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Reports from stakeholder workshops on biomass-based carbon dioxide removal (CDR)

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Abstract

"How are different processes for removing CO_2 from the atmosphere perceived by stakeholders in different regions of Germany?" This question was explored in workshops of the project BioNET ("Multi-stage assessment of biobased negative emission technologies")[1] in order to better understand the potential and challenges of biomass-based carbon dioxide removal (bioCDR) technologies. Experts from industry, agriculture, forestry, NGOs and policy were involved in four stakeholder workshops to discuss bioCDR measures, their regional characteristics and socio-political trust. The results show that bioCDR technologies such as afforestation, pyrolysis of biomass (PyCCS) and peatland rewetting are seen as promising, but face regulatory, economic and social barriers. While there are regional differences in feasibility, there are recurring challenges such as land competition, lack of political support and uncertainties in financing. Particular emphasis was placed on the importance of cascading use in order to maximize the efficiency of bioCDR. The "Carbon Cascadia" simulation game we developed supported the discussion on biomass cascades and long-term CO_2 storage. The results highlight the need for targeted funding instruments and a coordinated policy framework, including citizen participation, in order to establish bioCDR in the long term. Without clear strategies and societal involvement, there is a risk that the potential of these technologies will remain untapped. The report provides valuable insights for research, policy and practice for the further development of bioCDR in Germany.

Keywords: biomass, climate policy, stakeholders, carbon dioxide removal, negative emissions, biomass-based carbon dioxide removal (bioCDR) technologies

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[1] See project website and profiles of different CDR methods: https://datalab.dbfz.de/bionet/home?lang=de

1 Introduction: BioCDR as an under-researched climate topic

Climate change continues to intensify, while international mitigation efforts remain insufficient to meet global targets (IPCC 2022). One increasingly prominent strategy for addressing this gap is carbon dioxide removal (CDR), also referred to as negative emissions (see overview in Smith et al. 2024). CDR methods remove CO_2 from the atmosphere in a variety of ways. These include afforestation and ocean fertilization as well as mechanical CO_2 sequestration (DACCS) or biomass energy with carbon capture and storage (BECCS). A substantial share of these approaches is based on biomass from wood, agricultural products, residues and waste (Borchers et al. 2024a). Biomass-based carbon dioxide removal (bioCDR) offers a key advantage in that it utilizes renewable or residual biomass to achieve long-term carbon removal and storage.

Climate policy measures related to bioCDR will remain highly relevant for the federal government during the 2025–2029 legislative period, as climate targets must be achieved and industrial interests in carbon capture and storage (CCS) negotiated at both the European and national levels. Key issues—such as the potential integration of promising yet conditional technologies like bioenergy with carbon capture and storage (BECCS) into Germany's long-term strategy for negative emissions (*Langfriststrategie für negative Emissionen*, LNe)—must not be neglected. Several scholars argue that, in addition to a long-term strategy, a "short-term strategy" is also required, given that the deployment of CDR involves significant lead times and cannot be deferred until the moment it becomes urgently necessary (Schenuit and Treß 2025).

The BioNET research project carried out a comprehensive assessment of the socio-political and scientific-technical aspects of bioCDR (https://www.ufz.de/index.php?de=49066). This endeavour involved the development of a transparent knowledge base, which included the creation of fact sheets (Wollnik et al. 2024) and the creation (Wollnik et al. 2025) and modelling of scenarios (Sadr et al. 2024) related to biomass use for CO_2 removal. Furthermore, the project engaged stakeholders from industry, agriculture and forestry, NGOs, politics and administration in the research process (Otto and Matzner 2024). The aim was to familiarize foresters, biochar producers, environmental protection associations and other interest groups with the current research, while also soliciting their assessments of contemporary issues arising from the practical implementation of bioCDR measures.

Climate change represents an unavoidable global challenge; however, the implementation of climate protection measures occurs primarily within regional contexts. This is particularly true for CDR, as many of the available approaches have seen limited regional deployment to date, despite their prominent role in international climate policy debates. Given that regional perspectives on CDR have thus far received insufficient attention in both policy and academic discourse, our research focuses on the concrete challenges of implementation at the regional level. Preliminary findings from surveys and interviews have shown the complexity of regional bioCDR deployment. Knowledge of some processes, particularly so-called "novel" technologies such as bioenergy with CCS (BECCS, Thrän et al. 2024; Sadr et al. 2024), is at best average or even low (Otto and Matzner 2024, p. 6). While the perceived relevance of bioCDR is consistently rated as high, levels of trust in political institutions and societal capacities to effectively implement climate technologies remain low (ibid., pp. 7-10). Our interviews reveal a lack of trust in the climate policy objectives of society as a whole (Matzner et al. 2025), which creates uncertain conditions for investment in CDR initiatives.

The workshops conducted as part of this study expand on the project's social science findings by incorporating the perspectives and knowledge of stakeholders, thereby providing valuable insights into the current state of CDR in Germany. The findings helped further to identify scenarios of bioCDR development (Wollnik et al. 2025). As we report below, the stakeholders are extremely diverse. Agricultural economists, land planning authorities, moor conservationists and even soccer clubs that want to offset their high CO_2 emissions from away games are all concerned with CDR or 'negative emissions'. Our stakeholder workshops took place in exchange with activities of the CDRterra research program funded by the Federal Ministry of Education and Research, which reflected that some stakeholders, for example, still have great reservations about the topic of CDR (El Zohbi et al. 2024).

Below we present the four BioNET stakeholder workshops from 2023-2024 in detail. This presentation is aimed at researchers, stakeholders and the interested public. Further scientific and policy advisory publications of the project are listed at the end of this article.

2 Overview of the stakeholder workshops

BioCDR has received limited attention in Germany to date and is currently applied only on a small scale. In response, the project team aimed to convene key stakeholders to foster dialogue and exchange. The workshops were designed to create a space for discussing the specific regional challenges and opportunities associated with bioCDR. The diversity of bioCDR approaches and the range of involved actors resulted in a complex and multifaceted picture. At the same time, it became evident that not only technical aspects, but also the broader societal attitudes towards bioCDR and carbon dioxide removal more generally, play a crucial role. In the following, we describe the structure and content of the workshops (see Table 1 for an overview).

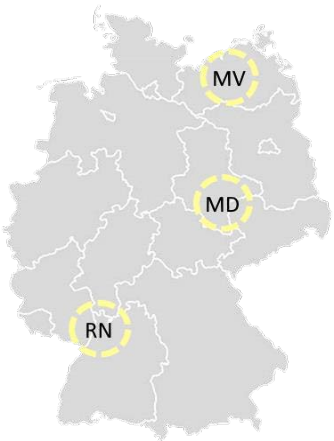


Figure 1: Regions of the Workshops Mecklenburg-Western Pomerania (MV), Central Germany (MD) and Rhine-Neckar (RN)

The first three workshops took place at regional level in 2023. They aimed to explore the potentials and challenges of bioCDR for the regions of Mecklenburg-Western Pomerania, Central Germany and Rhine-Neckar (Figure 1[2]) and to analyse the interactions between these technologies. In addition, the workshops aimed to (i) communicate findings from our research project to stakeholders, including via technology profiles, (ii) facilitate exchange between stakeholders and (iii) collect social science data. The discussions on data collection were structured by various methods, including (a) ranking the technologies according to their potential for the region, (b) discussing the challenges and (c) creating an interaction matrix in which different technologies were compared with each other.

[2] All photos and illustrations were created as part of the BioNET project. The rights are held by the authors of the article.

