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The Role of Negative Emissions Technologies in 2050 Decarbonation Pathways
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Coordinating the Deployment of Bioenergy with Carbon Capture and Storage

Emma Jagu Schippers[1,2,3,*], Pascal Da Costa[1], and Olivier Massol[1,2,3,4,5]

[1] CentraleSupélec, Université Paris-Saclay, Laboratoire Genie Industriel, 3 rue Joliot-Curie, 91192 Gif-sur-Yvette, France
[2] Center for Energy Economics and Management, IFP School, 228-232 av. Napoléon Bonaparte, 92852 Rueil-Malmaison, France
[3] IFP Energies nouvelles, 1 et 4 av. de Bois-Préau, 92852 Rueil-Malmaison, France
[4] Department of Economics, City, University of London, Northampton Square, London EC1V 0HB, UK
[5] Climate Economics Chair, Palais Brongniart, 28 place de la Bourse, 75002 Paris, France

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Abstract. Bioenergy with Carbon Capture and Storage (BECCS) is a negative emissions technology that allows the removal of CO_2 from the atmosphere while producing energy or goods. This technology has been increasingly pictured as key to reaching the Paris Agreement targets. But with only a few demonstration projects currently in operation, its deployment is far from projected. The large-scale deployment of BECCS is hindered by economic, social, and environmental barriers that have been subject to an increasing number of studies. As most research on BECCS tends to adopt a central planning perspective, the barriers related to strategic interactions and coordination issues within the BECCS value chain are often overlooked. Based on a systematic literature review, we identify coordination-related challenges for BECCS deployment. We describe three challenges to BECCS deployment that should be further examined through the lens of coordination: (i) trading biomass and ensuring its sustainability; (ii) reducing costs through synergies with other industries and shared CO_2 infrastructures; and (iii) coordinating policies internationally to provide revenues for BECCS.

Keywords: Bioenergy with Carbon Capture and Storage, Negative emissions, Coordination problems.

1 Introduction

A recent IPCC report [1] highlighted that carbon dioxide removal will likely be necessary to limit global warming to 2 °C and that Bioenergy with Carbon Capture and Storage (BECCS) will have a critical role to play in meeting this objective. BECCS combines the natural carbon sequestration potential of biomass growth with permanent geological carbon storage. Contrary to afforestation, BECCS is a source of energy, which explains its considerable role in many Integrated Assessment Models (IAMs) scenarios [2]. By 2050, BECCS is expected to scale up from today's Megaton scale of carbon removal capacity to the Gigaton scale [2–4]. Even though these speculative scenarios have been criticized for their modeling assumptions and associated ecological risks, they are nevertheless useful exploratory tools for policy-making [5–8]. Few models, however, take a decentralized approach to BECCS deployment.

The value chain of BECCS combines two *a priori* independent processes: The upstream bioenergy chain and the downstream Carbon Capture and Storage (CCS) chain. The bioenergy chain includes land preparation, biomass growth, harvesting, processing, and transportation. The CCS chain consists of the chemical process of CO_2 capture and the logistics of CO_2 transport and storage [9–11]. BECCS plants originate from various contexts: some are former coal power plants being converted to bioenergy [12], and others are already functioning with bioenergy, such as pulp and paper industries and biorefineries [13, 14]. BECCS thus mobilizes a complex supply chain that requires the joint participation of heterogeneous agents. While most studies implicitly posit that a unique decision-maker – usually in the form of a benevolent social planner – controls the whole value chain [15–17], economic agents are unlikely to follow their guidelines without tailored incentives. A closer examination of the coordination issues faced by the agents is needed, especially if they can behave strategically. A number of extensive literature reviews focusing on deployment barriers to BECCS have already

* Corresponding author: emma.jagu@centralesupelec.fr

been written [2, 4, 18–21]. However, to the best of our knowledge, none focuses on coordination issues.

