about CDR methods is important. A large share of the respondents did not feel confident in assessing the potential of BECCS for countries in the Global South, although global modelling studies predict high development potential for BECCS in the Global South, with Latin America, Asia and sub-Saharan Africa identified as promising regions (Ricci and Selosse 2013, Nemet *et al* 2018, Hanssen *et al* 2020b, Roe *et al* 2021, Nabuurs *et al* 2022), given the availability of important areas that could provide biomass energy and storage capacities (see, e.g. Ricci and Selosse 2013, Hanssen *et al* 2020b). Moreover, the results show that without approaching more respondents from the Global South in the third survey round, we would have a strong geographic bias in the results, marked by an underrating of grains and sugar crops as biomass feedstock used for BECCS in the biofuel industry (Tanzer *et al* 2021). BECCS in bioethanol production is assumed to have considerable development potential in Brazil where biofuel production and consumption are likely to further increase in future (Moreira *et al* 2016, de Andrade Junior *et al* 2019, IEA 2023, Restrepo-Valencia and Walter 2023). In contrast, from 2035, the EU plans to only allow the registration of new vehicles powered by fully CO_2-neutral fuels (see EU 2023). China, however, remains a blind spot in this research as we were unsuccessful in including Chinese experts in the survey. Given the important BECCS potential projected for China (Nemet *et al* 2018, Xing *et al* 2021), refining estimates for China could be decisive for the contributions of BECCS to climate mitigation efforts.

The forest sector is increasingly being integrated into various policies that could compete with or support each other, depending on local conditions and policy implementation specificities (Nabuurs *et al* 2022). Considering the high relevance of wood residues in BECCS in thermal power generation, Hanssen *et al* (2020b), Babin *et al* (2021), and Rosa *et al* (2021) argue that more research on the representation of wood residues in IAMs and their increased use in bioenergy production is needed to clarify the related impacts on forests and their other ecosystem services. Wood residues are used energetically and materially (Saal *et al* 2017, Grebner *et al* 2022). The increased energy use of wood residues may lead to trade-offs or synergies with other wood uses depending on local conditions (Cowie *et al* 2021). Using wood residues for bioenergy could improve the financial returns of harvest activities, thereby promoting forest management over other land uses (Dale *et al* 2017, Favero *et al* 2020). At the same time, it may cause competition in feedstock use (Lauri *et al* 2017, Daioglou *et al* 2020) and increase the removal intensities of forest biomass with possible repercussions for biodiversity (Costanza *et al* 2017), carbon sequestration in different pools (Favero *et al* 2020, Lan *et al* 2024), and forest productivity (Cowie *et al* 2021). IAMs usually rely on average shares of sustainably available residues to reflect and limit such trade-offs with other ecosystem services (Daioglou *et al* 2016, Hanssen *et al* 2020b). Revising their representation by accounting for local conditions might increase costs and affect the availability of wood residues (Hanssen *et al* 2020b, Babin *et al* 2021). In return, this could influence the deployment of BECCS.

Considering these trade-offs, the compatibility of an increased use in wood residues for BECCS to the extent projected in climate mitigation scenarios consistent with the Paris Agreement, in policies promoting a circular bioeconomy (e.g. EU 2022), or biodiversity protection (e.g. EU 2020), is questionable (Cowie *et al* 2021, Funk *et al* 2022). Given the limited availability of forest biomass and land, policies must be science-based and carefully balanced to optimize the use of feedstock while enhancing or preserving other ecosystem services (Nabuurs *et al* 2022) and addressing equity issues (Reisinger *et al* 2024). Here, interdisciplinary modelling studies considering sectoral impacts on forest-based ecosystem services and cross-sectoral substitution effects of raw materials could deliver valuable insights for coordinating these policy targets.

SRC was viewed as a promising feedstock for BECCS by all respondents. Although the literature underlines the potential of SRC, e.g. growth on marginal land and reducing competition with other agricultural activities (McElroy and Dawson 1986, Spiegel *et al* 2018, Fernández *et al* 2020), investment costs, economic risks, and farmer inertia lead to a slow adoption of SRC cultivation (Alexander *et al* 2014, Matthias and Oliver 2014, Pereira and Costa 2017, Spiegel *et al* 2018, Ranacher *et al* 2021), so that realizing its potential remains uncertain. In line with the respondents, also the literature mainly highlights the potential of SRC in electricity and heat production (Alexander *et al* 2014, Spiegel *et al* 2018, Fernández *et al* 2020)

5. Conclusions

This study aims to obtain predictions relating to BECCS development and technical estimates, including operating costs, capture potential, scalability, and biomass use, to provide more consistent information for economic modelling and trade-off analysis. The survey conducted provides an expert evaluation of estimates for BECCS production stated in the current literature and derives assumptions that can be used in economic models (e.g. CGE models) for future regional and global BECCS production and the feedback effects on the industrial and agricultural sectors, trade, welfare, CO_2 pricing, and GHG emissions. Whereas the survey reflects to some extent the degree of uncertainty for the long-term development of BECCS, it provides valuable information for the prospects over the next 20 years and enables trade-off analyses for the first phases of BECCS deployment. Over time, as new technologies that can be used in BECCS production processes enter the market, new technological forecast studies need to be conducted to stay up to date. Gaps remain, especially concerning (a) specific regions and countries, including, e.g. China and other areas in the Global South, (b) the relevance of specific biomass sources and sectors, e.g. the use of secondary biomass, and (c) specific components of the applied technology, e.g. the operating cost of facilities.

In terms of the use of biomass and application area for BECCS, we find significant differences depending on the geographical background of the respondents. The study affirms that BECCS technologies using secondary wood biomass in thermal power generation will play a major role in the Global North, while high relevance is given to BECCS using sugar crops and grains in the liquid biofuel industry in the Global South. Even though the pulp and paper industry is considered a key sector for BECCS in the literature, we were unable to collect additional empirical information on BECCS in this sector. Therefore, additional expert studies concentrating on BECCS in the pulp and paper industry are recommended.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no competing interests.

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