The fourth and final workshop was conducted nationwide and held online in February 2024. It focused on various dimensions of the development and implementation of biomass-based CDR processes. The aim was to discuss regional differences in the use and potential of CDR and to shed light on the political and legal framework conditions and possible application scenarios along various utilization paths. After an initial discussion on regional potentials and differences in CDR utilization, participants engaged in a simulation game in which they collaboratively developed CDR deployment cascades. This exercise aimed to identify potentials and difficulties along diverse utilization paths and to facilitate collective reflection on these aspects. The workshop concluded with a keynote speech offering detailed insights into current political and legal frameworks and ongoing policy developments.

<table>
<tr><th></th><th>Workshop 1</th><th>Workshop 2</th><th>Workshop 3</th><th>Workshop 4</th></tr>
<tr><td>Region</td><td>Central Germany,
Presence in Leipzig, 2023</td><td>Mecklenburg-Western Pomerania, online, 2023</td><td>Rhine-Neckar,
Presence in Mannheim, 2023</td><td>Supraregional,
online, 2024</td></tr>
<tr><td>Topics</td><td colspan="3">Potentials, challenges and interactions of bioCDR measures for each region</td><td>Scenarios and modeling of the development of CDR methods
Regional differences in CDR use and potential
Current framing of CDR
CDR usage cascades</td></tr>
<tr><td>Goals</td><td colspan="3">Providing information on the project and technology profiles
Exchange between stakeholders
Data collection</td><td>Presentation of project results
Exchange on regional differences in CDR use and potential
Lecture on the current political and legal framework of CDR
Identification of potential along various CDR usage cascades</td></tr>
<tr><td>Participants</td><td>7 participants from industry, agriculture, forestry, association of regional players, infrastructure and environmental protection</td><td>5 participants from industry, forestry, environmental protection & ecological management</td><td>10 participants from industry, agriculture, landscape conservation and research</td><td>11 participants from industry, agriculture, environmental protection, regional development and certification</td></tr>
<tr><td>Elements</td><td colspan="3">Project presentation
Round of introductions and expectations
Presentation of project results
Expert survey
Plenary and group discussions (data collection)</td><td>Project presentation
Round of introductions and expectations
Presentation of project results
Discussion (data collection)
Simulation game (data collection)
Keynote (Dr. Felix Schenuit, SWP)</td></tr>
<tr><td>Methods of data collection</td><td>Small group discussion: Ranking of technology options according to their potential
Plenary discussion on challenges
Interaction matrix (technologies compared)</td><td>Ranking of technology options according to their potential
Plenary discussion on potentials and challenges
Interaction matrix (technologies compared)</td><td>Small group discussion: Ranking of technology options according to their potential and challenges
(Interactions were recorded as part of the general discussion)</td><td>Plenary discussion on regional similarities and differences
Simulation game to identify potentials and challenges along various CDR usage cascades</td></tr>
</table>

Table 1: Overview of stakeholder workshops

3 Workshop 1 in Leipzig/Central Germany

3.1 Potential and challenges of bioCDR measures

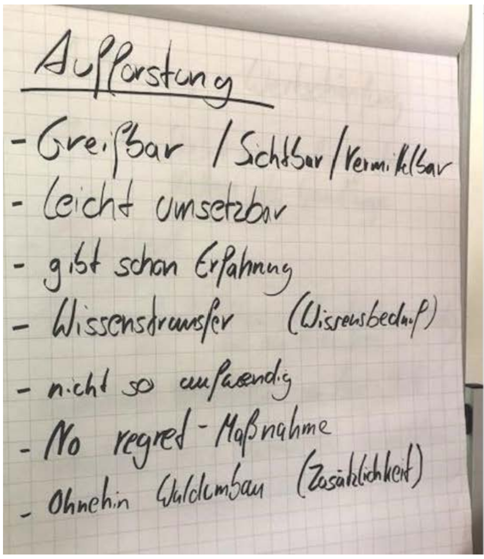
During the first workshop (Figure 2), participants identified afforestation and pyrogenic carbon capture and storage (PyCCS*, also known as biochar carbon removal, BCR*) as the most promising technologies, followed by agroforestry. Additionally, some participants advocated for peatland rewetting and paludiculture, decommissioning forest areas, and processing biomethane.

Figure 2: Workshop 1 in Leipzig. Presentation of interim results from the BioNET research project.

3.1.1 Afforestation

Stakeholders saw afforestation with different tree species as a central and promising silvicultural measure (Figure 3). According to experts in the research project, the potential of afforestation lies in its visibility, ease of communication, and relatively straightforward implementation that can draw on existing experience and expertise. Compared to other CDR approaches, afforestation is technologically less complex and is already being implemented in many regions as part of ongoing forest conversion processes and as a natural climate protection measure. It was therefore frequently described as a *no-regret* measure*.* Significant additional potential for afforestation and forest conversion was seen in the improved engagement of small private forest owners, who often make limited use of their land. Regarding its role in regional value creation, participants emphasized that afforestation represents the initial stage of regional value chains, thereby forming a foundational component. Regarding the question of what role afforestation can play in regional value creation, the participants emphasized that afforestation is at the beginning of the regional value chain and thus forms an essential basis for it.

Despite the many advantages, some of the challenges of afforestation also became clear. For example, it was pointed out that sufficient planting material is a prerequisite for long-term and successful afforestation. Although sufficient seed and planting material is still available nationwide, the shortage already occurring in central Germany could lead to problems in the long term. The afforestation of new forest areas is particularly affected by the shortage, as it takes a back seat to the currently necessary afforestation of existing forest areas, i.e. the reforestation of areas affected by calamities. Calamities must also be considered a challenge for the long-term planning of CO_2 sequestration. A possible double counting of afforested areas – on the one hand for government targets and on the other for offsetting the private or company CO_2 footprint – poses a further hurdle for afforestation as a climate protection measure.



Afforestation

- Tangible/visible/conveyable
- Easy to implement
- Experience already exists
- Knowledge transfer (knowledge needs)
- Not overly complex
- No regret measure
- Forest conversion takes place anyway (additionality)

Figure 3*: Afforestation as the most promising bioCDR measure in Workshop 1.*

3.1.2 PyCCS/Biochar

Pyrogenic carbon capture and storage (PyCCS) was given the highest priority among the long-lasting building materials. According to the experts, the potential of the technology lies in the fact that pyrolysis is a common technology for which there is already scientific and technical experience in the region, as the example of lignite shows. Carbon storage through PyCCS is less dependent on environmental factors and aims for durability – two further advantages that were mentioned in the workshop. In addition, the potential to link PyCCS with existing utilization paths such as bulky waste, sewage sludge and the recycling of residual materials was pointed out to enable synergies through a cascade extension and thus actual negative emissions. Sewage sludge processing is already taking place in the region. Other materials, such as bulky waste, could also be made usable for pyrolysis and no longer be used purely for energy. Overall, it was pointed out that PyCCS can be used in a variety of ways and therefore offers great CO_2 removal potential. Good feasibility and manageability were cited as further arguments.

On the one hand, natural gas could be used to produce biochar, which could then be stored in coal deposits. At the same time, a hydrogen network could be established for the Central German region. The use of biochar as a soil additive in agriculture was described as challenging, as the requirements for application under current fertilizer legislation are difficult (due to possible heavy metal contamination). In contrast, the use of PyCCS in the production of building materials was deemed more feasible.