The need for coordination is most often mentioned as a side note in the literature of BECCS, while the concept has been explored in several other disciplines and sectors, including industrial ecology and economics. Coordination can be described as "the process of managing dependencies among activities" [22]. Whenever a value chain is not entirely integrated, questions of interdependencies between agents and activities arise, potentially leading to suboptimal market equilibriums that can hamper the deployment of new technologies. For example, two main types of dependency are described in industrial ecology: symbiotic resource dependencies (when the output of one agent is the input of another) and competitive resource dependencies (when several agents need the same limited resource) [23, 24]. To resolve these dependencies, coordination mechanisms can be established by centralized institutions or between agents themselves in a decentralized manner. As an illustration, firms can coordinate themselves through contracts to manage symbiotic resource dependencies, sharing resources such as infrastructure and waste products, thereby reducing costs.[1] Meanwhile, centralized institutions – *e.g.*, regulators, governments, and international organizations – can provide coordination mechanisms by facilitating international agreements to address competitive resource dependencies.[2]

In terms of theoretical frameworks, the economics literature provides several key concepts to understand coordination processes. While such analyses have, to the best of our knowledge, not yet been carried out in the context of BECCS, three relevant concepts can be cited. First, cooperative games assess the conditions under which agents individually accept to form coalitions to gain from cooperation [25–27]. Second, coordination failures occur when agents fail to reach the optimal market equilibrium due to a lack of coordinated decision-making [28]. Finally, coordination generates transaction costs [29, 30] during negotiation phases – when contracts or agreements are drafted – and throughout monitoring and enforcement steps [31]. The Coasian "Hold up" problem reveals that opportunistic behavior can arise from dependency asymmetry, *i.e.,* when one actor is more dependent on its partner than the other [29].

We aim to present a new lens to the challenges of BECCS by providing an overview of deployment barriers that can be addressed through coordination. We show that this is a crucial specificity of BECCS, using a systematic literature review methodology to identify the most extensive possible range of issues. In particular, we identify dependencies described in the BECCS-specific literature that could be examined using the theoretical frameworks described above to evaluate possible coordination mechanisms either between the agents themselves or through a centralized institution with the role of a social planner. Out of an initial sample of 750 papers on BECCS retrieved from Scopus and Web of Science, we identify 77 articles that describe interdependencies between actors or activities of the value chain to some extent, but only one explicitly modeling them.

Our analysis highlights that, while cooperation is repeatedly called for, little modeling effort has yet been directed toward a broader understanding of the drivers of successful cooperation for BECCS processes. Furthermore, we identify 16 potential coordination failures and detail three coordination challenges that may require more modeling efforts.

The paper is organized as follows. Section 2 presents our systematic literature review methodology. Section 3 details the three main coordination issues we have identified. Section 4 concludes.

2 Methodology and data

A systematic literature review methodology was used to identify the main coordination problems in the deployment of BECCS. In May 2020, we performed an initial screening through papers on BECCS published after 2007, when the first IPCC report that mentions BECCS was published [32]. More recent references were added to the discussion in a second step. In this section, we describe our systematic literature review methodology. We then provide some remarks on the screening process, and the resulting data is synthesized in Tables 1–4.

2.1 Systematic literature review methodology

To achieve an extensive overview of the literature, we successively carry out the following four steps [33]: (i) we define a focused research question; (ii) we choose a set of sources and databases and design search queries that cover the largest relevant volume of literature; (iii) we formulate inclusion and exclusion criteria to select a set of papers, and finally; (iv) we apply the criteria and synthesize the data.

Thus, after an initial review of socio-economic barriers to the deployment of BECCS [2, 4, 18–21], we narrow down our research objective to the identification of coordination issues in the BECCS value chain, as such a decentralized perspective on BECCS had, to the best of our knowledge, not been taken before. Therefore, we formulate our research question as follows: Which critical barriers to the deployment of BECCS are subject to coordination failures? Then a search was conducted on Scopus and Web of Science. We designed search queries to identify all scientific papers that focused on BECCS; we combined synonyms of "bioenergy" with synonyms of "carbon capture"; then, we used a set of inclusion and exclusion criteria to decide which papers to keep in the study. The articles needed to (i) focus on BECCS and (ii) mention some form of interdependencies between actors or activities of the value chain. Following

[1] Such cooperation is known as an eco-industrial park. Kalundborg Industrial Park in Denmark, created in 1959, is considered the first such park.

[2] Since the Earth Summit in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) has started a coordination process on a competitive resource dependency: Humanity's remaining carbon budget. More recently, the Paris Agreement achieved a global consensus on the need for climate change mitigation [97, 98].

Table 1. Bioenergy.

Issue	Interdependencies	Stakeholders	Suboptimal market equilibrium	Policy recommendations in the literature	Sources
1. Large enough supply of biomass	BECCS projects rely on the provision of large enough biomass supplies, but there is a locational and economic disconnect between regions with biomass potential and regions with CCS projects. International biomass trade would have to scale up	• Countries with biomass production potential • Companies that invest in BECCS plants • Farmers	Without economic incentives, failure to allocate marginal lands to energy crop production in developing countries	International financial incentives such as: • Clean development mechanisms • An international negative emissions market • Sustained investment through aid programs	[39, 40, 66, 80]
			Uncertainty over how trade and markets will develop	NA	[8, 17, 81]
			NA	No restriction to market mechanisms if side effects do not exceed the cost of market restrictions	[35]
2. Infrastructure deployment	The deployment of large-scale biomass supply chains may benefit from infrastructure sharing – due to technological learning and economies of scale. Ergo, biomass producers and transportation operators need to cooperate	• Farmers • Biomass transportation operators • Bioenergy processing firms	Suboptimal infrastructure deployment due to lack of cooperation Free-riding behavior	Financial and institutional conditions that minimize the risks of investment and facilitate dissemination	[82]
3. Sustainable biomass production	Environmental side-effects will be mostly borne by the biomass producing countries, while the negative emissions production will probably be attributed to the CCS project countries	• Countries with biomass production potential • Countries with CCS projects • Companies that invest in BECCS plants • Farmers • Local population	Unfair distribution of the costs and impacts of BECCS, in particular in countries where institutions are weak. Negative externalities may include: • Marginalization of poor local populations due to land use and land grabbing • Resource competition (land, energy, water…) • Deforestation, biodiversity reduction	Define a set of 'system-level' indicators to assess unintended negative consequences	[19]
				International sustainable biomass certification mechanism	[11, 19, 20, 42, 43, 83–85]
				Public oversight and an independent judiciary "[…] *could play a role in some countries, but they may not be effective everywhere*" [40]	[37, 39, 40]

Table 2. CO_2 infrastructures.

Issue	Interdependencies/ antagonisms	Stakeholders	Suboptimal market equilibrium	Policy recommendations in the literature	Sources
1. CO_2 transportation infrastructure deployment	Carbon capture, transport, and storage are complementary markets and face a typical "chicken and egg" dilemma: What comes first, the infrastructure or the capture technology?	• Infrastructure operators • Fossil energy with CCS (FECCS) and BECCS plants	Barriers to investment, both in carbon capture technologies and CO_2 infrastructures	Public support and subsidies to reduce risk and improve investor confidence	[18, 36, 56, 60, 61, 86]
	CO_2 transportation infrastructures are subject to economies of scale	• Infrastructure operators • Fossil energy with carbon capture (FECC) and BECC plants • Countries	If there is no international coordination, CO_2 infrastructure will not benefit as much from economies of scale	International coordination of CO_2 infrastructure deployment	[83, 87]
	The optimal infrastructure deployment also depends on uncertain future demand for carbon capture (building ahead of demand)	• Infrastructure operators • FECCS and BECCS plants	Additional costs are borne by the infrastructure operators for an oversized infrastructure, making the technology less competitive in the initial stages	Polluter pays: spreading the costs of the infrastructure overall fossil-fueled power generators through a carbon tax or CCS obligation certificates	[18]
	There are political risks related to the lengthy time needed to develop a CCS project: The availability of funds by the time the project is ready for the final investment is uncertain	• Investors • BECCS plant • Infrastructure operators • Fund provider	Barriers to investment	Contract for Differences (CfD) allocation process	[18]
	Investment in CCS infrastructures has been mostly financed by fossil-fueled industries	• CO_2 transportation operator • CO_2 storage operator • FECCS and BECCS plants	*BECCS lock-out*: BECCS projects could be *de facto* precluded by a CCS transportation design that does not anticipate their participation	• Co-firing could pave the way for BECCS by forming a bridge between coal and biomass • Storage sites should be situated close to large CO_2 emitters from biomass	[63, 64]
2. CO_2 storage infrastructure deployment	Post-decommissioning CO_2 storage risk	• CO_2 storage operator	Barriers to investment	Public support and subsidies to reduce risk and improve investor confidence	[18]
	CO_2 needs to be stored and monitored over generations	• CO_2 storage operator • Future generations	No guarantee that future generations will continue to monitor the storage site	Monitoring, reporting, and verification (MRV) mechanisms	[20]

Table 3. Bioenergy with carbon capture.