3.1.3 Agroforestry

Agroforestry was identified as a particularly promising measure and was ranked as the highest priority by workshop participants among the concepts related to agriculture and soils. Agroforestry systems are regarded an attractive and relatively easy-to-implement technologies that offer temporal flexibility. In addition to their climate protection potential, these systems provide multiple co-benefits, including increased biodiversity, as well as improved soil quality and landscape structure. A combination of agroforestry systems and biomass utilization (e.g. in the form of biogas plants) was also discussed as a possibility in agriculture. From a regional value chain perspective, such integration could contribute to local energy supply and, due to its diverse cultivation and utilization options, play a significant role in regional value creation. Short rotation plantations (SRP)[3] were cited as practical examples of agroforestry systems that have been successfully established in the region over the past decade. Participants emphasized that legal support could significantly ease the implementation of such systems. Regarding challenges, the discussion focused on the legal requirements for EU funding opportunities for agroforestry systems. It was noted that EU funding has generally available for greening areas[4], but not specifically for agroforestry systems. Conversely, some participants highlighted that EU funding was also aimed at co-benefits and that funding for agroforestry systems was therefore also possible. The challenge was identified as the conversion times after a few years. Many farmers see hurdles or are unclear as to whether and how land can be converted. Like products derived from paludiculture, those from short rotation plantations are currently not profitable – at least not without subsidies. This situation could change if stricter decarbonization regulations increase the profitability of materials from renewable sources. However, there is an overall lack of technological openness and promotion, or political attention is focused on heat pump and solar technologies.

3.1.4 Peatland rewetting and paludiculture

Peatland rewetting was not ranked as a top priority in the workshop; however, it was identified as a relevant measure for reducing emissions in the LULUCF sector (land use, land use change and forestry). In Central Germany, particularly in Saxony-Anhalt, rewetting plays a significant role. Currently, 80,000-100,000 hectares of peatland in the region are drained and emit greenhouse gases. At the same time, there is limited awareness of the issue among many stakeholders. One way of increasing the attractiveness of rewetting is the dual use of land, combining agriculture with agrivoltaic systems.

3.1.5 Permanent and temporary set-aside of forest areas

This measure was not prioritized by the participants, as the set-aside of forest areas is associated with difficulties depending on the tree species and prevents climate-adapted forest management. While setting aside beech forests could allow for long-term carbon storage, the associated carbon stock would ultimately be released if the trees die due to climate change impacts, such as prolonged drought or heat stress. Targeted, climate-adapted forest management through the introduction of different tree species would not be possible with set-aside of forest areas.

[3] Fast-growing and productive woody plants such as willow and poplar are planted on short-rotation plantations. SRC and SRC strips are also referred to as energy forests due to the frequent use of woody plants as an energy source. They can also be used as agricultural land ("agricultural timber") (see e.g. https://www.nabu.de/umweltund-ressourcen/nachhaltiges-wirtschaften/biooekonomie/biomasse/kup.html).

[4] To be eligible for European Union agricultural subsidies under the Common Agricultural Policy, farms with more than 15 ha of arable land must create ecological focus areas (EFAs) or greening areas on 5% of their arable land.

3.1.6 Processing of biomethane

The processing of biomethane was briefly discussed as a possible supplementary measure to relieve the electricity grid and provide gas for electricity generation.

3.2 Interactions between bioCDR methods

Land competition emerged as a dominant theme throughout the workshop discussions, particularly regarding the need to continuously expand afforestation to achieve negative emissions (Figure 4). In addition to agriculture, afforestation also competes for land with renewable energies such as photovoltaic and wind power plants. This competition is expected to intensify as energy sector decarbonization increasingly demands renewable raw materials from agricultural sources. Several positive interactions were identified in carbon utilization cascades, particularly where paludiculture provides biomass for PyCCS. However, the industry's material quality requirements remain high. Similarly, cascade applications linking afforestation with biogenic gasification and PyCCS offer multiple benefits: efficient gas utilization, methane emission avoidance, and carbon removal from the atmosphere. In interactions between afforestation and agroforestry systems, a higher diversity of tree species minimizes the risk consequences of calamities. In the context of afforestation, small plants and birch seedlings can initially grow under the protection of the agroforestry practice "birch forest". Nevertheless, certain trade-offs require consideration. Short rotation plantations used for energy production may compromise building material quality due to high bark content. Furthermore, agroforestry and afforestation systems may compete directly due to product similarities, potentially displacing industrial wood sales from traditional forests with agroforestry-derived timber. The weak timber market is not good news for the forestry industry.

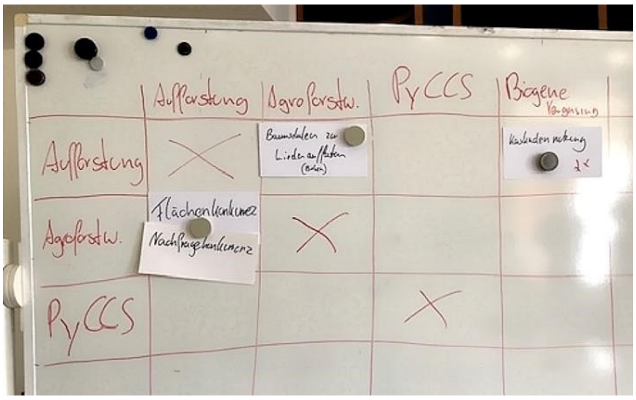


Figure 4: Interactions of the selected bioCDR measures

4 Workshop 2 in Mecklenburg-Western Pomerania (online)

4.1 Potential and challenges of bioCDR measures

In the second workshop, participants selected the rewetting of peatlands and paludiculture as the most promising technologies, followed by afforestation with various tree species and the conversion of arable land into permanent grassland and biochar as a soil additive (online ranking in Figure 5).

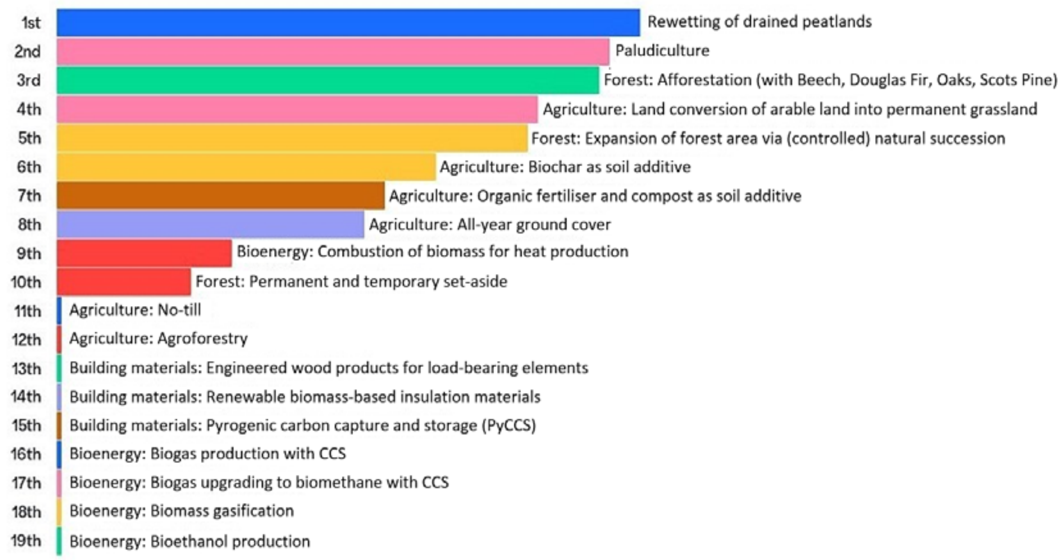


Figure 5: Online ranking of promising technologies for Mecklenburg-Western Pomerania