Issue	Interdependencies/ antagonisms	Stakeholders	Suboptimal market equilibrium	Policy recommendations in the literature	Sources
1. Conversion to bioenergy (in the case of power plants)	BECCS plants may substitute other energy options. BECCS plants need to be integrated into the electrical grid in the case of power plants.	• BECCS plants • Other actors in the electricity market	Investment in bioenergy might lead to more emissions in the long run through the substitution of low-carbon renewable energy options	NA	[8]
			If BECCS power plants are operated at higher load factors to increase negative emissions production, the differential cost between BECCS and alternative power options needs to be covered	Direct government intervention	[11, 80, 88–90]
2. Cost reduction	BECCS plants can build symbiotic relations with other technologies	• BECCS plant • Negative Emissions technologies, District heating actors, etc.	NA	• Subsidize R&D • International policy coordination	[4, 50, 51, 55]
	Learning curve and economies of scale on bioenergy combined with carbon capture	• BECCS plant and competitors	Free riding	NA	[18, 80]

Table 4. Overall implementation.

Issue	Interdependencies/ antagonisms	Stakeholders	Suboptimal market equilibrium	Policy recommendations in the literature	Sources
1. Negative emissions accounting	Negative emissions accounting is complex: it should be based on a life cycle assessment across international supply chains, with GHG emissions at numerous stages		• Incentive to withhold information on process emissions • Lack of transparency and permanency, risk of double counting	• International coordination in negative emissions accounting. • Apply a rate of discount when a state report international negative emissions transfers • Implement monitoring (of CO_2 streams and transfers), Reporting, and Verification (MRV) processes	[40, 42, 84]
2. International cooperation	Countries have common but differentiated responsibilities	• Countries with biomass production potential • Countries with CCS projects	• Many developing countries have the potential to deploy BECCS but do not prioritize climate mitigation • International cooperation is needed to ensure cost-efficient BECCS systems	• High levels of support from rich countries sustained over decades • Sustainable Development Mechanisms	[20, 80, 91–95]
3. Public perception	Local populations are affected by the deployment of BECCS	• Local population • BECCS plant • CO_2 operators • Bioenergy operators	Local opposition against CO_2 storage or land-use change	Inclusive and transparent decision-making process and benefit-sharing	[18, 66, 80, 96]

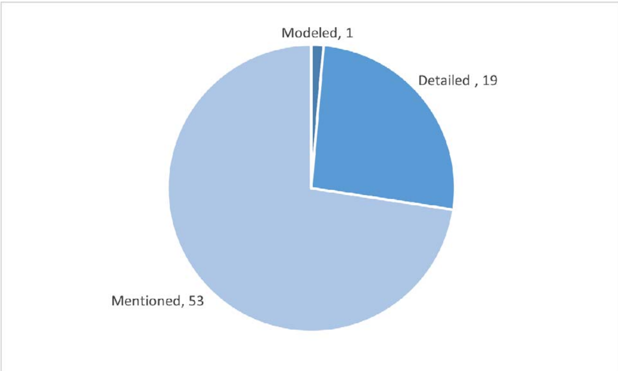

Figure 1. Levels of description.

the definition of coordination by Malone and Crowston [22] in Section 2, we focus on identifying dependencies in the BECCS value chain that can be addressed with a coordination process – *e.g.*, contracting, forming coalitions, and negotiating agreements. In other words, we do not search for specific terms such as "coordination" or "dependency" during screening. Rather, we attempt to identify processes that imply at least two distinct decision-making actors and evaluate whether their activities are dependent.

Such a broad literature filtering was made possible by the relatively small volume of literature on BECCS. The papers were screened on the open-source software *CADIMA* [34]. The inclusion and exclusion criteria were used first on titles, abstracts, and finally, full text. The information on coordination issues was then extracted from the resulting papers and summarized in Tables 1–4.

2.2 Remarks on the screening process

The screening process allowed us to select 77 papers from an initial sample of 750 papers. We were able to pinpoint coordination issues within these papers by identifying mentions of interdependencies – between activities or actors of the value chain – and their consequences on market equilibriums. We then classified the papers by the level of description of the coordination issue.

If these interdependencies are described through a set of mathematical equations based on theories of economic behavior, we label the paper as "Modeled". When there is no modeling but a qualitative analysis on coordination issues (*e.g.*, giving normative viewpoints or perspectives), the paper is labeled "Detailed". The label "Mentioned" gathers simple mentions of coordination issues, such as future research perspectives, and mentions of interdependencies between stakeholders of the BECCS value chain with no description of associated coordination issues. Figure 1 shows this label information and points out that only one paper makes a modeling effort to represent the agents' interdependencies [35]. This proves that, although the importance of coordination in the success of BECCS deployment is known, it is barely accounted for in economic models.

We then extracted the data from the first three label categories (*Modeled*, *Detailed,* and *Mentioned*) by value chain segment: the bioenergy chain in Table 1; the CCS chain in Table 2; the BECCS plant in Table 3; and the overall implementation in Table 4. The first column of Tables 1–4, labeled "Issue," gives a general description of the deployment barrier. Then, in the second column, we identify interdependencies between activities or actors related to the given issue. When relevant, the associated stakeholders are identified in the third column. The consequences of the interdependencies on the market equilibriums are pictured in the fourth column, labeled "Suboptimal market equilibrium". Altogether, these pieces of information characterize coordination problems that may be addressed with policy recommendations, as described in the fifth column. Finally, the last column gathers the related sources.

3 Main coordination challenges to successfully deploying BECCS

Based on the systematic literature review described in Section 2, we portray three main coordination challenges to the upscaling of BECCS: (i) trading biomass and ensuring its sustainability; (ii) reducing costs through synergies with other industries and by shared CO_2 infrastructures; and (iii) coordinating policies internationally to provide revenues for BECCS.

3.1 Trading biomass

The scale of biomass supply needed to support an upscaling of BECCS consistent with Paris Agreement targets can be enormous, exacerbating the competitive resource dependency between countries for biomass supply and its complementary resources (*e.g.,* water, land, and energy). Smith *et al.* calculated that up to 700 Mha of land would be needed in scenarios relying heavily on BECCS [4]. Such an area is equivalent to Australia and up to 25% of global agricultural land. Hence, the envisioned BECCS deployment relies on the availability of a large enough sustainable biomass supply (which can be various, going from dedicated crops to algae and agroforestry residues). While domestic biomass supplies would be preferable, they may not always be sufficient or cost-effective for reaching national carbon removal targets, as Albanito *et al.* [36] showed for the United Kingdom. Hence, the locational disconnect between biomass potential and carbon storage potential suggests international trade. Favero and Massetti [35] model the international trade of biomass and suggest that unrestricted market mechanisms would be optimal as coordination means for a cost-efficient provision of biomass, as long as the environmental and social side-effects are low enough. These side effects are, in fact, concerning.

The environmental and social costs of BECCS have been a recurrent concern in the literature [37], and it is unclear how these could be internalized [4, 20, 38]. In an extensive review, Fuss *et al.* (2018) [3] classified the externalities of BECCS into three categories: (i) climate effects include direct and indirect land-use emissions related to deforestation and potential carbon leakage at storage sites; (ii) resource needs are affected by increased competition for lands, water, energy, endangering both food security and biodiversity; (iii) broader sustainability effects include the marginalization of poor local populations that are currently using marginal lands. Moreover, much of the biomass potential identified in IAMs lies in developing countries [39], where weaker institutions may allow an unfair distribution of the environmental cost of BECCS [40]. The marginal lands envisioned for biomass production may already be utilized by poor local populations living in informal economies, therefore not represented in economic models and political decisions [40]. Also, some African networks are concerned that negative emissions technologies such as BECCS could lead to more land grabbing on the African continent [39].

Taking into account previous considerations, many authors have recommended the use of sustainable biomass certification mechanisms [19, 20, 41–43]. Further research could explore the most appropriate market and contractual frameworks for large-scale international trade of sustainable biomass for BECCS.

3.2 Reducing costs

Implementing Carbon Capture and Storage (CCS) on top of bioenergy generates costs that are not yet covered by policy-enhanced revenues, *e.g.*, investment subsidies or tax reductions (see Sect. 3.3). Investments are hampered by high costs and investment risks associated with uncertain cost estimates and asymmetric information [44]. Leeson *et al.*, for example, provide carbon capture cost estimates ranging from 20 $/t$CO_2$ to 180 $/t$CO_2$ for refineries [45]. Therefore, knowledge sharing is critical for BECCS processes, especially as commercial deployment has not yet been reached [46, 47]. Some existing examples of knowledge sharing include partnerships with universities, such as for BECCS plant Drax and the University of Leeds in the United Kingdom [12], or with governmental bodies and knowledge-sharing platforms, such as for CCS cluster ROAD with the Dutch Ministry of Economic Affairs and the Global CCS Institute [48].