4.1.1 Peatland rewetting and paludiculture

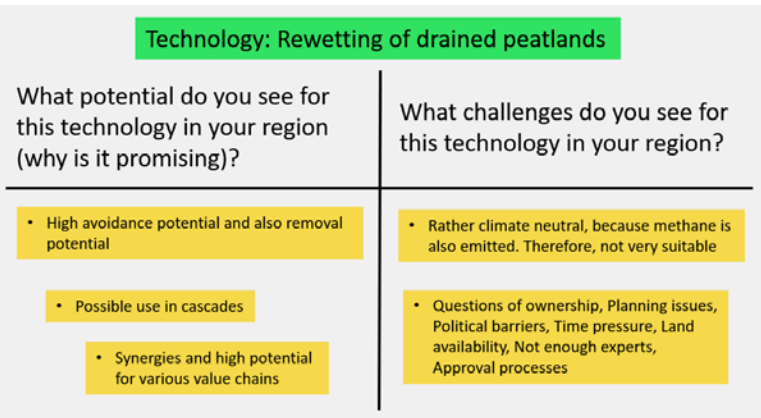


Figure 6: Potentials and challenges for rewetting

The potential of peatland rewetting and paludiculture lies in their capacity to avoid and remove CO_2 emissions, their possible cascading uses, the synergies between both approaches, and the facilitation of new value chains (Figure 6). Paludiculture can enable the continued productive use of rewetted agricultural land and offers various forms of value creation, such as energy production or the manufacture of insulation materials. However, significant challenges exist, particularly regarding the ownership and planning of rewetting measures. These include the need for a comprehensive overview of land availability, communication with landowners, approval processes, and land development. Moreover, there is a shortage of experts to support these planning and implementation processes. A further challenge concerns the rewetting of agricultural land, where usability and cultivability must be ensured for farmers.

The scaling-up of paludiculture is also hindered by a “chicken-and-egg” problem: since products such as reeds from paludiculture are not yet widely known or in demand, the number of potential buyers remains limited. This poses economic risks for farmers considering a long-term shift to paludiculture, as they may be left without a viable market for their products. Consequently, an accompanied transition to paludiculture is required, including suitable machinery and the development of upscaling strategies. A key prerequisite is the creation of market demand through increased awareness of paludiculture products. Finally, the discussion also highlighted that rewetting measures should not be considered entirely climate-neutral, given the release of methane emissions.

4.1.2 Reforestation

Important potentials of afforestation with different tree species are, on the one hand, the existing value chain and the growing demand for wood products. The prospect that forests and the use of wood as a durable building material (e.g. church roof trusses) enable long-term, centuries-long CO_2 storage was also highlighted as a major potential of afforestation. However, several challenges were also listed. As each afforested area can only be counted once, it must be considered whether an afforestation measure is either an initial afforestation or a reforestation, as only the former represents a negative emission technology. The amount of CO_2 stored can also be lower if monoculture (pure coniferous stands) is converted into mixed forests. Another limiting factor is the availability of land, which clearly limits the potential for afforestation in Mecklenburg-Western Pomerania (MV), for example. For example, 24 % of the state area in MV is forest, meaning that only a further 6 % (approx. 140,000 ha) could potentially be afforested to reach the national average of 30 %. In addition, there are risks of forest fires and other calamities, which can quickly release the stored CO_2 again. Finally, it was pointed out that although a cascade use of afforestation and PyCCS is promising, it requires several decades of growth. Consequently, reforestation cannot achieve rapid successes, which is problematic in terms of time regarding the climate targets to be achieved.

4.1.3 Conversion of arable land to permanent grassland

The conversion of arable land to permanent grassland and biochar as a soil additive were discussed as further important bioCDR concepts. The potential of arable land conversion to permanent grassland was mainly seen in the carbon storage through humus build-up in the soil, which is higher under permanent grassland compared to arable land use: a global humus build-up of 1 % can already achieve the global CO_2 storage potential. Compared to biochar, which requires plants to be burnt to produce it, building up humus allows more carbon to be permanently stored in the soil. Permanent grassland use also offers many advantages for nature conservation. The challenges of converting arable land to grassland include the loss of value for landowners when converting to permanent grassland, as this is worth less than arable land used for agriculture. Another problem is the Permanent Grassland Conservation Act. According to this law, grassland must be ploughed every five years (for example by growing maize) to maintain its status as arable land, which in turn would be devastating for the storage of CO_2.

4.1.4 Biochar as a soil additive

The potential of biochar for use as a soil additive is seen in its contribution to building up humus and thus in its high and long-lasting CO_2 storage potential. Biochar also enables the versatile use of biomass/residual material streams (e.g. sewage sludge) that are currently unused or are only incinerated or used for energy generation. Not only wood, but also many other organic materials could be converted into biochar by means of pyrolysis. In contrast to the use of biomass for biofuels, which does not remove CO_2 from the cycle, biochar offers the advantage of being an actual negative emission technology. Challenges in the use of biochar were seen in particular in the competition with other possible uses and the (limited) availability of biomass. There is a risk here that various technologies, such as the production of biofuels, also consume biomass and therefore compete with biochar, but do not contribute to the storage of CO_2. The fact that sales opportunities for the waste heat generated, for example in the form of district heating pipelines, have not yet been established in some cases is another challenge. In order to supply the waste heat to the right customers, plants must be installed close to the customers' locations. However, due to the existing lack of space, it is difficult to obtain the necessary permits. Another problem is that the production of biochar is not economically viable if there is no connection to the district heating network.

4.2 Interactions between bioCDR measures

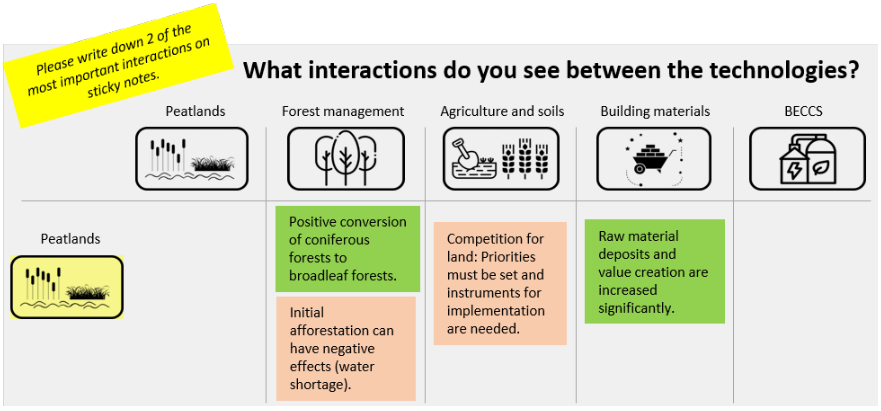


Figure 7: Concept Board on interactions between bioCDR measures (detail)

During the workshop, the interactions between silvicultural measures and peatland rewetting and paludiculture were discussed (Figure 7): The conversion of coniferous forests into deciduous forests, which enables better groundwater storage, was listed as a positive interaction. One disadvantage is the competition for water from initial afforestation near a bog. Negative interactions between peatland rewetting and all technologies in the agriculture and soils category were seen primarily in terms of competition for land on organic and mineral soils. There is a need for agreement on the prioritized land use and the instruments of implementation. The question was also raised as to whether there could be other options for prioritization beyond monetary "levers". For example, it was pointed out that the biodiversity crisis should also be addressed in the debate on these technologies and not just the need to protect the climate - for example in the case of grazing and species conservation. Synergies in this regard would be possible as part of the "Natural Climate Protection" action program (ANK). The interactions between peatland rewetting, paludiculture and long-lasting building materials were clearly classified as positive, as both raw material deposits and value creation are greatly increased by combining these technologies. However, for the potential between paludiculture and sustainable building materials to be exploited, the chicken-and-egg problem described above must be solved.