Besides knowledge, other symbiotic resource dependencies can be identified, such as waste and infrastructures that can be shared to reduce costs [24, 49]. A typical example of waste sharing is the potential synergy between BECCS and biochar through wood ash recycling, which decreased CO_2 abatement costs by 15% [50, 51]. In terms of CO_2 transportation and storage infrastructure sharing, a growing literature has explored the potential for CCS clusters [52–55]. This challenge has often been overlooked in IAMs, despite representing a crucial barrier to the upscaling of the technology [8, 56]. BECCS plants can only claim to remove CO_2 from the atmosphere if the CO_2 is stored permanently – *i.e.*, trapped geologically for at least several centuries. To that aim, the deployment of BECCS requires the construction of costly CO_2 transportation and storage infrastructures – usually pipelines or shipping lines for transportation [57, 58] and saline aquifers or depleted gas fields for storage [59]. Coordination is needed, as CO_2 capture, transportation, and storage are complementary activities [60], leading to the classic "chicken and egg" problem observed in network industries. That is to say: it is not worth building an expensive pipeline infrastructure without a critical mass of emitters capable of supporting its construction, and, reciprocally, absent any pipeline, the potential demand from users is unlikely to materialize.

Additionally, the early adopters of CCS typically face the dilemma of building the infrastructure ahead of demand – and thus operating the infrastructure with a low degree of capacity utilization during the early years – or installing a suboptimal infrastructure [18]. If the infrastructure's capital needs to be financed by the project's future cash flow stream, installing too much excess capacity can substantially raise the cost and, thus, the users' cost rates. If the initial output is small (which is likely to be the case with a nascent technology), one may wonder whether the revenue stream will be sufficient to recover the infrastructure costs.[3] Hence, deploying a shared CCS infrastructure requires cooperation between major industrial emitters within geographical clusters [18, 56, 61]. Governments could facilitate coordination between large emitters and CO_2 infrastructure operators by acting as central planners for CCS deployment or entering public-private partnerships [48, 60].

Finally, some specificities related to bioenergy need to be emphasized. BECCS remains a niche within the niche of CCS (as an example, the Global CCS Institute referenced over 150 CCS projects in 2020, of which 18 projects were referenced as BECCS projects [62]). Hence, although fossil energy with CCS and bioenergy with CCS (BECCS) can share the same infrastructure, there is a risk of BECCS lock-out in the deployment of CCS networks [63, 64]. CCS has primarily been financed by oil and gas stakeholders, conceivably because it can be considered a way to extend much of the fossil industry's operating time. Rent-seeking behavior and maintaining entry barriers through patents on carbon capture could be feared.

3.3 Coordinating policies

The lack of political prioritization remains one of the strongest barriers to the deployment of BECCS [65, 66]. Reducing the cost of BECCS processes (Sect. 3.2) will not be sufficient if available revenues remain scarce. Contrary to Fossil energy with CCS (FECCS), BECCS plants cannot benefit from tax reduction because of the (theoretical) neutrality of bioenergy in carbon accounting [67]. Therefore, policy-enhanced revenues are needed, *e.g.,* subsidies or carbon removal markets [21, 43]. While we will mention some policy instruments described in the literature, we mainly focus on the need for international policy coordination. This need is especially strong for the creation of regulatory safeguards.

[3] On that point, the literature on infrastructures provides several insights. Pipeline systems exhibits pronounced economies of scale, and their construction has an irreversible nature. In case of a growing future use, these two features together make it rational to engage in "building ahead of proven demand", as installing some degree of overcapacity may lower the present value of the infrastructure's total cost [99, 100]. These considerations are not specific to BECCS and are frequently discussed in the context of infrastructure projects located in developing nations [101, 102].

BECCS provides an environmental service by removing CO_2 from the atmosphere from a life cycle perspective [9], but the calculated volume of negative emissions can vary with methodology and scope [41]. Hence, negative emissions accounting needs to be standardized and coordinated internationally to (i) ensure transparency and comparability and (ii) avoid informational asymmetry and risks of double-counting [42, 68]. Considering the side effects described in Section 3.1, the design of environmental and social safeguards within such accounting and certification schemes will be critical. Some advances have recently been achieved in that regard, as Nehler and Fridahl highlight [68]. A proposal for carbon removal certification is underway within the European Union [69].