5 Workshop 3 in Mannheim/Rhine-Neckar region

5.1 Potential and challenges of bioCDR measures

In the third workshop, insulation materials based on renewable raw materials and load-bearing elements made from engineered wood products were considered to be of high regional relevance in the building materials category (Figure 8). Year-round ground cover and agroforestry were also classified as relevant. The following technologies were discussed less intensively in the afternoon: Biogas, durable building materials, bioethanol and managed succession.

Figure 8: Workshop 3 in Mannheim. Discussion with the BioNET experts.

5.1.1 Building materials: Insulation materials based on renewable raw materials

A wide range of potentials has been identified for insulation materials based on renewable raw materials, particularly in the context of waste prevention, as they are generally easier to dispose of than conventional building materials. Compared to chemical insulation materials, those derived from renewable resources offer significant advantages in terms of disposal. Moreover, these materials provide a synergy effect during use: they contribute to energy savings while enabling long-term carbon storage. The construction industry offers numerous opportunities to integrate such substitute products. Depending on the type of raw material, cascading use of residual materials can also create additional sources of income—for instance, through the production of value-added products such as mushrooms cultivated on agricultural by-products. Further potential lies in the recycling of residues for electricity generation. A central challenge, however, is to ensure the consistent supply of raw materials. Wood waste and cellulose must be generated and reliably sourced, and local wood supplies must be secured. Cellulose foams made from beechwood could be particularly promising in regions with extensive beech forests. Yet, the absence of local manufacturers and suppliers presents a logistical barrier. Additional challenges include competition for land use, as well as ensuring the durability and quality of the materials (Figure 9).

Figure 9: Workshop 3 Potentials and challenges of four bioCDR measures

5.1.2 Building materials: Load-bearing elements made from engineered wood products

The discussion on load-bearing elements made from engineered wood products was concise but highlighted key aspects. Participants emphasized the material's potential, noting its ease of implementation and excellent structural properties as a building material. Despite being a well-established construction material, challenges remain regarding regional availability. Engineered wood products are not produced locally in the Rhine-Neckar region, and only a few manufacturers exist within Germany. Consequently, these materials often need to be imported over long distances, leading to delivery times of several months. Moreover, loadbearing timber products have high technical requirements, particularly in terms of statics and corresponding regulations (e.g. fire protection).

5.1.3 Agriculture: Year-round ground cover

The storage of carbon was identified as a potential benefit of soil cover, alongside its protective effects against evaporation and soil erosion. An additional co-benefit lies in the preservation and potential enhancement of soil biodiversity. Participants also noted possible synergies with the Federal Ministry of Food and Agriculture's (BMEL) Protein Crop Strategy. At the time of the workshop, demonstration farms were being sought to test and promote the approach. Realizing the potential of the BMEL's protein crop strategy requires active involvement from the industry. This includes informing and engaging farmers, as well as establishing a functioning value chain. However, the actual effectiveness of carbon storage through continuous soil cover remains contested. Further challenges include the impracticability of many phytosanitary measures and conflicts between plant species and local moisture conditions. While year-round ground cover is a widely discussed and increasingly implemented practice, its suitability is highly site-specific and depends on factors such as soil type. Moreover, many farmers remain sceptical about its economic viability. As with all technologies, acceptance, stakeholder engagement, and effective knowledge transfer and information are crucial. The use of modern communication channels—such as YouTube—was highlighted as a promising means to support these efforts.

5.1.4 Agroforestry

Numerous potentials were identified for agroforestry systems. These include the diversification of farms, enabling them to become more resilient to market fluctuations and to enhance their economic viability;

the possibility of dual land use, thereby increasing the effective land area; contribution to local recreation, positive effects on the landscape, erosion and evaporation control, and the promotion of biodiversity. Furthermore, agroforestry is considered to be well-suited to adapting to accelerated climate change, and its full potential may not yet be realized. Pharmaceutical companies, for example, have expressed interest in domestically produced phytopharmaceutical plants, which could be cultivated in shaded agroforestry systems. This could also increase the added value from agricultural production. In this context, participants emphasized the importance of considering and appropriately valuing the full range of ecosystem services provided by agroforestry systems – ideally also in monetary terms.

However, significant challenges were also identified. Current policy frameworks do not sufficiently support agroforestry, and the increased production costs—due to more complex management requirements and long establishment periods—are difficult to compensate. Additional investments in machinery and infrastructure may be necessary. These factors pose obstacles in the Rhine-Neckar region, where farming is often conducted on a part-time basis. Although a machinery ring exists in the region, allowing farmers to share equipment, broader (especially political) support is lacking for the efficient implementation of such systems. Another regional limitation is the small size of agricultural plots, which constrains the integration of additional structural elements. Overall, the development of value chains and acceptance among actors must be strengthened. Concerns were also raised regarding potential displacement effects – both of certain animal species and of food production – through the cultivation of renewable materials. Although orchards are formally classified as agroforestry systems, they were assessed as economically unviable for the region.

5.1.5 Biogas

The potential of biogas for bioCDR applications is primarily seen in its ability to provide reliable base-load energy. Unlike intermittent renewable energy sources such as solar and wind, biogas can supply energy constantly and independently of sunshine or wind. Stakeholders highlighted the advantage of being able to integrate biogas into existing infrastructure as well as the additional potential of utilising waste heat. Regionality was identified as another key strength of biogas applications, particularly in terms of generating regional economic value. For example, biogas-generated electricity can be used locally for electric car-sharing services, and waste heat can be used to warm outdoor swimming pools. The combination of energy generation from waste processing could also be expanded. For example, the material use of cardboard packaging could be promoted and energy use at the end of the cascade. The reuse of waste from insect farming – particularly for fat and protein production – was noted as another promising avenue. However, concerns were raised regarding the efficiency of biogas systems: in particular, the ratio of energy output to the material and energy inputs remains unclear. This issue is especially pertinent in the context of biowaste, which is typically heterogeneous and subject to seasonal fluctuations. Such variability leads to lower specific yields and requires biogas plants to be highly flexible to process diverse feedstocks efficiently. Social acceptance emerged as a critical challenge. The negative public perception of biogas – especially from maize – persists due to the “food vs. fuel” debate, even though maize, in technical terms, has good properties as an energy source and requires relatively low chemical input. Here, too, stakeholders emphasized the lack of financial support as a major barrier. Stable and long-term funding is needed to ensure planning security considering the substantial investment costs associated with biogas infrastructure.

5.1.6 Durable building materials

The potential of durable building materials is primarily seen in the circular economy or sensible cascading use. Renewable raw materials and biochar were identified as particularly promising components in this context. However, participants noted that the broader adoption of durable, bio-based materials is hindered by the strong influence of established industry actors, particularly within the cement sector. This lobbying power presents a significant structural barrier to market entry and scaling. To make durable building materials competitive with conventional ones, stronger support measures are needed. This includes promoting their use more actively so that they can be priced on equal terms, particularly in view of the significantly lower life cycle costs of conventional materials.

5.1.7 Articulated succession in silviculture

In addition to its carbon storage function, the potential of articulated succession in silviculture lies in the possibility of creating species-rich habitats through targeted management. However, legal regulations that prohibit grazing in forests were identified as a key obstacle. As a result, managed succession is currently not economically viable. There is a need for a regulatory framework that allows for experimentation in this area.

5.1.8 Bioenergy

Stakeholder saw biomass as a viable alternative to fossil fuels for energy generation, offering a comparatively low CO_2 footprint. They identified considerable potential in further integrating energy production with waste processing. This, in turn, could enable regional electricity supply and create local economic value. At the same time, stakeholders noted that bioenergy with carbon capture and storage (BECCS) is not expected to play a significant role in the region in the near future. Concrete applications of biogas and bioethanol were also discussed in more detail (see below).

5.1.9 Bioethanol

Bioethanol was regarded as a raw material that can replace fossil-based ethanol. A key advantage lies in the possibility of using existing infrastructure, which could facilitate its integration into current systems. However, workshop participants also emphasized a major challenge common to many bio-based technologies: the need for large quantities of biomass. Biomass is already cost-intensive compared to fossil resources, and increasing demand — along with competition for its use — is expected to drive prices up further. Without regulatory intervention, stakeholders argued, this situation is unlikely to change, and the economic viability of bioethanol will remain limited.

5.2 General discussion

In the overarching discussion on bioCDR, stakeholders called for clearer strategic objectives. At the same time, they repeatedly emphasized the importance of addressing specific technical and contextual details. Participants noted that any broader assessment of bioCDR must be grounded in a clear understanding of which raw materials should be used for which purposes. For example, if the primary goal is CO_2 avoidance, sugar beet was seen as a promising feedstock. If, by contrast, the focus is on promoting a circular economy within a heterogeneous landscape, other plant varieties may be more suitable for biogas production. In such cases, stakeholders stressed that high-quality biomass should be prioritized for high-value uses, such as food production. The role of catch crops, such as hemp, was also highlighted – not only for their biomass potential but also for their contribution to soil improvement. In this context, some stakeholders questioned whether it might be necessary to move away from the current focus on homogeneous, plannable raw materials, particularly when aiming for pure CO_2 capture and storage. Overall, the discussions underscored the need to consider how diverse biomass uses can be meaningfully integrated into cycles.

6 Workshop 4 – Supra-regional synthesis workshop

6.1 Discussions on the role of regions in bioCDR

Figure 10: Synthesis workshop across the three regions. Participants anonymous

The first discussion in the fourth workshop focused on the similarities and differences between the three regions and, more broadly, on the role of regions in the implementation of bioCDR (Figure 10). Stakeholders responded positively to the presentation of project results, though some offered critical remarks – in particular, the need to take international supply chains into account, even when working from a regional perspective. According to participants, the significance of regions for bioCDR implementation is closely tied to questions of economic viability. For most technologies, a central consideration is whether it is more cost-effective to use regionally sourced biomass or to rely on imports, either from other federal states or from abroad. In this context, cheap imports were seen as a major factor in economic calculations. Examples included wood chips from Poland for use in combined heat and power plants, or wood imports from Ukraine and Romania, which remain less expensive, as regulatory standards applicable in Germany often do not apply to production in these countries. Stakeholders emphasized that the issue of biomass pricing is likely to intensify in the future, particularly if new technological applications further increase demand, such as the use of biochar in the cement industry. At the same time, supply chains for regionally available alternative raw materials, such as those from paludiculture, are not yet sufficiently developed. As a result, market transparency is lacking. For operators of combined heat and power plants, this leaves an incalculable risk as to whether about whether adequate raw material supplies can be reliably secured if they commit to using paludiculture feedstocks. In light of these risks and given that imported materials are already cheaper and reliably available, decisions often favour imports over regional alternatives.

Potential sales markets were also mentioned as a key factor in determining the profitability of bioCDR technologies. Biogas plants could generate higher revenues if they were able to feed into the existing gas grid. However, this connection is technically complex and therefore costly. In addition, many grid operators impose barriers to access – such as minimum feed-in quantities – which are often unattainable for smaller plants. Instead, these operators frequently source gas from other European countries. This situation further complicates regional implementation, particularly because – as with biomass supply chains – the market for biogas in Germany remains insufficiently secure and structured. As a result, again, imports are often preferred due to their reliable availability. Many participants viewed this reliance on imports critically, particularly from an environmental perspective. Concerns were raised about the externalization of environmental burdens to other countries, including the generation of significant transport-related emissions. These emissions, stakeholders noted, are not currently reflected in the pricing structures, which distorts the comparative assessment of regional versus imported options.

Questions of justice, including climate justice and concerns about food insecurity in certain countries, were also considered relevant by many participants. However, other stakeholders challenged the argument of land-use competition. They pointed out that many bioCDR technologies already rely on residual materials from food production, which should be viewed as part of a cascading use system rather than as direct competition with food production. Reducing societal meat consumption was mentioned as a strategy to decrease pressure on land use. Further potential for reducing land-use conflicts was seen in the use of paludiculture, which could also serve as a feedstock for biochar production. In this context, stakeholders noted that energy use may be particularly viable on land that is otherwise unsuitable for agricultural or other productive purposes.

The topic of political support was the subject of controversial debate among participants. Some stakeholders advocated for stronger national regulation to safeguard or enhance the economic viability of producing regional raw materials. They argued that regional biomass can only compete with imported alternatives if clear political decisions are made in favour of regional sourcing, environmental protection, climate justice, and CO_2 avoidance across the entire supply chain. Various regulatory approaches were discussed. One option identified to strengthen regionality is the expansion of municipal heat supply systems. In this context, participants referred to the municipal heat planning law, which encourages municipalities to promote regional processes. The energy transition was also seen as a strategic opportunity for municipalities that engage early: by positioning themselves on the path to climate neutrality, they can actively attract businesses and, in doing so, potentially increase local tax revenues.

Another option discussed by participants was to account for the origin of biomass when calculating negative emissions, to evaluate whether net negative emissions are achieved once transportation-related emissions are considered. One proposal was to introduce a CO_2 surcharge at the border to create a level playing field between regional and imported biomass. However, stakeholders also noted that certification systems are not without drawbacks. There is a risk that land-use conflicts could intensify – as is already observable in the context of agrivoltaics, where land is being diverted from food production. The problem of "double-claiming" was also raised as a concern, particularly considering the increasing number of different certificate schemes entering the market.

Previous subsidy schemes were critically reflected upon. For instance, participants pointed to subsidies for bio-LNG in truck transport, which had temporarily reduced imports. With the expiration of these subsidies, more biomass imports are now expected.

Not all participants supported the idea of further political intervention. Some warned of over-regulation and criticized existing measures. The "maize cap," for example, was seen as politically driven and responsible for price increases. Others mentioned exhaust gas regulations that prohibit straw burning, thereby limiting its use as a residual material.

6.2 Simulation game on bioCDR cascades

The frequent discussions and critiques of biomass cascades in the first three workshops prompted the project team to explore the concept of cascade utilisation of biomass for CO_2 removal in greater depth. BioCDR cascades offer not only the advantage of allowing biomass products and biogenic CO_2 to be used in multiple stages. Cascades are also necessary to ensure that biomass and its products provide long-term CO_2 storage. For example, trees extract greenhouse gases from the atmosphere and store them in wood. The decommissioning of the forest causes the carbon to be stored in the forest itself (see Figure 11). However, this storage is vulnerable to disturbances such as forest fires. Processing harvested wood into biochar and storing or applying it extends the cascade and enhances the durability of carbon storage.

The project team, in particular Danny Otto and Nils Matzner, designed a card game called "Carbon Cascadia" for mapping bioCDR cascades. This card-based mapping game is designed to help players construct and analyse potential bioCDR cascades. The goal is to develop cascades that are efficient, cost-effective, long-term, and sustainable – ideally producing additional co-benefits such as energy generation or biodiversity conservation (for more information, see http://carboncascadia.org/).