In addition to negative emissions accounting, economic incentives will be essential to ensure revenues and investor confidence. BECCS plants and CCS infrastructures face large capital needs, which can be supported through public funding (*e.g.*, the European Innovation Fund and Connecting Europe Facility) and public-private partnerships [70, 71]. Some dependencies described previously can be partly addressed by policy-enhanced revenues. Contracts for differences and reverse auctions, for example, have been proposed to cover the cost of providing negative emissions as a co-benefit and to cover the cost of building CCS clusters ahead of demand [9, 18, 70, 72].

Lastly, carbon removal credits illustrate the need for international policy coordination. The Paris Agreement acknowledges that international cooperation is a useful tool for cost-efficient carbon mitigation, especially considering that countries have "common but differentiated responsibilities" toward climate mitigation. In that line, the carbon mechanisms framed within Article 6 could facilitate international financial transfer towards BECCS and other negative emissions technologies [73]. Similarly, negative emissions credits could be integrated into domestic emissions trading systems like the EU ETS [70, 74]. At the time of writing, however, compliance markets for carbon removal remain immature, and carbon removal credits are essentially circulating on voluntary carbon markets (*e.g.*, Puro Earth) [72]. In addition, opinions on negative emissions pricing are divided. Zakkour *et al.* [75] suggest that negative emissions could be either rewarded identically to mitigated emissions – to ensure a cost-effective mitigation system – or at a higher rate, to account for the environmental service of removing CO_2 from the atmosphere. Torvanger [42] suggests that negative emissions should be discounted because of global carbon cycle feedback. A final strand of the literature suggests that negative emissions could be rewarded through cumulative emission taxation. In other words, firms pay for their cumulated emissions from the tax implementation date until they remove an equivalent amount from the atmosphere [76, 77].

Successful international coordination for reaching carbon removal targets may rely on markets for carbon removal credits – although there are still many implementation challenges to these markets. But even if carbon removal credits are to be exchanged, a high enough price for carbon removal has to be reached, and hence, enough demand for carbon removal [78]. Some firms have already shown a high willingness to pay for carbon removal [79], but national commitments will be needed too – for example, through Nationally Determined Contributions. If countries enter bilateral arrangements to exchange carbon removal credits, successful cooperation will rely on the possibility of reaching fair gainsharing.

4 Conclusions and future research

We most often recognize coordination when it is absent – whether it is a poorly managed supply chain or an unfair allocation of resources. Hence, this issue tends to be overlooked in the study of new technological processes such as BECCS, but it remains crucial. We described three main coordination issues that deserve more modeling efforts: (i) trading biomass and ensuring its sustainability; (ii) reducing costs through synergies with other industries and shared CO_2 infrastructures; and (iii) coordinating policies internationally to provide revenues for BECCS. These issues require policy regulations to account for externalities across international value chains, for example, through sustainable biomass and carbon removal certification. Public support is also needed to unlock complementary markets in the case of CCS chains, in which carbon capture, transport, and storage are highly dependent processes operated by distinct agents.

As expected, the broad definition used here presents limitations. The number of articles that fall into our scope is large, and dependencies may not be identified as such by the authors. A careful examination of each paper was required. Hence, we may have missed some relevant articles, and there is room for bias when deciding which activities are dependent or not. Additionally, our literature research focuses solely on BECCS, while additional articles can also be found in the literature on bioenergy and CCS separately. That said, we argue that the volume of literature we have examined is sufficient to identify the most relevant coordination issues.

The question of coordination has gained attention in the literature on BECCS but has yet rarely been subject to further consideration. Within our initial sample of 750 papers, we found 77 papers that mentioned some coordination need, but only one paper explicitly modeled the coordination process. Hence, while cooperation is repeatedly called for, future research could model and investigate the conditions for the successful coordination of BECCS deployment. For example, international cooperation is deemed to make it possible to leverage interregional differences in conditions and endowments to lower the total cost of BECCS.

However, such cooperation can only succeed if a mutually acceptable and fair distribution of the costs and benefits can be achieved. Identifying such a sharing can be complex and has extremely important policy implications and tangible effects in achieving the global greenhouse gas targets. Against this background, at least two strands of research offer relevant perspectives: (i) the empirical case studies of supply chains, which can consider the decision-making processes of various parties and the associated spatial consequences based on real data, and (ii) the application of cooperative game-theoretic notions, as this mathematical framework is particularly well-suited to examine gain-sharing problems. These methodologies could usefully inform the debates and represent an appealing direction for further research.

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