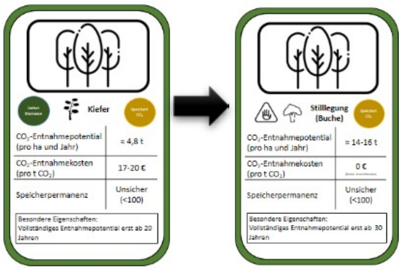


Figure 11: "Carbon Cascadia" simulation game on bioCDR cascades

Game materials – including playing cards, arrows to link cards into cascades, markers, and a game board (or a suitable surface) – were printed on paper and sent to participants ahead of the workshop. During the workshop itself, the online version of *Carbon Cascadia* was played collaboratively and subsequently evaluated by the group.

6.2.1 Group 1 – Focus on wood biomass and utilization issues

The cascade developed by the first group (Figure 12) began with afforestation as a form of forest expansion, although there was disagreement among the participants regarding the choice of tree species. Douglas fir was considered by some to offer economic potential, while others rejected it due to its status as a non-native species. As an alternative, oak was proposed, particularly for its positive effects on biodiversity.

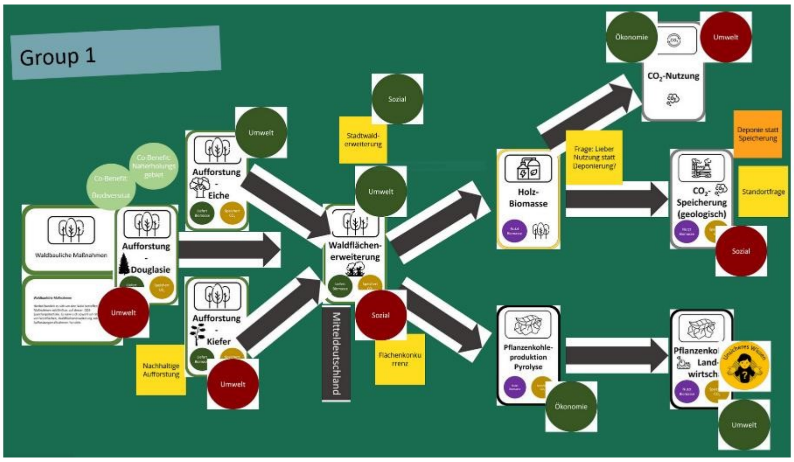


Figure 12: Biomass cascade of group 1 in the "Carbon Cascadia" simulation game

A mixed forest was also discussed as a viable compromise, as it can provide multiple co-benefits — for example, serving as a local recreation area and contributing to urban climate adaptation by offering cooling effects in summer when located near cities. Nonetheless, participants noted that forest expansion also has drawbacks, most notably the increased competition for land, particularly in relation to agricultural use.

The group discussed two possible pathways for utilizing the harvested wood within the cascade. One option was the generation of electricity through combustion. The resulting CO_2 could be captured and used in the beverage industry, which is currently an attractive option. While CO_2 utilization has the disadvantage of not resulting in permanent carbon storage, it was noted that it can at least displace fossil-based CO_2 sources (for modelling of such utilization pathways, see Sadr et al. 2024). Regarding long-term CO_2 storage, participants expressed concerns about both the social acceptance of storage technologies and the availability of suitable storage sites within Germany. One participant emphasized that this does not necessarily require a binary choice between utilization and storage. Instead, a phased approach could be pursued: CO_2 utilization might continue in the near term, while negative emissions become more relevant closer to 2050. The second pathway discussed was pyrolysis of wood to produce biochar. The main economic advantage of this approach was seen in the marketability of biochar, especially given its low transport costs and potential for international trade. However, participants also highlighted the benefits of domestic application – particularly in agriculture, where biochar can improve water retention and contribute to humus formation.

6.2.2 Group 2 – Forest set-aside and agricultural recycling management

Group 2 explored regional aspects of expanding forest areas and afforestation in the Rhine-Neckar region (Figure 13). Participants noted that certain areas – for example, elevated or sloped terrain – could be designated as long-term forest set-asides due to their geographical characteristics. These areas were considered to offer particularly high potential for CO_2 storage. As in Group 1, participants emphasized the recreational value of expanded forest areas and identified biodiversity co-benefits associated with afforestation.

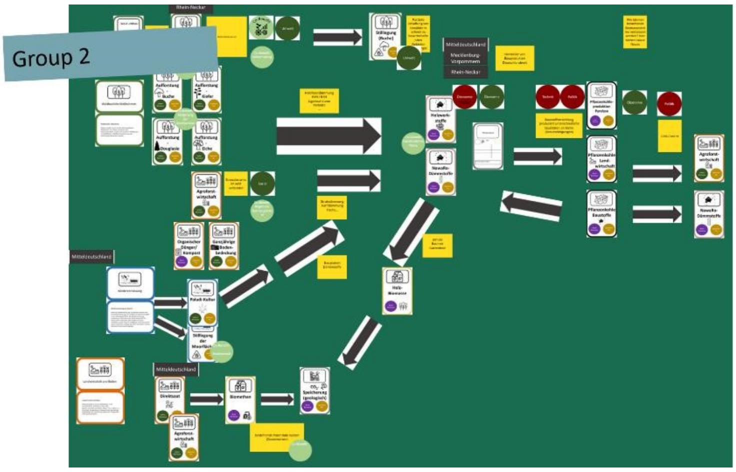


Figure 13: Biomass cascade of group 2 in the "Carbon Cascadia" simulation game

Afforestation on calamity areas in the context of forest conversion was also seen as advantageous in terms of the effectiveness of land use. This could create synergies with existing adaptation needs – not only in the Rhine-Neckar region, but also in Saxony-Anhalt. The group discussed multiple potential uses for the harvested wood, including its application in wood fibre insulation (KHV/BHS), lignin foam, and parquet flooring. Substitution effects were identified as an additional co-benefit, and participants noted that energy recovery could help extend the lifetime of building materials and insulation products made from renewable raw materials (NawaRo).

Participants also highlighted the cyclical nature of these material flows: cascades could be designed to include repeated loops, feeding materials back into circular systems. However, some challenges were also discussed. Long transport distances to processing facilities were seen as a limiting factor. Moreover, downstream uses such as charring waste wood may be complicated by the presence of chemical additives or variable wood quality.

6.2.3 Group 3 – Wood biomass and biochar

Group 3 also began their cascade with silvicultural measures, in particular reforestation (Figure 14). The focus was on mixed forests of pine and Douglas fir, which are considered more adaptable. Nevertheless, participants emphasized that beech and spruce should also play a role. Forest set-aside was discussed as another option, particularly with a view to promoting natural growth and integrating nature conservation objectives. However,

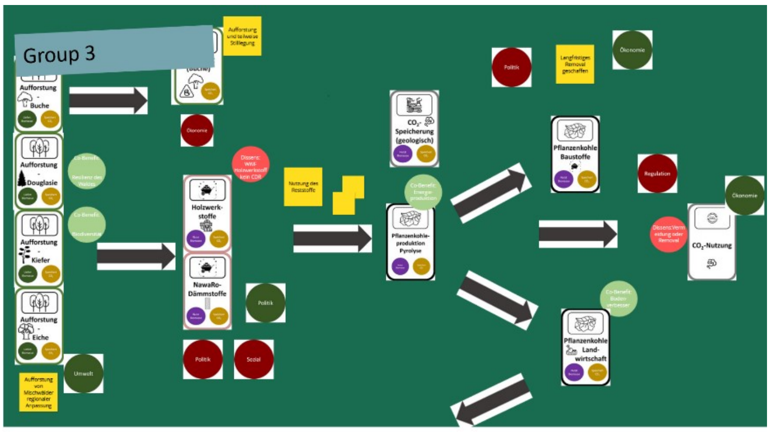


Figure 14: Biomass cascade of group 3 in the "Carbon Cascadia" simulation game

participants pointed out the economic disadvantage of this strategy, as it does not generate direct revenue.

The group identified wood-based materials as one possible use for the harvested wood. It was noted, however, that such applications serve primarily as avoidance strategies rather than as carbon dioxide removal (CDR) methods in the strict sense. Another discussed option was the production of insulation materials from renewable raw materials (NawaRo), which could be supported through policy instruments such as environmentally friendly public procurement under the EU Green Public Procurement framework. The production of biochar via pyrolysis, particularly from residual biomass, was also discussed, as this allows CO_2 to be captured and stored. Pyrolysis with energy production was seen as a co-benefit. In addition, the use of biochar in agriculture was discussed, especially for improving soil fertility. There was disagreement within the group regarding the potential use of the CO_2 produced during pyrolysis. Some participants questioned whether this offered long-term removal potential. Overall, the cascade was discussed primarily in terms of maximizing CO_2 removal, though participants also emphasized the importance of further considering economic aspects.

6.2.4 Group 4 – Wood-based materials and agroforestry

As in the other groups, Group 4 identified afforestation as a top priority, particularly in central Germany and the Rhine-Neckar region (Figure 15). The discussion focused on Douglas fir in mixed forests with spruce. However, participants critically noted that these species are less climate-resilient and susceptible to pests such as the bark beetle. A further challenge lies in the procurement of saplings, which must be sourced regionally. Due to limited supply and high demand, prices are correspondingly high.

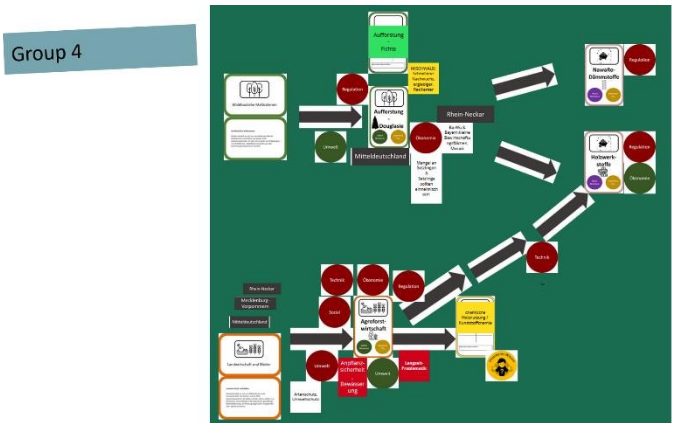


Figure 4 Biomass cascade of group 4 in the "Carbon Cascadia" simulation game

In the positive side, participants emphasized the existing expertise in forest management and wood processing. Reforestation was generally seen as beneficial for the environment, with additional resilience gains in calamity areas, for example, improved stability in the face of storms.

NawaRo is seen as a possible use for the wood and for CO_2 storage. However, regulatory barriers remain, particularly in relation to fire protection. Similarly, the use of wood in construction (as wood-based materials) faces constraints due to fire safety and noise protection regulations. Nevertheless, participants noted that increased scaling could reduce costs in timber construction, potentially creating an economic advantage.

A second cascade discussed by the group cantered on agriculture and agroforestry. Disadvantages identified included the high maintenance requirements, fragmented land ownership, and legal constraints. Many lease agreements are tailored to conventional agriculture, making transitions to agroforestry difficult from both a regulatory and contractual standpoint. Political support was considered essential to facilitate the establishment of orchards and other agroforestry systems.

The environmental impacts of agroforestry were seen as highly dependent on the design of the areas. For instance, poplars, while resembling monocultures, can still contribute positively to biodiversity, microclimates, and habitat for beneficial insects – as well as providing shade. However, poplars are currently not in demand as a construction material due to technical limitations; existing processing technologies and material standards are not adapted to these species. That said, participants saw potential for future applications in lightweight construction, such as tiny houses or mobile homes.

Chemical applications of agroforestry products were also briefly mentioned, though the group did not pursue this further due to limited knowledge. At the end of the cascade, energy use was considered a reasonable option to recover value from residual biomass.

6.2.5 Evaluation of the simulation game

The "Carbon Cascadia" simulation game was characterized by lively and engaged discussion. Although some participants were initially hesitant to engage with the online whiteboard format, everyone was ultimately able to articulate their critical perspectives. The game highlighted that cascades pose challenges at certain points, as well as conflicts of interest between the individual stakeholders.

In their cascade designs, participants demonstrated a strong focus on solution-oriented approaches. They sought to construct coherent cascade sequences and to identify key opportunities and challenges at each stage. This emphasis on practical problem-solving suggests that stakeholders, when provided with a structured and participatory format, are inclined to think constructively across sectoral boundaries.

During the plenary discussion, participants proposed several practical measures. One suggestion was the establishment of a central EU-level register for carbon monitoring, i.e. a central recording and regulation of flows like that for green electricity. However, participants also pointed out that such an approach could be hindered by excessive regulatory complexity and conflicts between EU and national regulations. Similarly, a certification system (e.g., a "green certificate") was viewed critically, as it could impose higher costs, increased bureaucratic requirements, and additional administrative burdens on suppliers.

These discussions reflect broader findings of this study: stakeholders can generate innovative governance proposals when engaged in interactive formats, yet they remain acutely aware of the practical and political barriers to implementation. The simulation game thus served not only as a tool for eliciting ideas but also as a mirror of the institutional and regulatory constraints that shape real-world bioCDR deployment.

The success of the mapping game motivated Danny Otto and Nils Matzner to develop Carbon Cascadia further. The future game will be a serious game for schools, which explains how difficult but interesting cascading of CDR can be.

7 Concluding remarks

The workshops conducted in both regional and supra-regional contexts generated a range of detailed findings and valuable social science data. They also achieved the objective of providing stakeholders with opportunities for knowledge exchange and active integration into the research process.

Stakeholders faced the complex task of critically discussing and weighing diverse goals and values in relation to CDR. Among the many issues addressed, a recurring tension emerged between the aim of ensuring safe, long-term CO_2 storage and the preference for ostensibly “near-natural” solutions such as reforestation, agricultural measures, or peatland rewetting. The sustainability of CO_2 storage in such approaches is increasingly called into question, not least due to the impacts of advancing climate change.

Stakeholders also highlighted significant political, technical, environmental and regulatory challenges and took a particularly critical view of newer approaches such as BECCS. In addition, the use of captured CO_2 proved to be a contentious issue, industrial applications were seen by some as incompatible with long-term removal objectives, raising doubts about their genuine climate benefit. Clear differences between stakeholder groups – particularly between industry and NGOs – were apparent in these debates.

A key finding of the workshops was the recognition of the importance of cascading biomass use. The need to link biomass production, processing, and storage in a coherent and efficient manner, frequently discussed in the first three workshops, informed the design of the *Carbon Cascadia* simulation game. Its application in the supra-regional workshop provided further insights into cascade construction preferences and illustrated how partially conflicting interests could be navigated in a concrete implementation scenario. The simulation game thus served as both a means of eliciting practical proposals and a reflection of the regulatory, technical, and political constraints that shape real-world bioCDR deployment in Germany.

Overall, the diversity of bioCDR methods, their potential cascading configurations, and the variety of associated stakeholders create a level of complexity that policymakers and the wider public must understand to enable meaningful and sustainable implementation. No single method emerges as the unequivocally “best” option. Rather, a portfolio approach – tailored to regional conditions and balancing the respective advantages and disadvantages of different CDR measures – appears most promising for integrating bioCDR into effective climate strategies.

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